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Effects of aggregate size on water retention capacity and microstructure of lime-treated silty soil

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Lime treatment is a common technique of improving the workability and geotechnical properties of soils. In this study, the aggregate size effects on the water retention capacity and microstructure of lime-treated soil were investigated. Two soil powders with different maximum aggregate sizes (D_{max} = 0·4 and 5 mm) were prepared and stabilised by 2% lime (by weight of dry soil). Soil samples were prepared by compaction at dry side of optimum water content (w = 17%) with a dry density of 1·65 Mg/m^3. Suction and pore size distribution were determined after different curing periods. The results obtained show that: (*a*) the treated soil with smaller D_{max} presents relatively smaller modal sizes and lower frequency of macropores (10–330 μm); (*b*) lime addition effectively improves the soil water retention capacity and decreases both the modal sizes of macro- and micropores gradually over time. Moreover, a higher air entry value and larger water retention capacity were also observed for a smaller D_{max} value, in agreement with the pore size distributions.

KEYWORDS: fabric/structure of soils; laboratory tests; soil stabilisation

INTRODUCTION

Lime treatment is a widely used soil improvement technique that can efficiently modify soil plasticity, compaction properties and the hydromechanical behaviour (Boardman *et al*., 2001; Russo, 2005; Consoli *et al*., 2009; Al-Mukhtar *et al*., 2010; Tang *et al*., 2011; Tran *et al*., 2014). It was reported that soils treated in the field behave differently from those prepared in the laboratory. Generally, field samples have higher hydraulic conductivity (Bozbey & Guler, 2006), higher swelling potential (Cuisinier & Deneele, 2008), and lower strength and stiffness (Kavak & Akyarh, 2007; Tang *et al*., 2011). It is believed that the soil aggregate size effect may be one main factor for this difference, as indicated by Tang *et al*. (2011). Indeed, in the laboratory, soils are usually air dried and ground into few millimetres, then treated with lime; a similar procedure is applied in the field, while the size of soil aggregates could be several centimetres before lime treatment.

It is recognised that water retention curve is an important element in analysing the hydromechanical behaviour of unsaturated soils (Barbour, 1998; Fredlund, 2000). Russo (2005) and Tedesco (2006) determined the water retention curve of a lime-treated silt using a pressure plate apparatus and observed that the water retention capacity increased significantly with curing time. Khattab & Al-Taie (2006) also observed an increasing water retention capacity of a lime-treated soil with the increase in clay fraction, lime content and curing time.

Based on the pore size distribution (PSD) curve obtained from mercury intrusion porosimetry (MIP) test, the soil water retention curve can be determined (Prapaharan *et al*., 1985; Romero *et al*., 1999). Moreover, the MIP test provides a good insight into the soil microstructure. Numerous studies have shown that the microstructure of lime-treated soils changed during curing. It was reported that the addition of lime affected the macroporosity for a short term due to the flocculation process of clay particles, while in the long term an increase in smaller micropores occurred due to pozzolanic reactions (Russo *et al*., 2007; Lemaire *et al*., 2013; Russo & Modoni, 2013). To the authors' knowledge, no study has been conducted to investigate the effect of aggregate size on the water retention capacity and microstructure of lime-treated soils. This constitutes the main objective of this study.

MATERIALS AND METHODS

Silty soil with 27% clay-size fraction was used. Table 1 presents its basic geotechnical properties. The main minerals are quartz (55%), kaolinite (12%), feldspaths (11%), illite (10%), goethite (6·5%), montmorillonite (4%), chlorite (1%) and rutile (0·5%) (Deneele & Lemaire, 2012). The collected soil was first air dried, ground and passed through two target sieves in order to get two powders with different aggregate sizes, namely $S_{0·4}$ and S_5 (Fig. 1). D_{max} is 0·4 mm for $S_{0·4}$ and 5 mm for S_5. Based on the dosage applied for the construction of an embankment, a lime content of 2% (CaO content of 97·30%) by weight of dry soil was selected. The soil powders were first hand mixed with lime, and then humidified by spraying distilled water to reach the target water content (17%, dry of optimum) and compacted statically to reach the target density (1·65 Mg/m^3). The final dimensions of the samples for suction measurement are 38 mm in diameter and 100 mm long, while those for the MIP tests are 50 mm in diameter and 20 mm long. After compaction, the samples were covered by plastic films and cured for 7, 28 and 90 days, respectively.

