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Effects of cement and foam addition on chemo-mechanical behaviour of lightweight cemented soil (LWCS)

Domenico De Sarno[1,*], *Enza* Vitale[2], *Dimitri* Deneele[3], *Marco Valerio* Nicotera[1], *Raffaele* Papa[1], *Giacomo* Russo[1,2], and *Gianfranco* Urciuoli[1]

[1]University of Naples Federico II, Department of Civil, Building and Environmental Engineering, Italy
[2]University of Cassino and Southern Lazio, Italy
[3]Institut des Matériaux Jean Rouxel (IMN), Université de Nantes, CNRS; IFSTTAR, France

Abstract. One of the main problems encountered in civil engineering is the management of large amounts of excavated soil, especially when the mechanical properties of this soil are not suitable for its reuse as a construction material. However, the excavated soil could represent a resource if appropriately improved. A suitable solution is the addition of cement and foam to produce lightweight cemented soils (LWCS). In this paper, an insight into the influence of foam on chemo-mineralogical and microstructural features of soil-cement-water system is presented. Time dependent mineralogical and microstructural changes have been monitored by means of X-Ray Diffraction, Thermo-gravimetric analysis and Mercury Intrusion Porosimetry. The present study shows that addition of foam does not alter the chemo-physical evolution of the soil-cement-water system. Large voids are present in the samples as footprint of air bubbles upon mixing, thus increasing porosity. Macroscopic behaviour of treated samples has been investigated by direct shear and oedometric tests. Chemo-physical evolution induced by cement addition is the major responsible for mechanical improvement showed by treated samples. Porosity of samples induced by foam addition plays a key role in the mechanical response of LWCS, inducing a transition of stress-strain behaviour from brittle and dilative to ductile and contractive as a function of increasing foam content.

1 Introduction

Ground improvement techniques based on binder addition to improve mechanical performances of soils are well-established in geotechnical engineering practice, such as deep mixing and lime stabilization [1–3]. The latter, as well as cement stabilization, allows to reuse excavated soils, otherwise regarded as waste, as a construction material leading to clear advantages from both economic and environmental points of view. Due to the increasing importance of these ground improvement techniques, the mechanical behaviour of artificially cemented coarse and fine grained soils has been widely investigated [4–10].

A suitable technique to produce a geomaterial with specific properties is the lightweight cemented soil method [11], which requires the addition of air foam, a dispersion of air bubbles in a surfactant solution, to a soil-cement-water mixture. The method, in principle, can be applied to any kind of soil except for very coarse particles that can segregate in the fresh paste.

The soil cement-water-mixture must be characterized by low viscosity to be mixed with the foam which also enhances flowability; thus, the resulting mixture can be poured and easily used in different cases, such as void filling and trench reinstatement. Bubbles constituting foam are entrapped in the viscous slurry till setting and subsequent hardening, thus increasing porosity and decreasing bulk density; this also implies that compaction has not to be applied, which together with self-levelling properties related to the high flowability leads to a reduction of construction time. Due to low bulk density, this material can prove to be useful for construction purposes on soft soils, as shown by some authors [12–14]. However, chemo-mechanical properties of lightweight cemented soils have not been extensively investigated [15–17].

In this paper, an experimental study on the effects of foam on chemo-physical evolution of lightweight cemented soils is presented. Tests have been performed at increasing curing time to investigate the evolution of the soil-cement-water-foam system. At microscale, X-Ray Diffraction and Thermogravimetric analyses were carried out to investigate the mineralogical evolution, whereas microstructure was investigated by means of Mercury Intrusion Porosimetry. The effects of foam addition and chemo-physical evolution on mechanical behaviour of lightweight cemented soils have been investigated by means of direct shear and oedometric tests.

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[*] Domenico De Sarno: domenico.desarno@unina.it

2 Materials and methods

2.1 Lightweight cemented soil method

The lightweight cemented soil is produced by mixing soil-cement-water slurry with foam. This latter is a dispersion of bubbles in a surfactant solution [18].

