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Improvement of geotechnical characteristics of silts deriving from washing quarry gravel

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ABSTRACT: Quarrying activities worldwide produce large amounts of silt from washing gravel now considered as waste but, if treated, it might be utilized in civil and environmental works. The aim of the study is to quantify the strength and permeability variations of silts mixed with cement, bentonite, or both in percentages of between 2.5% and 5.0%. Laboratory compaction, unconfined compression and permeability tests have been performed on natural material and soil mixtures. Independently of the additive used, the values of maximum compression strength and dry unit weight rise with increased water content, reach a maximum at the optimum and then decrease for higher moisture. Nevertheless the efficacy of cement treatment on unconfined compression strength depends on water content and cement percentage. Whatever the water content, the stress-strain behaviour of the silt-cement mixture remains brittle, while for silt-bentonite mixtures it depends on moisture content. Natural silts permeability may be reduced by adding small quantities of bentonite to construct hydraulic barriers.

1 INTRODUCTION

Every year quarrying activity produces large amounts of silts, as a residual product of gravel washing, which are stockpiled in large basins near the washing plant. This material is not generally used because of its poor geotechnical characteristics and so is disposed of as waste.

This paper reports the preliminary results of an experimental study, as yet not completed, to determine how geotechnical properties of silts may be improved so that they can become available as a low-cost resource.

With this aim, compaction tests, constant head permeability in triaxial cell tests and unconfined compression tests have been performed on both natural material and mixtures with low percentages (2.5% and 5%) of bentonite and cement.

Cement is usually added to high plasticity natural soils in order to improve their strength and stiffness (Chew et al. 2004; Horpibulsuk et al. 2004; Bellezza et al. 1995), and to modify permeability properties of soils with different grain size distributions and plasticity characteristics (Bellezza & Fratalocchi 2006).

The use of bentonite as an additive to reduce soil permeability is widespread and well-documented (Daniel 1991), but there is little information (Bellezza et al. 1999) on the effectiveness of adding cement and bentonite to silty soils deriving from industrial processes.

2 EXPERIMENTAL PROGRAMME

The investigated material came from the clarification of water used to wash the gravel extracted from a quarry on the fluvial-glacial plain of Friuli Venezia Giulia (north-eastern Italy).

After extracting the material, the fine fraction has been separated from coarse fraction by washing, then deposited in special basins and lastly dewatered by a filterpress.

The first stage of the research investigated the main geotechnical properties of silt without additives; two samples were prepared for this by means of quartering material collected from different deposit zones.

The values of index properties (Tab. 1) measured for the two samples resulted as almost the same, so the material was classified as CL in the USCS system. The very low values of plasticity and activity indexes depend on the mineralogical composition of these silts, with a prevalence of carbonates and just traces of clayey minerals with low activity, such as illites and mica.

The tests included Standard Proctor compaction at different moistures, to determine the optimum water content and maximum unit dry weight. Oedometric and drained and undrained triaxial tests were only performed on samples at the optimum Proctor (Tab. 2).

The compressibility values are typical of low compressible and low swelling soils; the values of the coefficient of consolidation are instead dependent

Table 1. Main soil characteristics.

Sample n.	Grain size distribution					Plasticity		Activity		Classif.
	Sand (%)	Silt (%)	Clay (%)	D_{60} (mm)	D_{10} (mm)	LL (%)	PI (%)	AI	Gs	USCS
C1	6.35	79.92	13.73	0.0178	0.0015	24.5	5.2	0.38	2.73	CL
C2	7.5	79.19	13.31	0.0182	0.0010	25.7	7.0	0.52	2.73	CL

Table 2. Unconfined compression strength and deformability characteristics of compacted silt.

Unconfined compression test			Oedometer test		Triaxial test	
q_u kPa	E_{25} MPa	ε_r %	C_c	C_s	c′ kPa	ϕ' °
180	15.2	2.2	0.110	0.017	12	16

E_{25} = Young's modulus at 25% of unconfined shear strength q_u.

Table 3. Main index properties of silt–cement–bentonite mixtures.

Silts deriving from washing gravel with:	LL (%)	PL (%)	PI (%)	Gs
No additives	25.7	19.3	7.0	2.73
2.5% bentonite	35.3	18.0	17.3	2.77
5.0% bentonite	40.0	17.8	22.2	2.79
2.5% cement	36.3	22.2	14.1	2.76
5.0% cement	39.1	23.4	15.7	2.76
2.5% bentonite + 2.5% cement	43.1	22.9	20.2	2.79
5.0% bentonite + 5.0% cement	49.7	25.7	24.0	2.78

on the stress level and range between 8.76×10^{-3} and 1.37×10^{-2} cm^2/s. In undrained conditions compacted silt shows brittle behaviour characterized by high values of both stress-strain modulus and undrained shear strength, although the latter is reached for very low vertical strain and then quickly decreases. The very low effective shear strength value is typical of compacted silty soils.