For the MIP tests, one small piece of several grams was cut from a sample. It was freeze dried by following the procedure proposed by Delage & Pellerin (1984). For the determination of water retention curve, at a given curing time, one sample

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Table 1. Geotechnical properties of the studied soil

Property	Value
Specific gravity, G_s	2·70
Liquid limit, w_L: %	51
Plastic limit, w_p: %	28
Plasticity index, I_p: %	23
Value of blue of methylene: g/100 g	2·19
Optimum moisture content: %	17·9
Maximum dry unit mass: Mg/m^3	1·76

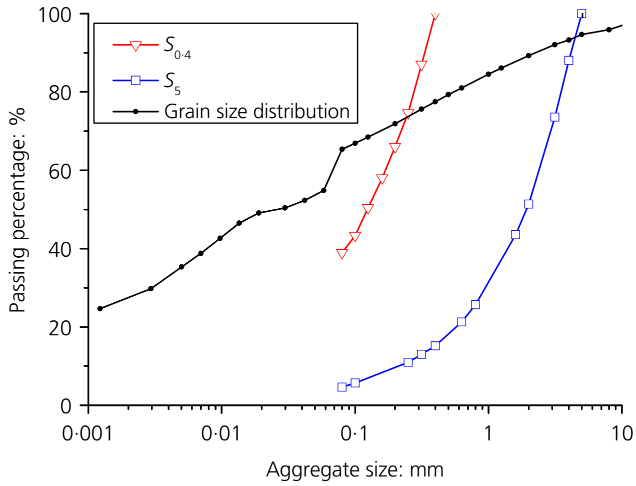

Fig. 1. Aggregate size distributions of the two soil powders ($S_{0·4}$ and S_5) and grain size distribution of the soil studied

was cut into more than eight small pieces (38 mm in diameter and 8 mm long). They were dried in air for different times – that is, 0·5, 1, 2, 4, 6, 8 h and so on. Afterwards, they were covered again for water content homogenisation. Suction measurement was taken on the second day after each curing time ($t = 7$, 28, 90 days) by means of WP4 dewpoint hygrometer. The corresponding water content was determined by the oven drying method (Table 2).

EXPERIMENTAL RESULTS

Figure 2 shows that for the cumulative curves of treated and untreated $S_{0·4}$, the total intrusion volume of lime-treated soil decreases gradually over time, and all those total intruded void ratios are slightly lower than the initial one calculated with the global parameters of samples. The PSD curves of $S_{0·4}$ compacted dry of optimum present a typical bimodal pattern, defining two pore populations corresponding to macro- and micropores (Romero, 2013). A comparison between the curves of treated and untreated soils shows that the addition of lime affects both kinds of pores gradually over time. Lime treatment shifts the modal sizes to smaller values during curing, with a slight reduction in their corresponding frequencies. In addition, the frequency of the undetected pores with a diameter smaller than 0·006 μm is higher for the treated samples.

Similar observation can be made on the results of S_5 (Fig. 3): (*a*) a smaller total intrusion volume of the treated samples as compared with that of the untreated one; (*b*) the bi-modal pattern of PSDs; (*c*) the decreased modal size values of both macro- and micropores due to lime treatment; and (*d*) the increase in frequency of undetected pores for lime-treated samples.

