POTENTIAL OF WASTEPAPER SLUDGE ASH TO REPLACE CEMENT IN DEEP STABILIZATION OF QUICK CLAY

P. M. S. Bujulu, A. R. Sorta, G. Priol & A. J. Emdal

Department of Civil and Transport Engineering, Geotechnical Division, NTNU, Norway

Paper prepared for presentation

at the "Characterization and Improvement of Soils and Materials" Session

of the 2007 Annual Conference of the Transportation Association of Canada

Saskatoon, Saskatchewan

ACKNOWLEDGEMENT

The work presented was carried out as part of a Marie Curie Research Training Network "Advanced Modelling of Ground Improvement on Soft Soils (AMGISS)" (Contract No MRTN-CT-2004-512120) supported the European Community through the program "Human Resources and Mobility".

ABSTRACT

About half of the cost of deep soil stabilization installation works is attributed to the cost of binder materials, mainly cement. Wastepaper sludge ash (WSA) is considered as a potential substitute for cement in construction of lime-cement columns. Suitability and performance of lime-WSA mixture in deep stabilization of quick clay are presently investigated at NTNU, Norway. Mineralogical and chemical analyses of WSA, laboratory mixing methods and proportioning and strength and deformation characteristics using unconfined compression tests were performed on lime-WSA mixtures and compared with the commonly applied lime-cement mixtures. The results show that equal proportions of lime and WSA produce the best results, with higher unconfined compressive strength, stiffness and unit weight for samples with 100 kg/m^3 *binder dose rate compared to samples with 150 kg/m*^{3}*. Stabilizing effects produced by lime-WSA mixtures are comparable to those of lime-cement binders, in addition to economic and environmental advantages of reusing WSA. However, it takes about 75 days for lime-WSA mixtures to achieve engineering properties equivalent to 28-days old lime-cement mixtures. Eighteen months old field samples from actual lime-cement and lime-cement-WSA columns were tested, where the lime-cement-WSA samples tested about five times stronger and fifty times less permeable, compared with the corresponding lime-cement samples.*

Key words: Deep stabilization, lime-cement column, wastepaper sludge ash, quick clay

1. INTRODUCTION

Deep soil stabilization refers to an in situ soil treatment technology used for improvement of thick strata of soft and problematic soils, whereby the soil is blended with cementitious or other materials capable of binding the soil into columns of mechanically stronger soil-binder mixtures. The method is primarily used for reduction of settlements and improvement of stability in infrastructural projects, such as roads and railways on soft or sensitive soil deposits, for stabilization of excavations and natural slopes as well as for environmental remediation purposes.

Quick clay is a clay whose structure collapses completely on remoulding and whose shear strength is thereby reduced almost to zero, without changing its pore water content, turning into a viscous fluid. When it is disturbed it transforms from a relatively brittle material to a liquid mass. The Swedish Geotechnical Institute defines quick clay as clay with a sensitivity of 50 or more and fully remoulded shear strength less than 0.4 kPa [1]. Quick clays are common in the Scandinavian countries and in some parts of Canada, particularly in the valleys of the St. Lawrence and Ottawa Rivers [2]. They are associated with various risks involving loss of stability, such as land slides and mud flows, and huge settlements leading to structural damages and loss of lives. Human infrastructural activities and erosion are the usual causes of instability and settlements in quick clays. Deep soil stabilization is an increasingly used method to stabilize quick and soft clays in the Scandinavian countries, Japan and USA. The technique is also relevant for Canada and other countries, where thick strata of quick clay or other problematic soils are found.

Although deep soil stabilization is normally a more economical method compared to the other conventional soil improvement methods, such as embankment piles and soil excavation and replacement, it is still a very expensive undertaking. In Sweden, Finland and Norway, where a total of about 6 million linear meters of treated soil columns per year has been reported, this is estimated to be worth about $45 to 60 million per year in total. Of this, 35 to 60 percent corresponds to the cost of binder materials, mainly cement [3]. Cement and lime are the common binders used for deep stabilization, resulting in lime-cement and cement columns. Depending on the diameter of the columns and lime-to-cement ratio, a total of more than 75 to 150 thousand tons of cement are needed for deep stabilization in the Scandinavian countries per year. This means that a very significant amount of money is used for this binder material annually. In order to check this cost, some industrial wastes in form of slag and ashes have recently been introduced to replace a portion of cement, where this has proved to be technically, environmentally and economically feasible. Fly ash, silica fume and ground granulated blast furnace slag are the commonly used industrial wastes so far [4].

Wastepaper Sludge Ash (WSA) is a waste from the combustion of wastepaper sludge in paper recycling factories. It is produced in hundreds of thousands of tons annually in the industrialized countries. In Trondheim, the source factory produces 800 tons each year, with much more for the entire Norway and Europe. UK, for instance, is reported to produce more than 100 000 tons each year, with the Aylesford Newsprint factory in Kent, alone producing 50 000 tons per year [5]. The usual method for its disposal is by land filling, which holds back the land from other beneficial uses and may lead to contamination of ground water and soil. Engineered landfills and long haulage distances to environmentally acceptable disposal places are likely to cause huge disposal expenses to the factories. Therefore, utilization of WSA as an alternative binder material for deep-mix stabilization is anticipated to be very advantageous, both economically and environmentally.