Soil is mixed with water at a water content, w_s, higher than liquid limit to obtain a slurry; cement, whose amount can be defined through the cement factor c/s, that is the ratio between the anhydrous cement (c) and the dry soil (s) [1], is added to soil slurry at a specific value of w_c/c, that is the ratio between water and cement by weight. The amount of foam can be set based on different approaches [8, 17, 19]. In this study, the porosity induced by foam n_f, defined as the ratio of volume of foam to theoretical total volume of material, was adopted. The theoretical volume of material (that is only a reference quantity, because it can be different from the actual volume) is the sum of volumes of grout, soil slurry and foam (V_{grout}, $V_{soil\,slurry}$ and V_f respectively) (1):

$$n_f = \frac{V_f}{V} = \frac{V_f}{V_{soil\,slurry} + V_{grout} + V_f} \qquad (1)$$

The volume of soil-cement-water mixture is assumed to be equal to the sum of volumes of grout and of soil slurry in the likely hypothesis that air is not entrapped in those components. When foam is added, due to the presence of air bubbles, actual volume of material and porosity induced by foam can result to be different from theoretical values; thus, n_f should be regarded as a design parameter. Once the volume of soil-cement slurry is known, the amount of foam can be easily calculated by introducing the variable e_f':

$$e_f' = \frac{V_f}{V_{grout} + V_{soil\,slurry}} = \frac{n_f}{1\text{-}n_f} \qquad (2)$$

The mix design parameters w_s, c/s, w_c/c and n_f have been used in this study.

2.2 Testing methods

2.2.1 Mineralogical and microstructural analyses

Mineralogical composition has been investigated by X-Ray Diffraction analysis performed on randomly oriented powder using a Brucker AXS D8 Advance Diffractometer with CuKα (λ = 0.154 nm) radiation and a step size of 0.021°. Thermo-gravimetric analyses (TGA) have been performed with the Netzsch STA 449F3 Jupiter, equipped with a mass spectrometer; samples were heated up to 1000 °C with heating rate of 10 °C min^{-1} under argon atmosphere. Mercury Intrusion Porosimetry (MIP) tests were performed by a double chamber Micromeritics Autopore III apparatus. The detected entrance pore diameters range between 134 μm and 7.3 μm (approximately 0.01 MPa - 0.2 MPa for a mercury contact angle of 139°).

2.2.2 Mechanical tests

Direct shear tests were performed with a standard displacement-controlled apparatus on prismatic 60 x 60 x 20 mm samples. Displacement rate was set to 0.005 mm/min in all the tests. Micrometer dial gauges with a resolution of 0.001 and 0.01 mm have been respectively used to measure vertical and horizontal displacements. Oedometric tests have been performed with a standard apparatus on cylindrical samples 20 mm high and 56 mm in diameter.

2.3 Materials

The soil used in this experimental study is the Speswhite kaolin, a fine-grained soil produced by Imerys Minerals, UK, from deposits in the Southwest of England, with specific gravity, G_s, equal to 2.6. The liquid and plastic limits are 70 % and 32 %, respectively. It is mainly composed of kaolinite with small amounts of muscovite and quartz. Portland limestone rapid hardening cement (CEM II/A LL 42.5R) was used as cementitious material. The foam was produced from a commercial surfactant solution with an industrial foam generator at a density approximately equal to 75 g/L.

2.4 Specimens preparation

Samples were prepared by following the lightweight cemented soil method procedure. Dry kaolin was mixed with distilled water at w_s=1.4, that is two times liquid limit. Grout was prepared with distilled water at w_c/c=0.5 and mixed thoroughly with soil slurry. The cement factor c/s was set to 0.2 and 0.4. Lightened samples were prepared with n_f equal to 0.2 and 0.4; tests on non-lightened samples were also performed. A summary of mixtures tested in this experimental study is reported in Table 1. Mixture was poured in moulds and seal cured. Specimens for mineralogical and microstructural analyses were trimmed from samples and freeze dried before testing.

In the following, samples are indicated by the acronym KcsXnfY_Zd which refers to specific mixture and curing time: “K” stands for kaolin, X is the cement factor in percentage, Y is the porosity induced by foam in percentage (if any) and Z is the curing time in days (d). Acronym of non-lightened samples is KcsX_Zd, with the same meaning of symbols.