To study the possibility of improving the geotechnical properties of washing silts, six series of samples were prepared mixing the untreated material with 2.5% and 5% of bentonite, cement and both respectively. Table 3 shows the main index properties and specific gravity of every blended soil investigated. An increase in liquid and plastic limits for low plasticity soils treated with low percentages of cement has also been reported by Chew et al. (2004) and Locat et al. (1990) explain this behaviour with the aggregation and cementation of particles into larger size clusters caused by the hydraulic binder.

Another possible reason is the water trapped within intra-aggregate pores which increases the apparent water content without really affecting interaction between aggregates (Locat et al. 1996). The increased plasticity in the specimen of silts mixed with bentonite is due to the high activity of clayey minerals in this additive.

All specimens were prepared mixing the additive (Portland 32.5 cement and/or sodium bentonite with a high content of montmorillonite) to the dry silt (ASTM 1997) and then wetting to a predetermined moisture content. The blended material was compacted with a Standard Proctor effort and two specimens then collected. At present, constant head permeability tests into a triaxial cell have only been completed for silts mixed with 2.5% bentonite.

The unconfined compression tests were performed after 28 days or 7 days curing for silt-cement mixtures and silt-bentonite mixtures respectively. Table 4 shows the values of W_{opt}, γ_{dmax}, q_u and stress-strain modulus (E_{25}) for the samples of Optimum Proctor compacted wet, and the ratio of the variation of these parameters from those of the untreated soil. All the blended samples show a reduction of compaction characteristics, with a decrease in dry density and an increase in optimum moisture, counterbalanced by a higher unconfined compression strength, but not always coupled with higher values of E_{25}.

3 INFLUENCE OF CEMENT CONTENT

The compaction curves for the mixture with cement are lower and to the right of the curve of the untreated silt (Fig. 1a): the reduction in dry density, of between 1.7% and 5.5%, is coupled with an increase in optimum wet of between 1.7% and 2.8%, in order to hydrate the added cement.

For both mixtures (2.5% and 5.0% of cement) the unconfined compression strength increases with water content until the optimum moisture and then rapidly decreases (Fig. 1b). The values of stress-strain modulus E_{25} for both series of specimens lie along an almost symmetric curve with respect to W_{opt} (Fig. 1c). Moreover, with the lower water contents the unconfined compression strength seems to be independent of the cement percentage.

Table 4. Compaction and unconfined compression strength characteristics of silt – cement – bentonite mixtures compacted at Optimum Proctor. (*7 days curing) (**28 days curing).

Silts with	W_{opt} (%)	γ_{dmax} (kN/m^3)	q_u (kPa)	E_{25} (MPa)	ΔW_{opt} (%)	$\Delta\gamma_{dmax}$ (%)	Δq_u (%)	ΔE_{25} (%)
No additive	14.1	18.1	180	15.2	–	–	–	–
2.5% bentonite*	17.9	17.3	204	3.2	3.8	−4.4	13	−78.9
5.0% bentonite*	17.2	17.6	232	5.4	3.1	−2.8	29	−64.5
2.5% cement**	15.8	17.8	1004	181.9	1.7	−1.7	458	+1097
5.0% cement**	16.9	17.1	1376	197.6	2.8	−5.5	664	+1200
2.5% bentonite + 2.5% cement**	17.8	17.4	1240	153.6	3.7	−3.9	589	+910
5.0% bentonite + 5.0% cement**	18.0	17.3	1503	114.0	3.9	−4.4	735	+650