WSA is presently being investigated at NTNU to establish the potential for its utilization in deep stabilization of clays, particularly the highly sensitive quick clays. For an industrial waste to be accepted as a binder, it must possess the desired stabilizing functions, as well as meeting the environmental requirements on the concentration of heavy metals and other hazardous substances that can leach out of the stabilized soil. Preliminary investigations on WSA have revealed that it is a pozzolanic material and its heavy metals content is below the limits stipulated by the World Health Organization (WHO), the United Nations Environmental Programme (UNEP) and the US Environmental Protection Agency (USEPA) for land applications of recycled materials [6]. This has led to further investigations into the mechanical and geotechnical properties of its mixture with lime, which is a necessary additive for the pozzolanic chemical reaction. This paper presents and discusses the results of laboratory tests on WSA-lime mixes, including index properties and uniaxial compressive strength tests at the curing periods of 7, 28, 56 and 90 days, and compares them with those of the traditional lime-cement (50:50) mix. Also, results of tests on samples cored from actual field lime-cement columns (25:75) and lime-cement-WSA (25:65:10) are presented and compared. The results from laboratory samples show that WSA-lime mixtures produce comparable stabilizing effects to the lime-cement mixtures, whereas the 18-month old field samples show that the lime-cement-WSA samples are more than five times stronger and fifty times less permeable, compared with the corresponding lime-cement samples.

2. TEST PROGRAMME AND MATERIALS

2.1 Test Programme

A test programme was prepared based on the results of the preliminary tests on the same materials, whereby equal proportions of lime and WSA (50/50) had proved to give the best results. Four mix types were tested, as summarized in Table 1. Dose rate refer to the mass of the binder mixtures (kg) per cubic meter of treatable soil. Mixing moisture content was determined based on the experience from the preliminary tests, whereby the water-to-total binder ratio of 7.5 gave the optimum consistency for the binder dose rate of 100 kg/m^3 for laboratory mixing and compaction. This corresponds to the overall moisture content of the mixture (related to dry weight of all solids) of 53% and a water-to-binder ratio of 5.2 for Mix IV (dose rate of 150 kg/m^3). For this mix, water-to-binder ratio of 7.5 gives a paste which is difficult to compact in the mould due to sticking of the paste onto the piston and the excess pore pressure caused by compaction, leading to specimens of poor quality due to air cavities and joints. Specimens were prepared for testing after 7, 28, 56, 90 and 180 days of curing (age of specimens).

Table 1: Mix types for laboratory samples

Mix type	Mix proportions [%]			Dose rate [kg/m^3]	Moisture content of mixture [%]	Water/binder ratio [-]
	L	WSA	C			
I	50	50	-	100	53	7.5
II	50	-	50	100	53	7.5
III	37.5	37.5	25	100	53	7.5
IV	50	50	-	150	53	5.2

2.2 Test Materials

Wastepaper Sludge Ash

Wastepaper sludge ash for this research was obtained from a paper factory in Trondheim, Norway. It has a bulk density of 460 kg/m^3, specific gravity of 2.6, ash content of 94% and a pH value of 11.4. It is composed of particles passing 150 µm sieve, with about 5%, 60% and 35% in the clay, silt and fine-sand size ranges, respectively. Mineralogical and chemical analyses of WSA were done at NTNU and the results are summarised in Tables 2 and 3 (in section 8), respectively. The material is essentially composed of amorphous silicates and aluminates, mainly gehlenite ($2CaO.Al_2O_3.SiO_2$) and melilite ($8CaO.3Al_2O_3.MgO.5SiO_2$), which are responsible for a pozzolanic reaction with lime.

Quick Clay

Quick clay was sampled at Tiller in Trondheim, Norway, from the depth of 7 to 15 meters. The clay is composed of 38% clay- and 62% silt-sized particles. It was practically fully saturated, with average natural moisture content of 38%, liquid limit of 26%, plasticity index of 8% and an average particle specific gravity of 2.80. It has a sensitivity between 70 and 150, remoulded shear strength of approximately 0.2 to 0.3 kPa, unconfined compressive strength of 38 kPa and a salt content of 0.4%., It is mainly composed of crystalline quartz (SiO_2) and albite [$(Na,Ca)Al(Si,Al)_3O_8$].

Lime

Standard quick lime, type 'Stabil A80' from the factory Franzefoss Kalk AS, Norway was used. It has the active CaO content of over 80%, pH value of 12.01, bulky density of 1100 kg/m3, particle specific gravity of 3.37 and the particles size less than 200 µm. Traditionally, quick lime is preferred to slaked lime in deep soil stabilization works, mainly due to its exothermic hydration reaction, which takes up the excessive water from soft clays and organic soils and accelerates the stabilization pozzolanic reaction, thereby promoting early strength development.

Cement

Fly ash cement (Standard Sement FA, type Cem II A-V 42.5R with 20% fly ash) from Norcem AS, Norway, was used. It is the cement type that is normally available on the market in Norway and almost exclusively utilized in the local construction industry. It is manufactured according to European standards NS-EN 197/1.