Table 2. Water contents and suctions of samples

Sample	Untreated		Lime treated, $t = 7$ days		Lime treated, $t = 28$ days		Lime treated, $t = 90$ days	
	w: %	Suction: kPa	*w*: %	Suction: kPa	*w*: %	Suction: kPa	*w*: %	Suction: kPa
$S_{0·4}$	5·30	31 550	5·05	26 270	6·05	20 080	5·71	24 720
	8·37	9680	5·49	21 970	7·64	12 960	7·29	15 560
	10·28	6460	6·11	17 540	8·31	11 020	7·39	15 400
	11·77	2880	6·54	15 810	9·33	8800	8·69	11 970
	12·40	1530	9·56	5670	10·32	6820	9·70	9270
	13·62	1650	11·78	3440	10·44	6380	10·52	8100
	15·28	970	13·26	2230	10·78	6050	11·60	6240
	15·33	1000	14·97	1360	11·66	5150	13·24	4290
	15·85	1010	17·12	3760	11·85	5100	13·83	3820
	16·56	610	—	—	13·05	3580	15·41	2320
	17·99	390	—	—	13·67	3330	16·92	610
	—	—	—	—	14·52	2530	—	—
	—	—	—	—	15·98	1360	—	—
	—	—	—	—	17·00	400	—	—
S_5	4·40	45 110	6·36	17 140	5·01	34 850	4·31	40 390
	5·53	24 790	8·13	10 340	5·93	23 120	6·74	18 340
	6·41	19 910	9·69	6300	6·68	19 630	7·49	12 920
	9·30	6550	10·78	5510	7·60	13 410	8·27	13 610
	10·19	5460	12·06	3660	8·14	10 800	9·34	10 130
	10·55	5010	13·65	2480	8·31	10 780	9·48	8750
	12·26	3110	15·76	1320	8·74	10 220	9·78	7490
	13·31	2160	16·78	480	10·87	6080	10·64	7290
	14·06	1480	—	—	13·27	3710	11·36	4860
	16·20	540	—	—	14·62	2230	11·85	4590
	—	—	—	—	16·91	380	13·22	3000
	—	—	—	—	—	—	14·54	2250
	—	—	—	—	—	—	16·45	860
	—	—	—	—	—	—	17·29	490
	—	—	—	—	—	—	17·43	390

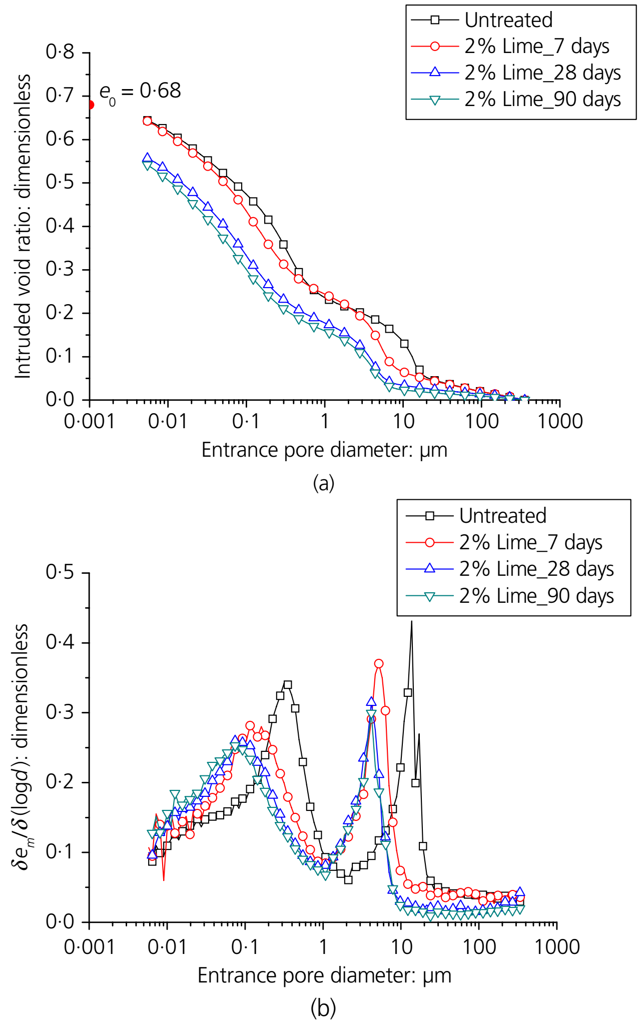

Fig. 2. MIP results of lime-treated soil and untreated soil, $S_{0·4}$: (a) cumulative intruded void ratio curves and (b) derived curves