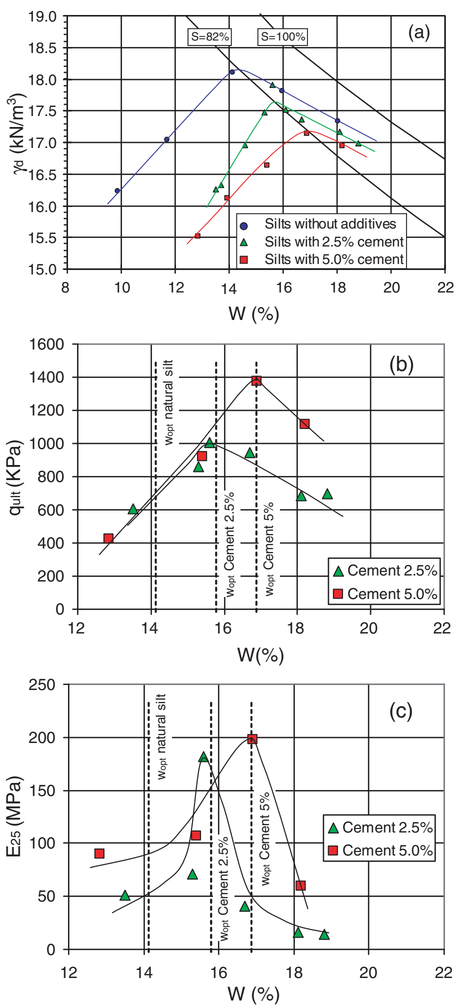

Figure 1. Silts mixed with cement: compaction curves (a); unconfined compression strength (b); stress-strain modulus (c).

The stress-strain modulus quickly increases with water content, reaches maximum for the optimum wet and then rapidly decreases to values three-four times lower than the maximum.

This behaviour may be explained considering that there must be enough water in the mixture to complete the hydration reactions, so that higher percentages of cement could develop further cementation bonds among grains.

The best water content to generate this process seems to be the optimum wet, instead for higher moistures the increase of the water-cement ratio in the mixture causes an increase in voids percentage not filled by hydraulic binder, with a consequent loss of strength and stiffness (Helal & Krizek 1992, Krizek & Helal 1992).

4 INFLUENCE OF BENTONITE CONTENT

Compaction curves for specimens with bentonite (Fig. 2a) also show reduced maximum dry density of between 2.8% and 4.4% compared to the untreated silts because of the larger quantity of fine fraction in the mixture.

In the dry side of the compaction curve the unconfined compression strength depends on bentonite percentage (Fig. 2b); for wet higher than optimum, q_u are instead almost the same, independently of the additive percentage. The trend of E_{25} always decreases with increasing water content (Fig. 2c) and appears to be independent of the percentage of bentonite in the mixture.

5 PERMEABILITY TESTS

Only two preliminary constant head permeability tests in triaxial cell have so far been done to evaluate the reduction in permeability related to the addition of bentonite.

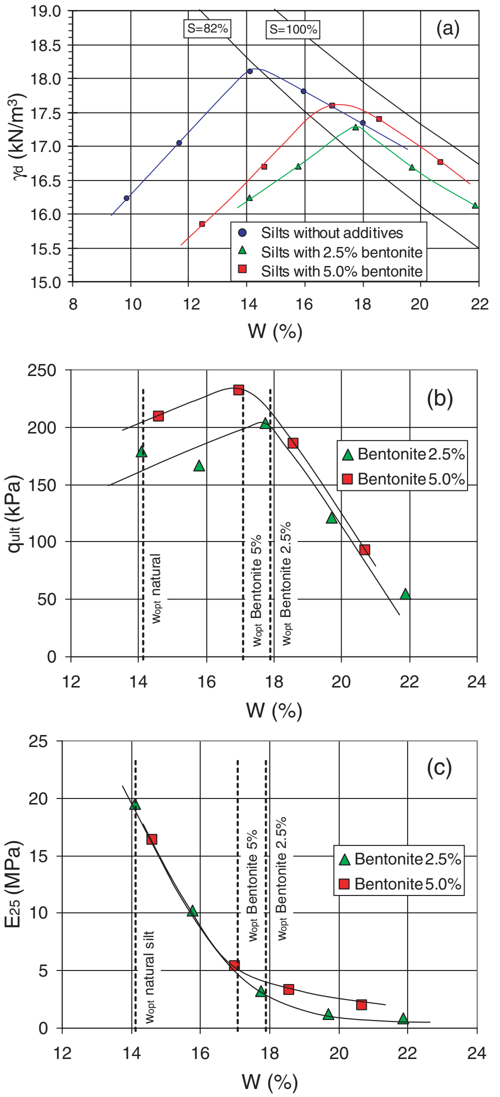

Figure 2. Silts mixed with bentonite: compaction curves (a); unconfined compression strength (b); stress-strain modulus (c).

The first was performed on the silts without additives, the second on the mixture with 2.5% bentonite; both tests were performed on specimens compacted to Proctor optimum wet and subsequently saturated and consolidated.