3. PREPARATION AND CURING OF SPECIMENS

3.1 Preparation of Specimens

Quick clay was extruded from sampling cylinders, completely remoulded and kept overnight in an airtight bucket, at the temperature of 5^oC, for homogenization. The natural moisture content of clay was determined for computation of the binder materials and additional water necessary for the required type of mixture. The mixture was prepared using the laboratory mixing apparatus and then introduced into plastic cylindrical moulds (54 mm diameter, 100 mm height) for compaction. Normally, the mixing process entraps air into the clay-binder paste, which leads to formation of air cavities in the specimens resulting in specimens of poor quality. Compaction of the mixture in the cylinders is also normally difficult due to sticking of the mix paste onto the piston and sides of the cylinder, and the presence of entrapped air between and within the layers of the mixture as it is being compacted. This leads to formation of more air cavities, cracks and horizontal joints, which affect strength and deformation characteristics of the specimens. However, the quality of specimens has been improved at NTNU by modifying the compaction piston to insert a porous stone in the piston head and perforating the mould cylinders. This provides openings to press the entrapped air out of the cylinder during compaction. Mixing was done for five minutes, starting with the clay, adding the stabilizer mixture and finally adding the predetermined amount of water to give an overall moisture content of 53%. This was quickly followed by compaction of the paste in the perforated and greased moulds, in four approximately equal layers, applying a static force of 100 kPa for one minute to each layer. The specimens were then wrapped up in two aluminium foils with a soaked absorbent paper in between, and placed in air-tight plastic bags to prevent loss of moisture during the curing period. Figure 1 (in section 8) shows the extruding, homogenizing, mixing and compaction processes, as an illustration of the procedure used in the laboratory.

3.2 Curing of Specimens

Specimens were cured for 7, 28, 56 and 90 days in a temperature controlled room, at 5^{o} C, which corresponds to the average ground temperature in Norway. Further tests are scheduled to be done after 180 days of curing.

3.3 Field Samples

Field samples were cored from actual lime-cement columns (25:75) and lime-cement-WSA (25:65:10) on the E6 road project at Ila in Trondheim, Norway. The columns were 17 months old and were constructed as ribs to support sheet piles for excavation retaining walls during construction. The samples had been stored by the project engineers for one month at room temperature before being subjected to uniaxial compression and permeability tests. The cored cylinders were sized and half of them soaked in water for 96 hours before testing, while the rest were tested unsoaked. Preparation of and testing on the field samples are illustrated in Fig. 2 (in section 8)

4. LABORATORY TESTING

4.1 Mineralogical and Chemical Analysis of WSA

Mineralogical analysis was done using the X-ray diffraction (XRD) method, according to Perkins [7]. The intensity of the strongest peak was assigned to 100% and reference data sets were used to identify the presence of other minerals. The results were interpreted and the type and form of the contained minerals identified. Analysis of the main element oxides of WSA was done using the X-ray fluorescence (XRF) method.

For chemical analysis, samples of WSA and quick clay were dissolved in concentrated nitric acid for 45 minutes at 180^{0} C and subjected to the ICP-MS analysis for determination of the concentration of various elements in the respective samples.

4.2 Unconfined Compression Test

The specimens were extruded from the moulds, levelled, measured for length and diameter, weighed and subjected to uniaxial compression test (UCT) at a constant rate of strain of 1% per minute. Deformation was measured by a frame-mounted displacement transducer (LVDT) and the load measured by a frame-mounted load transducer. Stress-strain curves were plotted and compressive strength and failure strain were determined. Comparison of the results was done in terms of strength, strain, modulus, unit weight and voids ratio.

4.3 Index Tests

For each type of mixture, liquid limit and plastic limit were determined using the Casagrande method and plasticity index was computed. The moisture content was determined for all specimens from the UCT and representative specific gravity of particles was also determined for all mix types, using the pycnometer method.

5. PRESENTATION AND DISCUSSION OF RESULTS

5.1 Mineralogical and Chemical Analysis of WSA

Mineralogical analysis

Results of mineralogical analysis of WSA show that the material contains a large amount of amorphous (glassy) silicates and aluminates, mainly gehlenite ($2CaO.Al_2O_3.SiO_2$) and melilite ($8CaO.3Al_2O_3.MgO.5SiO_2$). This makes WSA a pozzolanic material, capable of forming cementitious binders when it reacts with lime. The other components include fairchildite, sodium calcium silicate, quartz, calcite and lime. The results of the XRF are summarised in Table 2 (in section 8). It should be noted that most of the CaO contained in WSA is in a combined form (as silicates and aluminates), and not available for the pozzolanic reaction. Thus, the pozzolanic reaction of WSA requires a sufficient amount of free lime is to be added, the quantity determined by the type and composition of the soil to be treated and the desired properties of the end product.

Chemical Analysis

The results of the chemical analysis were analysed and the concentrations of relevant heavy metals were established. The results were evaluated against the relevant limits stipulated by WHO, UNEP and USEPA for reuse of industrial wastes in land applications [6]. The results are presented in Table 3 (in section 8).

The results show that the concentrations of the heavy metals are much lower than the pollution limits stipulated by WHO, USEPA and UNEP [6]. This justifies the acceptability of WSA for reuse in deep stabilization, where leaching of the heavy metals is likely to be substantially reduced by the binding effects of the cementitious reaction products and the low permeability of quick clay and stabilized columns.