Table 1. Summary of tested mixtures.

	w_c/c	w_s [%]	c/s [%]	n_f [%]
Sw kaolin	0.5	140%	20%	/
				20%
				40%
			40%	/
				20%
				40%

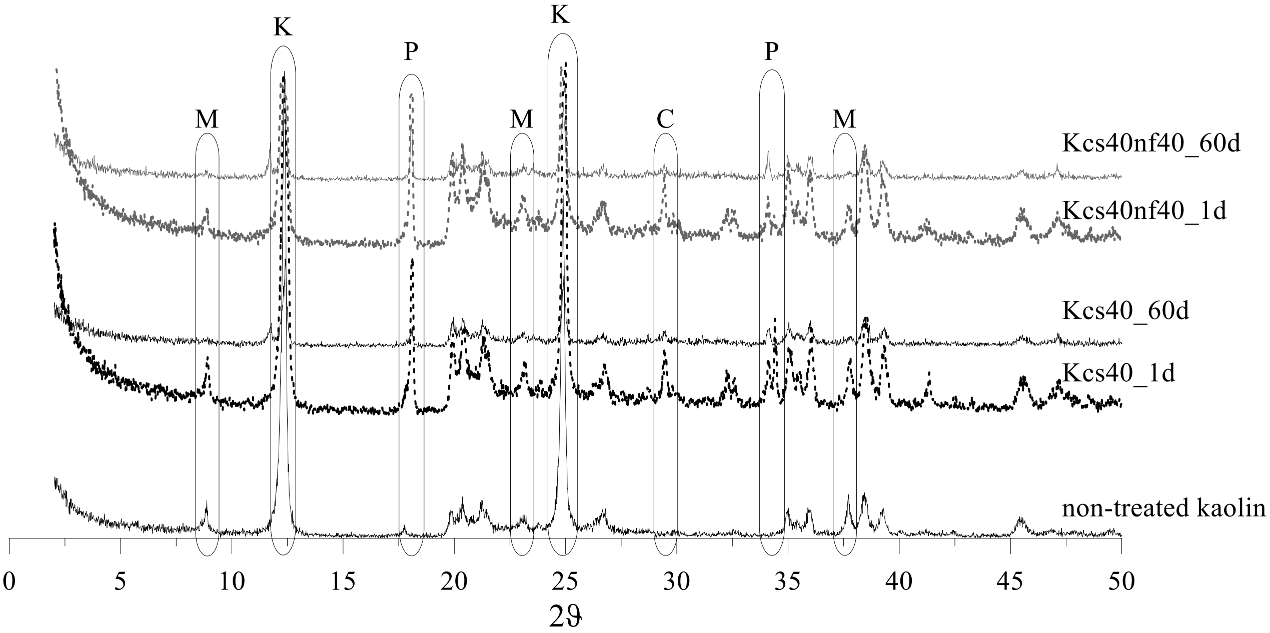

Fig 1. XRD analyses on treated and non-treated kaolin. C, K, M and P refer to Calcite, Kaolinite, Muscovite and Portlandite and Kaolinite, respectively.

3 Results

X-ray analyses on treated and non-treated kaolin are reported in Figure 1. Peaks observed on treated samples can be related to portlandite and calcite, which decrease over time, suggesting their partial consumption. Partial consumption of kaolinite and muscovite is also observed. Similar results are found on lightened samples, suggesting that there is no effect of foam on chemo-physical evolution of the system.