As is well known, bentonite has marked characteristics of imperviousness and an appreciable reduction in permeability can be obtained even with small contents (2.5%) (Fig. 3).

In the interval of consolidation pressures imposed (100–300 kPa) and with a hydraulic gradient of

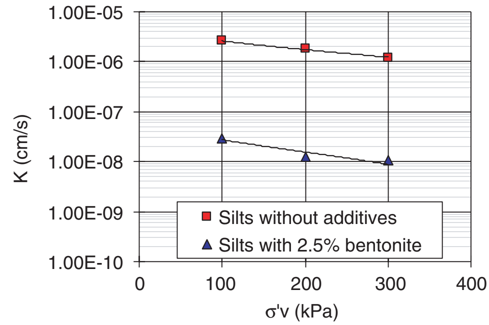

Figure 3. Results of preliminary constant head permeability tests.

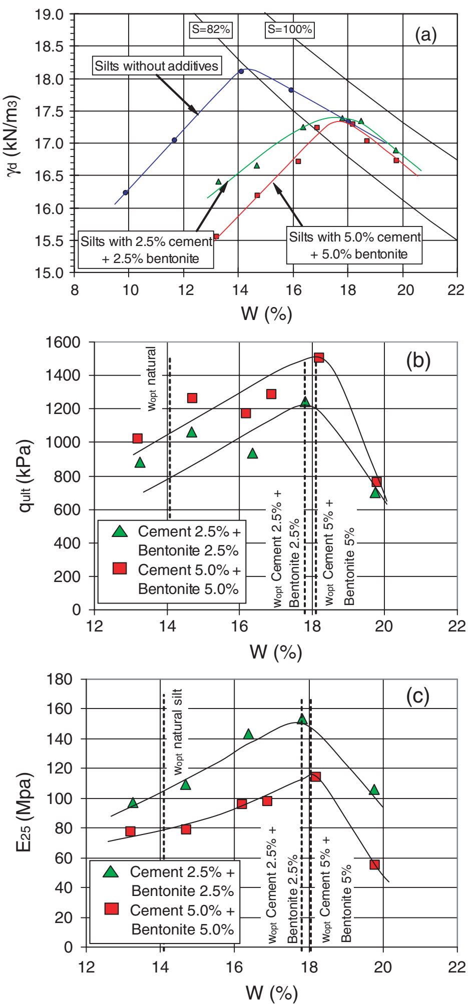

Figure 4. Silts mixed with cement and bentonite: compaction curves (a); unconfined compression strength (b); stress-strain modulus (c).

30 the decrease reaches two orders of magnitude compared to the silts without additives, from $k = 2.6 - 1.2 \times 10^{-6}$ cm/s to $k = 2.9 - 1.0 \times 10^{-8}$ cm/s. The latter values meet the international standards for hydraulic barriers, which recommend a permeability value lower than 1×10^{-7} cm/s.

6 INFLUENCE OF CEMENT AND BENTONITE CONTENT

Compaction characteristics for both cement and bentonite mixtures show comparable behaviour with similar values of W_{opt} and γ_{dmax} (Fig. 4a).

For $W < W_{opt}$ the unconfined compression strength depends on the percentage of additives (Fig. 4b); it reaches a maximum when $W = W_{opt}$ and then rapidly decreases to converge at the same value for both percentages of additive in the samples.

Instead, the stiffness of compacted mixtures depends on the water content, increasing for $W < W_{opt}$ and decreasing for $W > W_{opt}$ (Fig. 4c). The higher values of E_{25} for the samples prepared with 2.5% of cement and 2.5% of bentonite can be observed; this may be explained by the lower fine contents (especially less bentonite/montmorillonite), which reduce deformability.

The greater stiffness due to the higher percentage of cement (5%) is on the other hand partially counterbalanced by the increased deformability due to the 5% of bentonite.

7 EFFECTIVENESS OF ADDITIVES

In order to evaluate the efficacy of mixing silty soils with additives and the behaviour of the mixtures, the values of q_u and E_{25} have been normalized against the respective values at optimum wet obtained for the untreated soil $q_u = 180$ kPa and $E_{25} = 15.2$ MPa.

For mixtures with cement (Tab. 5), the maximum values of efficacy have been reached for moisture values very close to optimum wet (1%–2% near optimum); the mixture with 5.0% cement offers greater efficacy only for moisture higher than the optimum wet of the mixture with 2.5% cement.