5.2 Uniaxial Compression and Index Tests

The results of the uniaxial compression and index tests were analysed and evaluated. They are summarised in Table 4 and in Figures 3, 4, 5, 6, 7 and 8 (in section 8) as charts. Figures 3 and 4 correspond to the pilot tests done on samples with different ratios of lime to WSA, aimed at establishing the optimum mix proportions of lime and WSA for that particular type of quick clay. It was established that equal proportions of lime to WSA (50:50) give the optimum mix ratio, corresponding to the peak of the respective curves. This ratio was therefore adopted for the eventual testing programme on the same materials.

The results in Table 4 show that the moisture content of the stabilized material does not change much in the pozzolanic reaction during the 90 days of curing. Further, the results show that around 4% of the moisture (from 53% to around 49%) is consumed by both the hydration reaction of the quicklime (which is spontaneous and faster than the pozzolanic reaction) and the eventual chemical reactions between the components. However, the results show higher moisture contents for longer curing periods of 56 and 90 days when compared with 7 and 28 days. This could have been caused by absorption of moisture from the surrounding soaked absorbent paper, following disintegration of the inner aluminium foil. This disintegration was observed for all specimens to which lime and WSA were added and is believed to have been caused by a chemical reaction between the foil material and the components of the mixtures as the curing process continued in the perforated cylindrical moulds. Absorption of moisture from the surrounding soaked paper tends to simulate the actual condition in the field, where the columns are surrounded by wet (mostly saturated) clays and, therefore, have access to additional water during the curing process, at least in the outer parts of the columns. The unit weight and dry unit weight of the specimens vary between around 16.70 and 17.00 kN/m^3 and around 11.00 to 11.50 kN/m^3 respectively, and do not show significant variations. This signifies a fair uniformity of the materials and consistency in the procedure for preparation of the specimens. However, both are lower than those of the natural quick clay, mainly due to the addition of water during mixing (higher void ratios) and the mixing process that breaks the natural clay structure and introduces air into the mixture. Generally, the mixtures portray very high liquid limit, plastic limit and plasticity index ($\approx$ 25-30%) when compared to the low plastic natural quick clay (about threefold in each case). Mixtures with cement tend to reveal higher values of the Atterberg limits than WSA mixtures. The general trend can be explained by the effects of the added binder materials and the resulting chemical reactions, which tend to increase the salinity of the mixture (by releasing sodium and potassium cations through the cation-exchange process of the pozzolanic reaction). An increase in the salinity of quick clay decreases its sensitivity and increases its water retaining capacity due to increased interparticle forces. This behaviour of stabilized quick clay appears to be unusual when compared with other soils, where stabilization has the effect of decreasing the plasticity index (normally increases plastic limit against relatively unchanged liquid limit), particularly when lime is applied.

Uniaxial compressive strength and Young's modulus of all mixtures show a clear trend of increasing with the curing period (i.e. the age of samples). Whereas lime-cement mixture shows the highest strength and Young's modulus values at all sample ages, lime-WSA (150 kg/m^3) mixture shows the lowest values (Fig. 5). Lime-cement and lime-cement-WSA show relatively early strength development (as revealed by the higher q/q_{28}-ratios in the last column of Tab. 4). However, as the age of the mixtures increases the difference between the strengths of the mixtures decreases, implying a possibility of achieving more or less equal strengths after a certain period of time, and possibly the lime-WSA mixtures achieving higher strengths than the lime-cement mixes (as verified by the field samples discussed in the next section). On the contrary, the stiffness development with time shows a larger variation. Equally, lime-cement mixtures show relatively smaller failure strains when compared with the corresponding lime-WSA mixtures. This implies that the former are generally stiffer and more brittle than the latter. However, as all mixtures stiffen with age the failure strains become smaller and close to each other, as verified by the curves in Fig. 8. The original quick clay, in the undisturbed state, portrays higher compressive strength and stiffness and smaller failure strain than the 7 days cured lime-WSA specimens (Figs. 5, 6 & 8). This may be explained by the fact that quick clay, in its natural form, is a relatively brittle material that may have a substantial strength, whereas the mixing process remoulds the clay and breaks the natural cementation which takes more than 7 days to rebuild in the pozzolanic reaction. Lime-cement and lime-cement-WSA samples show early strength development, with higher strength and stiffness values after 7 days of curing than the undisturbed quick clay.

5.2 Field Samples

The results of tests on field samples are summarized in Tab. 5 and Fig. 9 (in section 8). In general, field lime-cement-WSA samples show higher strength, both in the soaked and unsoaked states, than the corresponding field lime-cement samples. The former are about five times stronger than the latter. That can be explained by the secondary cementation due to the pozzolanic reaction between WSA and lime, in addition to the strength produced by the hydration of cement. The presence of 'free' lime in lime-cement mixture, which could not go into chemical combination due to lack of enough pozzolanic materials, may have contributed to the lower strength portrayed by this mixture. The higher strength of lime-cement-WSA samples, compared with the samples without WSA, may have been caused by the fact that the samples had been stored under dry conditions at room temperature (around 24^o C, as compared to the average ground temperature of 5^o C in the field) for one month before testing. However, soaking of the samples substantially reduced the strength of both types of samples, with more effect on the lime-cement-WSA samples (by a factor of more than 2.5) compared with the lime-cement samples (factor less than 2). Although the soaked lime-cement-WSA samples appear to have higher 'wet' unit weight that the corresponding lime-cement samples, the former have higher moisture content than the latter, leading to almost the same dry unit weight ($\approx$14.30 kN/m^3) for both sample types. However, in the 'dry' condition, lime-cement samples show a relatively looser and more open structure, with much lower moisture content and a slightly lower dry unit weight (14.25 kN/m^3) compared to the lime-cement-WSA samples (14.50 kN/m^3). On drying, lime-cement samples lost more moisture than the corresponding L-C-WSA samples. As a result, lime-cement samples show a higher water absorption capacity than lime-cement-WSA samples (about 1.5 times higher). Also, the former portray a higher water permeability (189 x 10^6 cm/s) compared with that of the latter (3 x 10^6 cm/s).