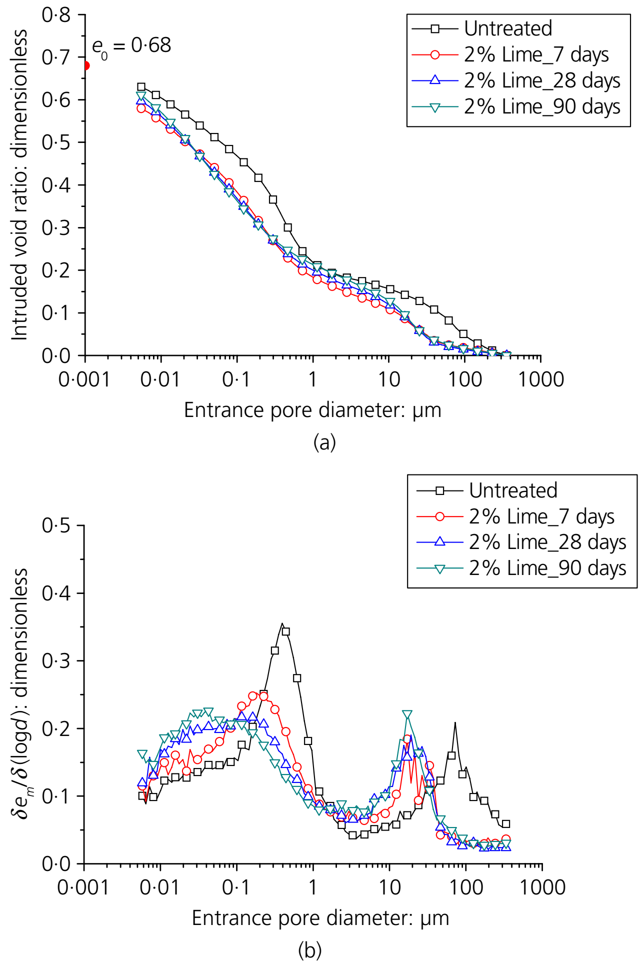

Fig. 3. MIP results of lime-treated soil and untreated soil, S_5: (a) cumulative intruded void ratio curves and (b) derived curves

To clarify the aggregate size effect, the cumulative (Fig. 4) and derived curves (Fig. 5) of both untreated and treated samples at $t = 90$ days are compared for $S_{0·4}$ and S_5. It appears from Fig. 4 that the total intrusion porosity of untreated samples is quite similar even with a large difference between the sizes of macropores [Fig. 5(a)]. However, the treated $S_{0·4}$ at 90 days presents a much lower total intrusion void ratio than the treated S_5. A significant frequency reduction is observed for $S_{0·4}$ in the range from 10 to 330 μm. This actually enlarges the difference in macropore distribution between the two treated soils with different aggregate sizes.

Figure 6 presents water retention curves from MIP tests and from direct measurements. On the whole, both methods reveal that lime treatment leads to a higher water content at a given suction. For the treated $S_{0·4}$, as shown in Fig. 6(a), its water retention capacity gradually increased during curing. The air entry value of lime-treated soil is much higher than that of untreated soil. Similarly, a slight increase of water retention capacity due to lime treatment is also observed for S_5 [Fig. 6(b)]. Note that a significant difference exists between the directly and indirectly determined curves and this difference can be attributed to the fact that the curve from MIP test does not include any effect of volume change, while that from direct measurements does.

To evidence the effect of aggregate size, water retention curves of both untreated and treated $S_{0·4}$ and S_5 ($t = 90$ days) are gathered in Fig. 7. It is observed that the water retention capacities of untreated soils with different aggregate sizes are quite similar in the high suction range (suction > 1000 kPa), while in the low suction range (< 100 kPa), a large difference exists, defining a higher air entry value for soil $S_{0·4}$.

DISCUSSIONS

Results of MIP test on $S_{0·4}$ and S_5 show a similar evolution of microstructure induced by lime treatment. Specifically, the total intruded void ratio of treated soils is observed to decrease during curing, with an increase in frequency of undetected pores. Besides, the modal sizes of both macro- and micropores shift to lower values. All these modifications induced by lime treatment can be attributed to the cementitious compounds produced in the pozzolanic process. These cementitious compounds gradually coat the surface of soil aggregates, filling the macropores over time (Shi *et al.*, 2007; Lemaire *et al.*, 2013). Some entrances of micropores can also be blocked by the cementitious compounds, reducing the interconnectivity of pores and changing some nonconstricted pores to constricted pores (Russo & Modoni, 2013). This pore filling by cementitious compounds leads to a decrease of the frequency of macropores, accompanied by an increase in the frequency of micropores.