TGA analyses on treated samples are shown in Figure 2; results on grout and non-treated kaolin are also reported. The latter shows a peak in mass loss between 500 and 600 °C, which is related to kaolinite and muscovite dehydroxylation. Mass loss of grout is mainly divided in three ranges of temperature: the weight loss in the range 105 – 350 °C is related to hydrates decomposition [20], the mass loss between 400 and 500 °C is related to portlandite decomposition, whereas calcite decomposition occurs between 700 and 900 °C, in accordance with results of Lothenbach et al. [21]. Lightened (Kcs40) and non-lightened (Kcs40nf40) samples at increasing curing time show similar patterns. The mass loss between 100 and 350 °C (absent in non-treated kaolin) is related to cement hydration products, which increase with curing time. Peak in mass loss of portlandite (which slightly decreases with curing time) cannot be well appreciated on treated samples due to proximity of kaolinite peak; however, at increasing curing time, a slight reduction of portlandite mass loss is detected, which is consistent with XRD results. As already pointed out, the weight loss in the range 105 – 350 °C is related to water chemically combined in products of hydration, and it can be defined as non-evaporable water, $W_{w\ n\text{-}ev}$, at 105 °C in cement paste.

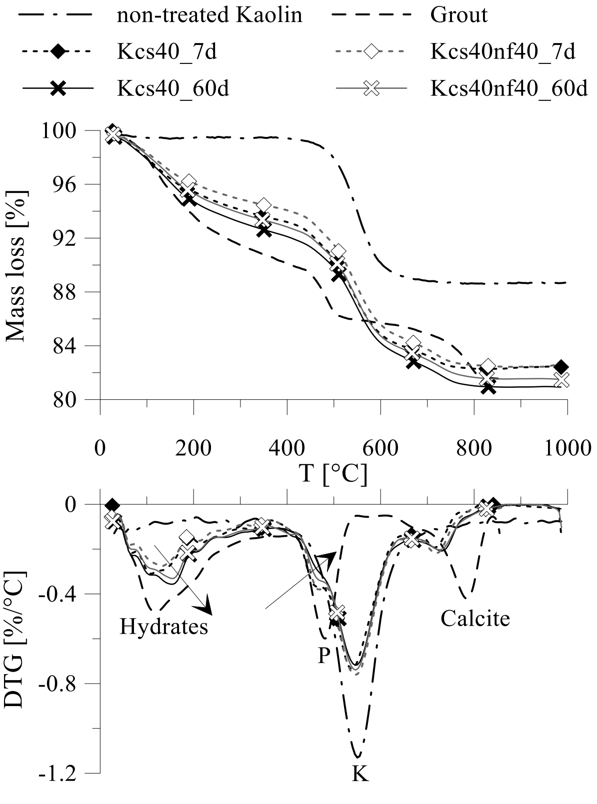

Fig 2. TGA on treated samples at different curing times; Speswhite kaolin (dotted line) and cement grout (dashed line) are also reported; P and K refer to Portlandite and Kaolinite, respectively. Arrows indicate increasing curing time. DTG is the rate of change of mass.

Non-evaporable water can be used to study the progress of hydration [22]. The ratio between non-evaporable water and the amount of anhydrous cement,

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[*] Domenico De Sarno: domenico.desarno@unina.it

αx, can be used to compare treated samples at different cement factors (3):

$$\alpha x = \frac{\text{Weight loss in } [105°\text{-}350°]}{W_{c,\,a}} = \frac{W_{w\,n\text{-}ev}}{W_{c,\,a}} \qquad (3)$$

In Figure 3 the evolution of αx for different mixtures is reported; the evolution of Kcs40 and Kcs40nf40 is quite similar; the same results have also been found on Kcs40nf20 samples, confirming that foam does not alter chemo-physical evolution of soil-cement-water system. Samples treated with c/s=0.2 show slightly higher values of αx.

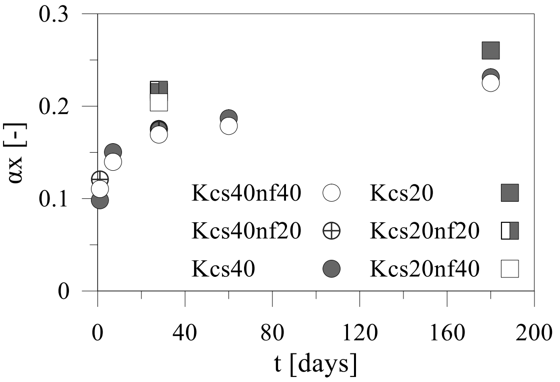

Fig 3. Evolution of αx with curing time on cemented and lightweight cemented kaolin.