6. CONCLUSIONS

The study has highlighted the possibility of re-using wastepaper sludge ash as a binder in stabilization of soft and problematic soils, thus saving on the cost of cement, disposal expenses, sparing land for other beneficial uses and reducing environmental pollution. Mineralogical and chemical analyses revealed that WSA will have no excessive consequences in terms of pollution of soil and ground water. Some protection may be required by the workers against excessive exposure to the material, which is however the same as that required when working with the naturally corrosive quick lime. Optimum mix proportions of lime-to-WSA and mixing moisture content have been determined to give the best stabilizing effect and specimens of good and consistent quality. The tests have also shown that increasing the dose rate in lime-WSA mixtures from 100 kg/m^3 to 150 kg/m^3 has negative effects to the mechanical properties of the mixtures. It has further been shown that the stabilizing effects produced by lime-WSA mixtures are comparable to those of lime-cement binders, but it takes longer time (about 75 days) for lime-WSA mixtures to achieve equivalent engineering properties to those of the 28 days old lime-cement mixture. Tests on the field samples have revealed that despite the uncontrolled storage conditions, specimens from lime-cement-WSA mixture, at the age of 18 months, are much stronger and less permeable than specimens from the corresponding lime-cement mixture.

In order to understand better the mechanical behaviour of lime-WSA treated clays, a new phase of this study has been launched and will include more elaborate laboratory tests, such as triaxial tests, consolidation tests (incremental and continuous loading) and creep tests. *In situ* tests using the laboratory-established mix proportions are recommended in order to validate the laboratory findings and to evaluate the performance of lime-WSA mixtures under the actual field conditions.

7. REFERENCES

[1] Rankka, K., Andersson-Sköld, Y., Hulten, C., Larsson, R, Leroux, V. & Dahlin, T.: "Quick Clay in Sweden". Swedish Geotechnical Institute, Report No. 65; Linköping. 2004

[2] Crawford, C. B: "*Quick Clays of Eastern Canada*". Journal of Engineering Geology. Elsevier Publishing Company, Amsterdam, Netherlands. 1968. pp. 239-265.

[3] Bruce D. A; Bruce, M. E. C; DiMillio, A. F.: "Dry Mix Methods: A brief overview of international practice", in H Bredenberg, G. Holm, and B. B. Broms, (Ed.): *Dry Mix Methods for Deep Soil Stabilization*; Proceedings of the Int. Conference on Dry Mix Methods for Deep Soil Stabilization; Stockholm, Sweden; 13-15 October, 1999. pp. 15-25.

[4] Janz M., Johansson S., 2002: The Function of Different Binding Agents in Deep Stabilization; Swedish Deep Stabilization Research Centre, Report No. 9; Linköping, Sweden, 2002.

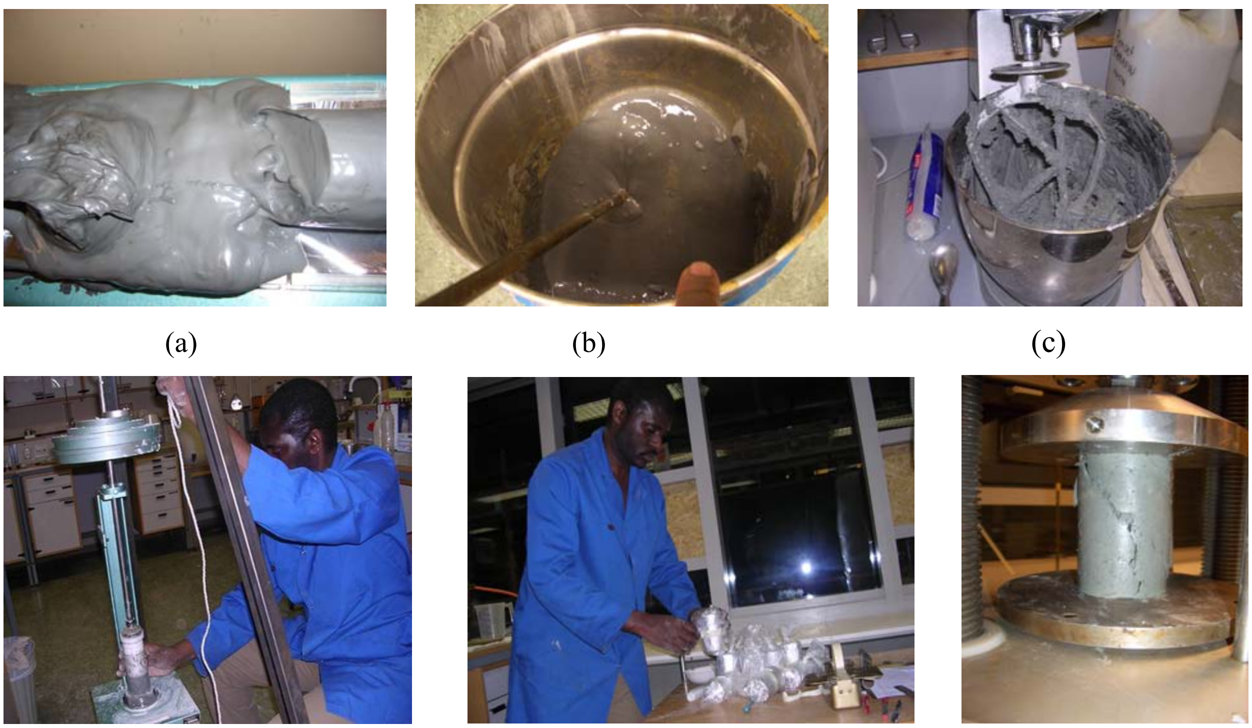
[5] Kinuthia, J.M. 2004: Innovative Use of Materials in the Construction Industry. Geoenvironmental Research Centre's Land Regeneration Network. www.grc.cf.ac.uk/lrn. 28th October, 2004.