As for the untreated samples, the total intruded void ratio of $S_{0·4}$ is observed to be similar to that of S_5, even though a large difference between the modal sizes of macropores is observed. Since the initial void ratio of all samples was

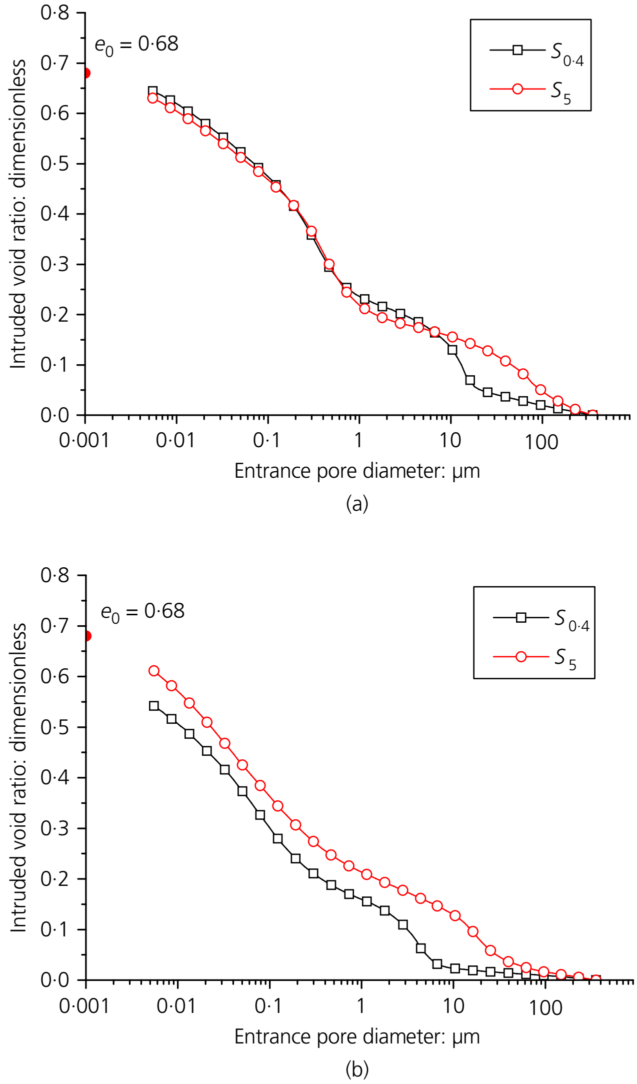

Fig. 4. Cumulative intruded void ratio curves of soils: (a) untreated soils and (b) lime-treated soils at a curing time of 90 days

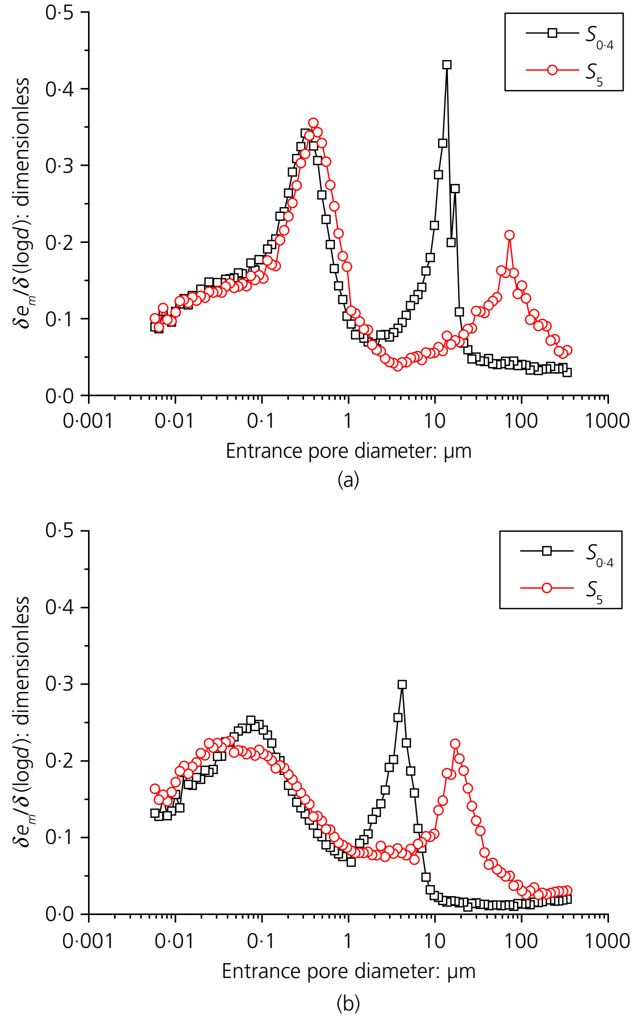

Fig. 5. PSD curves of soils: (a) untreated soils and (b) lime-treated soils at a curing time of 90 days