The effect of air foam on microstructure has been highlighted by means of MIP analyses. The addition of foam on soil-cement-water mixture does not alter the modal pore size but increases pore frequency above 0.5 µm and overall porosity (Figure 4).

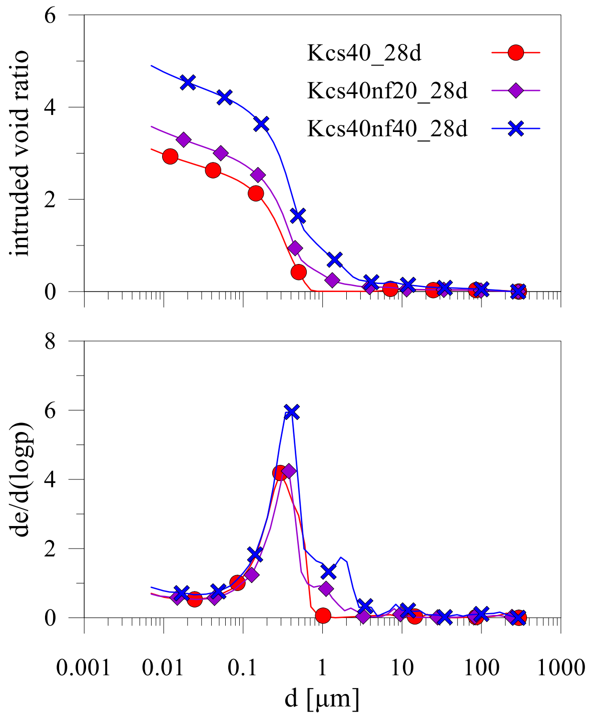

Fig 4. MIP analyses on treated kaolin at increasing foam content.

The increase of porosity determines a reduction of bulk weight. In Figure 5 average bulk weight of mixtures has been reported; lines refer to theoretical value assuming volume and weight as the sum of volumes and weights of soil slurry, grout and foam.

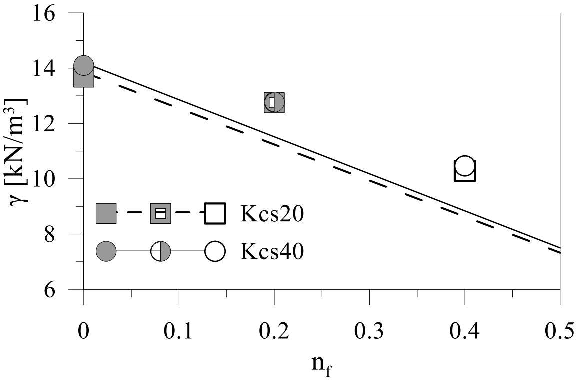

Fig 5. Average values of mixtures bulk unit weight at increasing foam content.

The bulk weight of lightened samples is higher than theoretical values, while the one of non-lightened samples is the same. This is due to bubbles breakage upon mixing of lightened mixtures. However, despite foam breakage, lightened mixtures are characterized by a significantly higher void ratio.

Figure 6 shows results of oedometric tests on treated kaolin. Regardless of cement factor, void ratio significantly increases with the addition of foam (Figure 6b). All the treated samples show the same stiffness in elastic region whereas unloading strains are negligible. However, the increase in porosity leads to a significant reduction of yield stress, which is highlighted in Figure 6a.