[6] McFarland, M. 2000: *Biosolids Engineering.* Technology & Industrial Arts. McGraw-Hill Professional, NY, USA, 2000.

[7] Perkins, D. (1998): *X-ray Diffraction.* Mineralogy. University of Dakota; Prentice Hall, New Jersey; pp.258-77

8. TABLES AND FIGURES

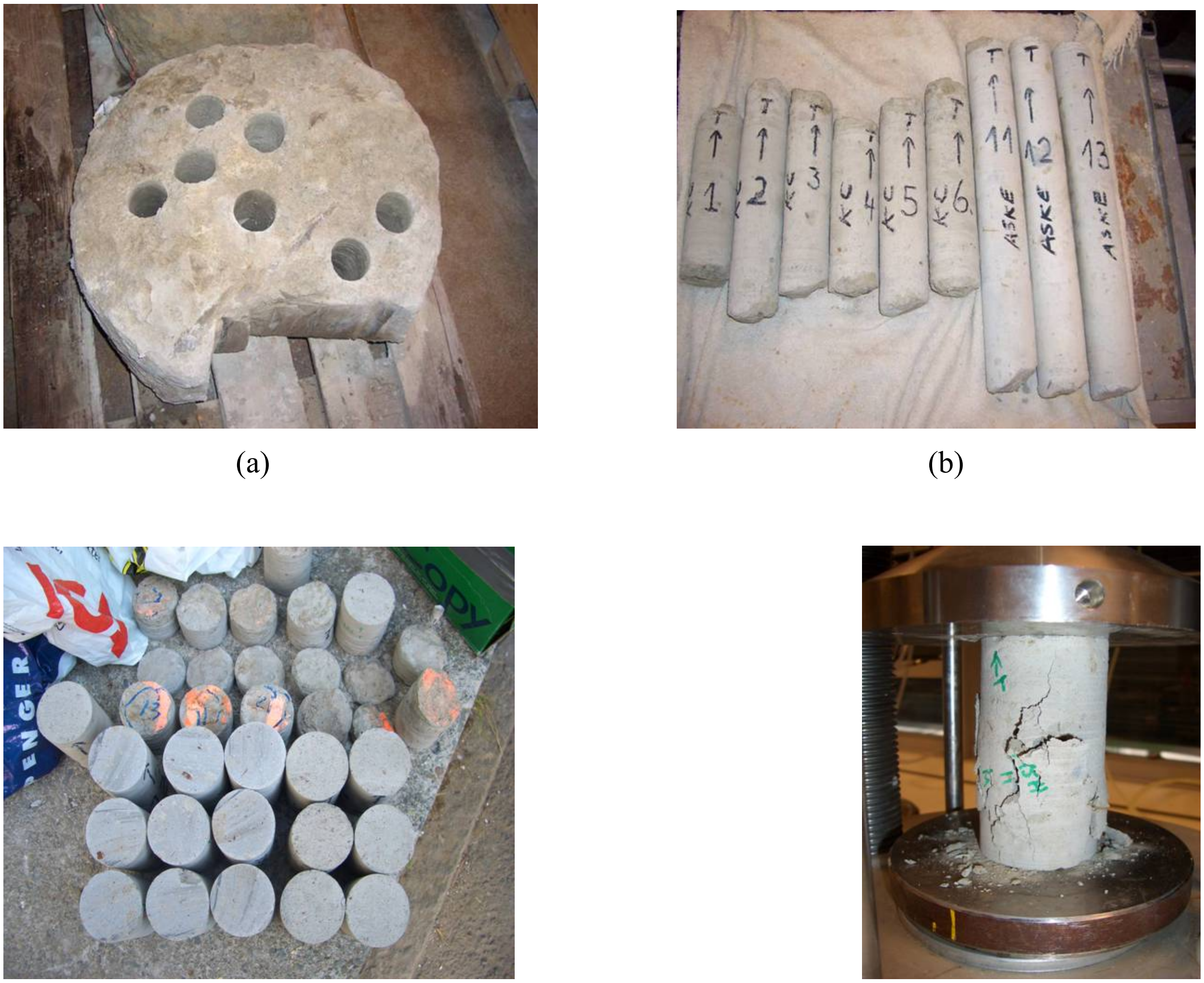
8.1 Illustrative Photographs



(a) (b) (c)