As expected, the addition of bentonite to the silt doesn't improve the mechanical behaviour, and for values of moisture higher than optimum it sensitively reduces the unconfined compression strength (Tab. 6), while for moisture lower than optimum there are negligible improvements. The only effect of the mixing with bentonite is in reducing stiffness of the silt and changing its behaviour from brittle to ductile, so that it can undergo large deformations.

Table 5. Efficiency of the cement addition on the properties of washing silt.

2.5% cement			5.0% cement		
W (%)	$E_{25}/E_{25\,nat}$	$q_u/q_{u,nat}$	W (%)	$E_{25}/E_{25,nat}$	$q_u/q_{u,nat}$
13.5	3.3	3.3	12.8	5.9	2.3
15.3	4.7	4.8	15.4	7.1	5.1
15.6 (w_{opt})	12.0	5.6	16.9 (w_{opt})	13.0	7.6
16.7	2.7	5.3	18.2	3.9	6.2

Table 6. Efficiency of the bentonite addition on the properties of washing silt.

2.5% bentonite			5.0% bentonite		
W (%)	$E_{25}/E_{25\,nat}$	$q_u/q_{u,nat}$	W (%)	$E_{25}/E_{25,nat}$	$q_u/q_{u,nat}$
14.1	1.3	1.0	14.6	1.1	1.2
15.8	0.7	0.9	17.2 (w_{opt})	0.4	1.3
17.8 (w_{opt})	0.2	1.1	18.6	0.2	1.0
19.7	0.1	0.7	20.7	0.1	0.5

Table 7. Efficiency of the cement-bentonite addition on the properties of washing silt.

2.5% cement + 2.5% bentonite			5.0% cement + 5.0% bentonite		
W (%)	$E_{25}/E_{25\,nat}$	$q_u/q_{u,nat}$	W (%)	$E_{25}/E_{25,nat}$	$q_u/q_{u,nat}$
13.3	6.4	4.9	13.2	5.1	5.7
14.7	7.2	5.9	14.7	5.2	7.0
16.4	9.4	5.2	16.2	6.3	6.5
17.8 (w_{opt})	10.1	6.9	16.9	6.4	7.1
18.7	7.4	2.9	18.2 (w_{opt})	7.5	8.4
19.8	7.0	3.9	18.7	4.5	4.6

The most important benefits in terms of effectiveness are obtained for mixtures with cement and bentonite at the same percentages (Tab. 7).

The increase of both additives at the same percentage improves, to the same level, the effectiveness of the unconfined compression strength ($q_u/q_{u,natural}$), which rises until maximum values of about 7–8 times the soil values without additives are reached; this is true for the optimum wet, whereas the trend quickly decreases for small increments of water content.

As far as the strain behaviour is concerned, the effectiveness of mixing still depends on the water content, while larger percentages of bentonite reduce stiffness.

8 CONCLUSIONS

Compaction, unconfined compression and permeability tests performed in the laboratory show that it is possible to improve the geotechnical characteristics of silts obtained from washing quarry gravel by mixing them with different additives.

- The use of cement as additive results as the most effective method to improve shear strength characteristics. Nevertheless, the efficacy of treatment, for the cement contents investigated, mainly depends on water content: there must be enough in the mixtures to allow the completion of hydration reactions, so that larger percentages of binder can develop further cementation bonds between grains. The highest shear strength and stress-strain modulus values are reached for moistures $W = W_{opt} \pm 1\%$, while for higher values of w they quickly decrease. On the other hand the addition of cement confers greater brittleness on the silts compared to the natural material, and this limits the application to a narrow range of stress states.
- The use of bentonite as additive produces a mixture with similar behaviour to compacted clayey soils: shear strength considerably reduces for $W > W_{opt}$, and at the same time the stress-strain behaviour becomes progressively ductile. The significant decrease in hydraulic conductivity obtained by mixing the silts with small percentages of bentonite suggests hydraulic barriers as a possible field of application.
- In the mixtures obtained blending silts with the same percentages of both additives, the cement is responsible for the shear strength increase but, as previously observed for the mixture with cement alone, its efficacy depends not only on the added percentage but also on the water-cement ratio. The strain behaviour instead primarily depends on the percentage of bentonite, and it makes even the mixture with the higher percentage of cement ductile. Permeability tests on these mixture types have not yet been completed, so no conclusion can be made about the effectiveness deriving from the concurrent addition of two types of additives.

The laboratory investigations performed on silts deriving from washing quarry gravel mixed with small amounts of different additives show that it is possible to improve the mechanical and hydraulic behaviour of the silt and transform it from a waste product into useful resource.

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