controlled at a same value, the frequency of undetected pores can be assumed to be similar for the untreated samples of different aggregate sizes. Furthermore, the PSD curves of untreated soils, as presented in Fig. 5(a), illustrate that the macroporosity largely depends on the soil aggregate sizes: smaller soil aggregates form a smaller modal size of macropores; nevertheless, the aggregate size cannot affect the microporosity. However, the total intruded void ratio of treated $S_{0·4}$ ($t = 90$ days) is much lower than that of S_5. This suggests that more undetected pores are formed during curing in the case of treated $S_{0·4}$ as compared with S_5. A possible explanation is that more pozzolanic reactions are expected to occur in $S_{0·4}$ due to its larger total surface of aggregates (Tang *et al.*, 2011). Indeed, soil with smaller aggregates can be better mixed with lime, resulting in a better distribution of lime particles, and improving the effectiveness of treatment as reported by Locat *et al.* (1990). In a curing time as long as 90 days, with a great amount of cementitious compounds produced, the difference between $S_{0·4}$ and S_5 is enlarged.

In terms of water retention capacity, the untreated $S_{0·4}$ and S_5 show a similar behaviour in the high suction range (suction > 1000 kPa). This shows that the aggregate size affects the macropores only, as illustrated in Fig. 5(a). In addition, as the air entry value usually decreases with the increase of macropores, the larger macropores detected for S_5 result in a lower air entry value, as shown in Fig. 7.

The increase of water retention capacity of lime-treated soils, in particular for $S_{0·4}$, can also be attributed to the production of cementitious compounds during curing. Tedesco & Russo (2008) proposed that the cementitious compounds between soil aggregates can be represented by ink-bottle pores, and these pores can improve the water retention capacity by retaining water in the wide inner pores on drying. The large reduction in the frequency of macropores (10–330 μm) which increases the air entry value, and the significant decrease in total intruded void ratio are observed for $S_{0·4}$. This suggests that the cementitious compounds that fill the macropores effectively reduce both the size and the interconnectivity of these pores. In addition, the increase of undetected pore amount in treated soil can also increase its water retention capacity. For S_5, however, less cementitious compounds are expected due to the smaller contact surface between soil and lime. Thus, the interconnectivity of macropores is not as affected as in the case of $S_{0·4}$.

CONCLUSION

The aggregate size effects on water retention properties and microstructure of a compacted lime-treated silty soil was