(d) (e) (f)

Fig. 1: Preparation of deep-mix laboratory samples: (a) Extrusion of quick clay from sampling cylinder; (b) Homogenization of natural clay; (c) Mixing of quick clay and binder materials; (d) Compaction of the mixture in cylindrical moulds; (e) Wrapping and labeling (f) Uniaxial compression test on lab specimen



(a) (b)

(c) (d)

Fig. 2: Preparation and testing of field samples: (a) Coring of cylindrical specimens from a block field sample; (b) Cored specimens before sizing (KC = lime-cement, Aske = ash => L-C-WSA); (c) Sized specimens, ready for testing; (d) Field specimens in the uniaxial compression test

8.2 Tables of Results

Table 2: XRF main element analysis of WSA

Oxides	Fe_2O_3	Al_2O_3	SiO_2	CaO	MgO	MnO	K_2O	Na_2O	P_2O_5	TiO	SUM
Content [%]	1.76	14.13	32.55	37.85	5.47	0.27	0.85	0.81	0.77	0.67	95.13

Table 3: Concentration of heavy metal in WSA and Tiller quick clay

Element	Content in Quick clay	Content in WSA		Content in Clay-WSA mix ø	Pollution Limit*	Ceiling Limit*
		Factory +	NTNU Lab.§			
-	[mg/Kg]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/kg]	[mg/kg]
As	3.0	20	27.2	5.42	41	75
Cd	0.39	3.1	3.16	0.71	39	85
Cu	45.3	390	747	115.47	1500	4300
Hg	-	0.3	-	(0.03)	17	57
Mo	0.30	3.7	5.64	0.84	-	75
Ni	112	44	60	106.80	420	420
Pb	9.07	119	141	22.26	300	840
Se	-	-	-	-	36	100
Zn#	123	930	1260	236.70	2800	7500

** WHO/UNEP limits for "land applications" (1 mg/kg = 1 ppm)*
+ Data from source factory
§ Lab analysis at Geology laboratory, NTNU (ICP-MS method; conc. HNO_3 solvent at 180^0 C)
 # Toxic only to plants (gardening, irrigation)
ø A clay-WSA mix with 10% WSA content was assumed, neglecting heavy metals in lime and/or cement

Tab.4: Results of unconfined compression and index tests

Age [days]	w [%]	γ [kN/m^3]	γ_d [kN/m^3]	e [-]	w_L [%]	I_p [%]	q [kPa]	ε_f [%]	E [MPa]	E/q [-]	q/q_{28} [-]
MIX I: LIME – WSA (100 kg/m3)											
7	48.16	16.98	11.46	1.42	61.89	25.20	34.26	5.10	0.60	17.52	0.40
28	49.23	16.88	11.31	1.45	65.26	26.58	85.23	2.70	4.72	55.42	1.00
56	50.99	16.91	11.20	1.48	61.20	23.05	164.15	2.42	11.14	67.89	1.93
90	50.62	16.88	11.21	1.48	63.57	25.88	193.92	1.96	17.04	87.89	2.28
Aver	49.75	16.91	11.30	1.46	62.98	25.18	-	-	-	-	-
MIX II: LIME - CEMENT											
7	48.10	16.76	11.32	1.44	67.55	29.31	122.56	2.45	8.39	68.47	0.69
28	48.19	16.65	11.23	1.46	70.55	29.68	177.05	2.02	13.95	78.78	1.00
56	48.60	16.69	11.41	1.42	69.08	28.63	215.06	1.76	17.27	80.28	1.21
90	49.77	17.02	11.36	1.44	66.50	25.88	241.66	1.34	35.22	145.75	1.36
Aver	48.67	16.78	11.33	1.44	68.42	28.38	-	-	-	-	-
MIX III: LIME – CEMENT - WSA											
7	48.30	17.01	11.47	1.42	65.60	28.27	87.45	2.76	4.06	46.43	0.69
28	49.97	16.58	11.05	1.51	67.08	28.62	126.20	2.47	8.29	65.71	1.00
56	50.99	16.91	11.20	1.48	71.00	28.59	178.19	2.14	14.64	82.18	1.41
90	50.33	17.05	11.34	1.45	66.09	23.25	226.51	2.17	17.74	78.30	1.79
Aver	49.90	16.89	11.27	1.46	67.44	27.18	-	-	-	-	-
MIX IV: LIME – WSA (150 kg/m3)											
7	49.11	16.55	11.10	1.50	58.94	24.30	33.72	8.88	0.59	17.46	0.45
28	48.99	16.69	11.15	1.49	67.31	29.76	74.85	4.05	3.13	41.79	1.00
56	50.35	16.80	11.17	1.49	62.90	23.60	105.13	1.78	7.82	74.39	1.40
90	50.62	16.89	11.21	1.48	64.88	26.48	170.62	1.93	12.24	71.74	2.28
Aver	49.77	16.73	11.16	1.49	63.51	26.03	-	-	-	-	-
NATURAL TILLER QUICK CLAY (Average values)											
Undist.	38.00	18.64	13.51	1.03	26.00	8.00	38.00	4.07	1.44	37.87	s_t = 95#
Remold	38.00	18.64	13.51	1.03	26.00	8.00	*0.40	-	-	-	