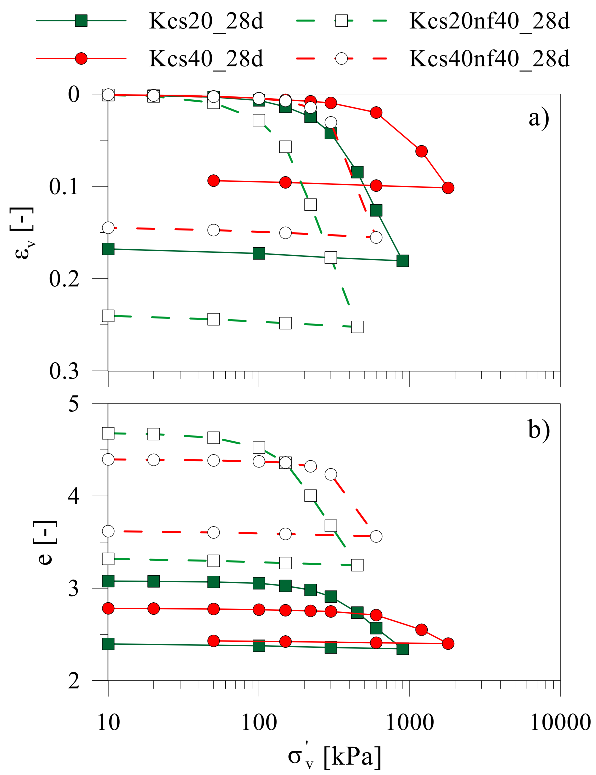

Fig 6. Oedometric tests on treated kaolin after 28 days of curing.

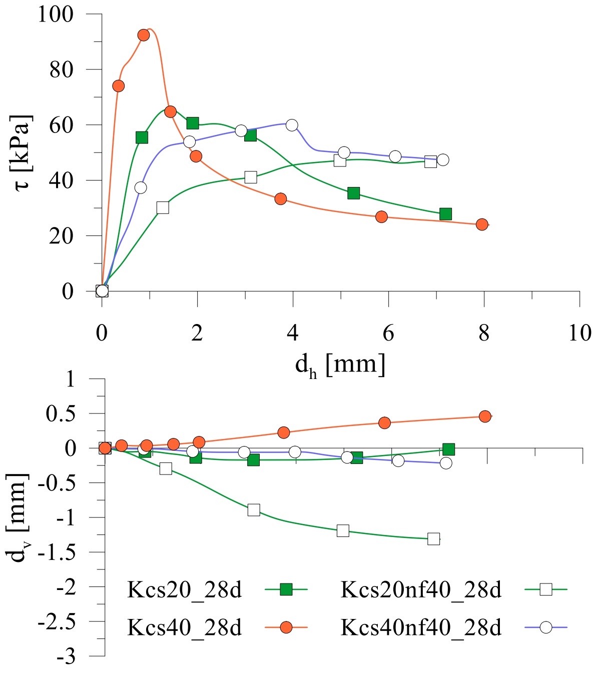

Fig 7. Direct shear tests on treated kaolin after 28 days of curing with σ'_v=50 kPa at increasing foam content.

Results of direct shear tests at 28 days of curing on treated kaolin are shown in Figure 7. Kcs40 sample shows a brittle behaviour with a clear softening after peak strength; the volumetric behaviour is slightly dilative. A similar behaviour was observed for Kcs20 sample; initial stiffness and brittleness decrease. By comparing lightened and non-lightened samples at the same cement factor, a transition to a ductile and contractive behaviour is observed, along with a significant reduction of peak strength. This gradual transition has been observed at increasing foam content, as shown in Figure 8.

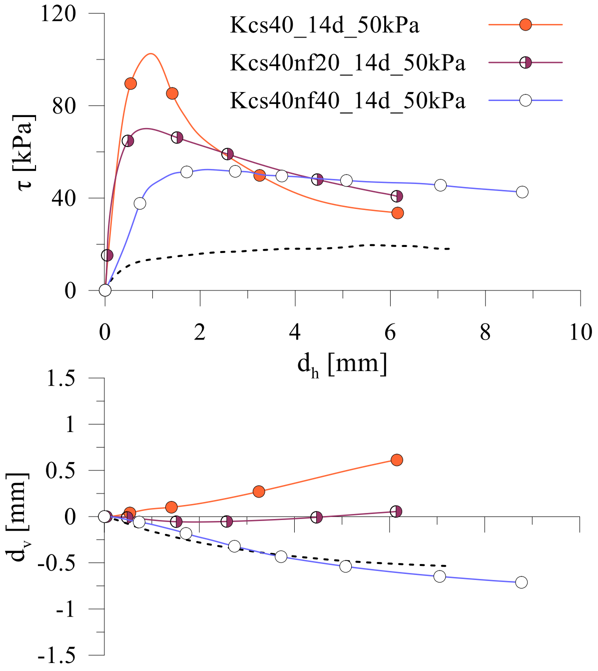

Fig 8. Direct shear tests on treated kaolin after 14 days of curing with σ'_v=50 kPa at increasing foam content; dotted line refers to non-treated kaolin.