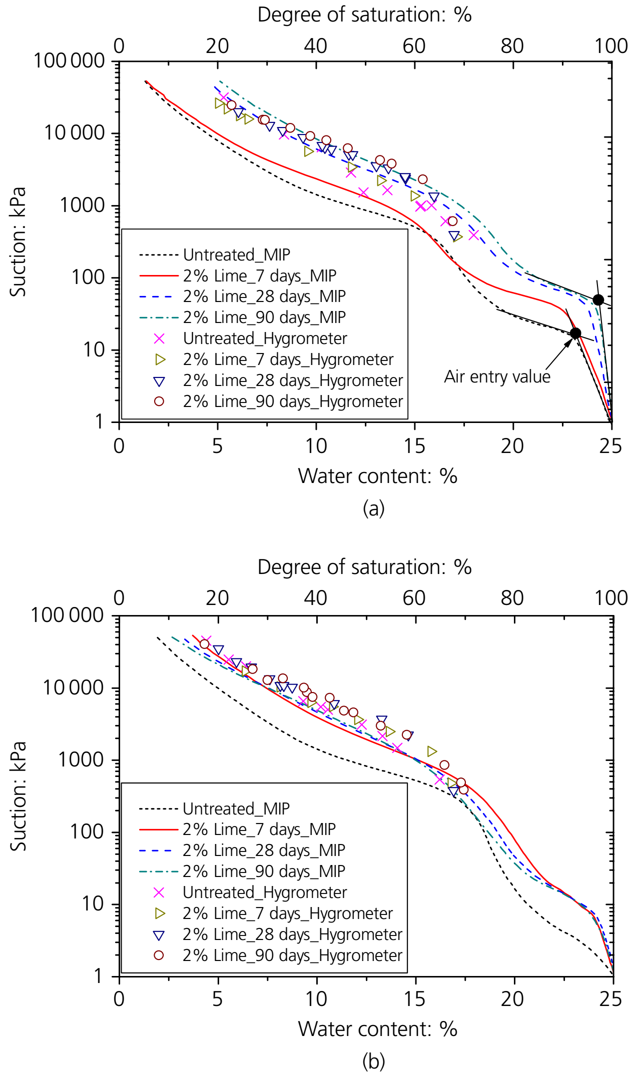

Fig. 6. Water retention curves from MIP tests and hygrometer measurements: (a) $S_{0\cdot4}$ and (b) S_5

studied. The results allow the following conclusions to be drawn.

- Lime treatment gradually shifted both the macro- and micropores to smaller values, due to the cementitious compounds created in the pozzolanic process. These cementitious compounds filled the pores, effectively increasing the soil water retention capacity.
- The compacted lime-treated soil with smaller aggregates has relatively smaller modal sizes. A significant decrease in frequency of macropores and a continuous reduction in total intruded porosity were detected in the case of smaller D_{max}, due to the larger total soil–lime contact surface.
- The treated soil with smaller D_{max} has a higher air entry value and a larger water retention capacity due to a higher production of cementitious compounds, reducing both the pore size and pore interconnectivity.

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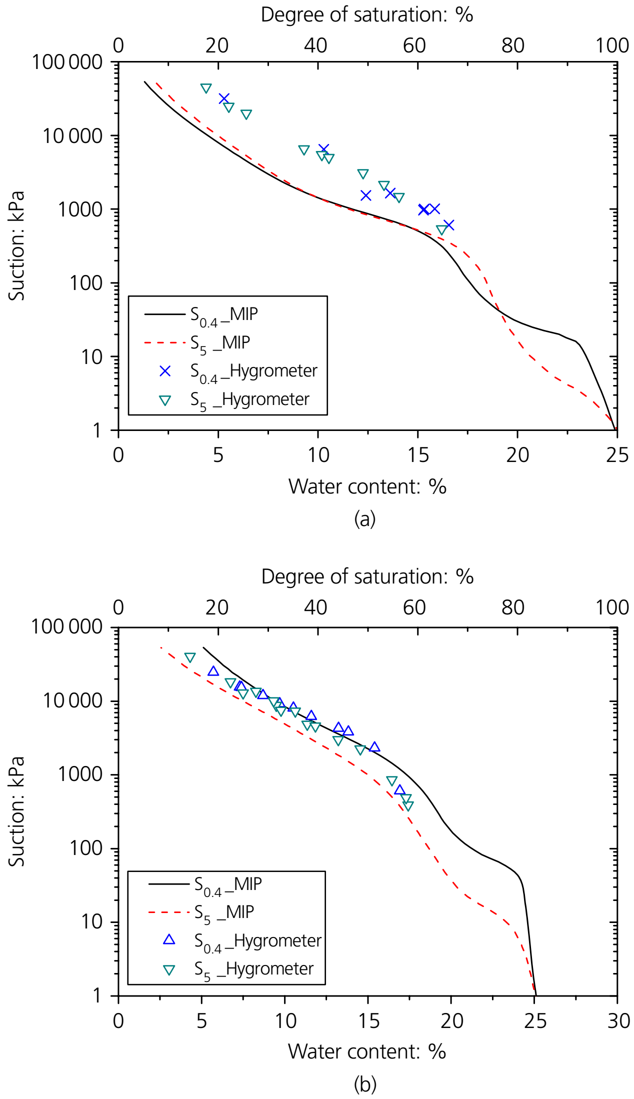

Fig. 7. Effects of aggregate size on water retention curves: (a) untreated soil and (b) 2% lime-treated soil at a curing time of $t = 90$ days

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