Finally, a comparison between direct shear tests at σ'_v=100 kPa on Kcs40 and Kcs40nf40 at increasing curing time (i.e. 7, 28, 60, 90 days) is presented (Figure 9). The non-lightened mixture shows an increase in the peak strength with time whereas the strength at high deformations is approximately the same; thus, a more brittle behaviour is observed. Volumetric behaviour is dilative after peak and deformations increase at increasing curing time. An increase in peak strength with curing time is observed for lightened samples too, which leads to a slightly softening behaviour after 90 days of curing. The volumetric behaviour is always contractive and (except for sample at 90 days of curing) deformations decrease with time.

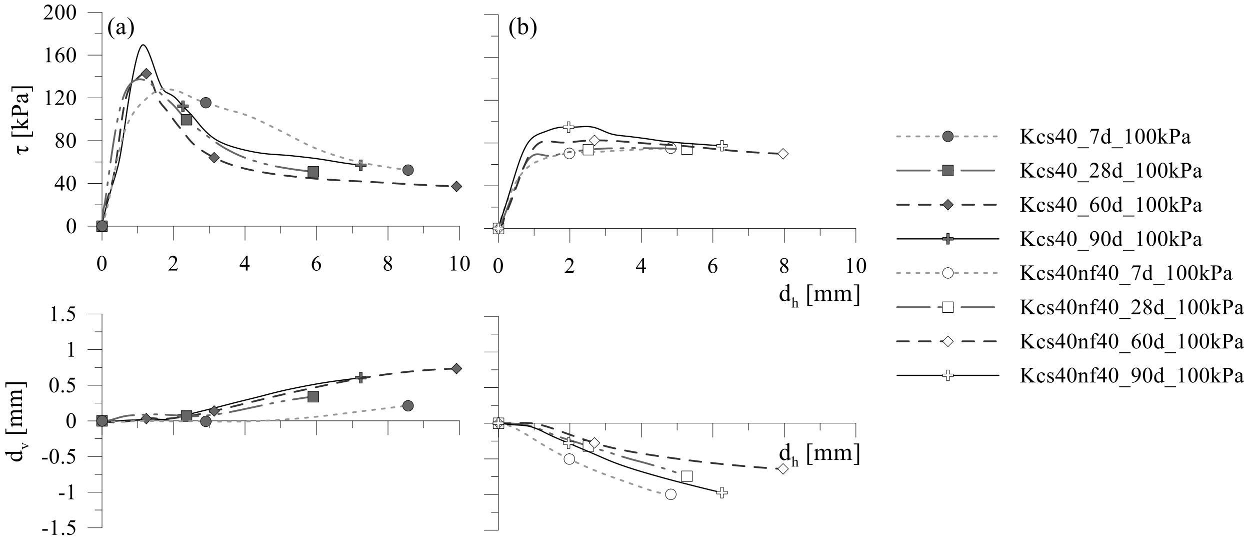

Fig 9. Direct shear tests on Kcs40 (a) and Kcs40nf40 (b) at increasing curing time (σ'_v=100 kPa).

4 Conclusions

In the present work, an investigation on chemo-physical evolution and mechanical behaviour of lightweight cemented soils has been shown. The effect of foam addition and curing time has been highlighted. Results of micro-scale investigations have been directly linked to the experimental evidences at the volume scale of the sample. Mechanical improvement of treated samples depends on cement hydration and pozzolanic reactions. Air bubbles are responsible for porosity increment of lightweight cemented samples whereas addition of foam does not alter the chemo-physical evolution of the system. The increase in porosity induced by foam is responsible for yield stress reduction in oedometric loading; furthermore, at increasing foam content, a transition from a brittle and dilative behaviour towards a ductile and contractile behaviour as well as shear strength reduction is observed.

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[*] Domenico De Sarno: domenico.desarno@unina.it