* Twice the remoulded shear strength, determined by the fall-cone test

Sensitivity, s_t = undisturbed shear strength /remoulded shear strength

Tab. 5: Field samples test results – Unit weights, water absorption and permeability

Sample (Φ54mm, H= 100mm)	Unsoaked				Soaked (96hrs)					
	Mass [g]	w [%]	γ [kN/m^3]	γ_d [kN/m^3]	Mass [g]	w [%]	γ [kN/m^3]	γ_d [kN/m^3]	Abs. [%]	Permeab. x10^6 [cm/s]
L - C	345.28	3.82	14.79	14.25	413.32	23.74	17.70	14.30	19.92	189.00
L-C-WSA	379.67	12.10	16.26	14.50	418.05	25.29	17.91	14.29	13.19	3.05

8.3 Results Plots

A: Results from pilot tests

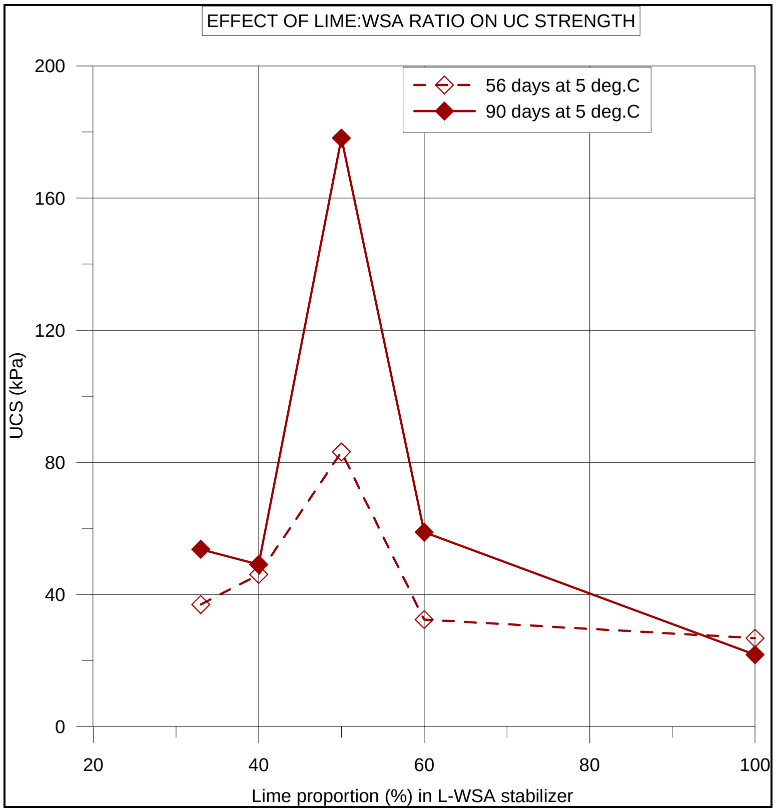


Fig. 3: Variation of uniaxial compressive strength with lime content of lime-WSA mixture

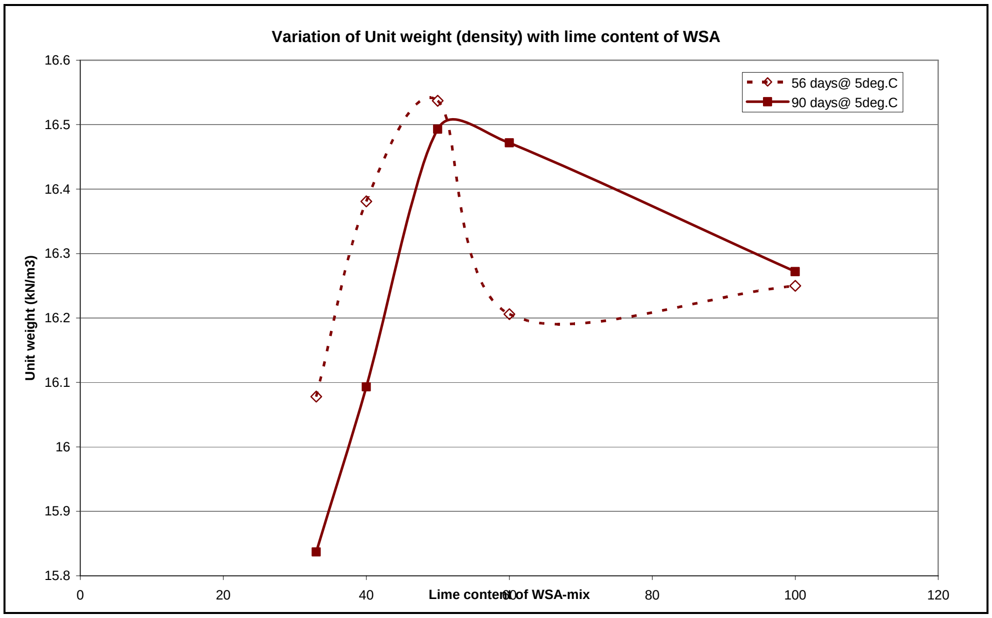


Fig. 4: Variation of sample unit weight with lime content of the lime-WSA mixture

B: Results from the actual laboratory test programme

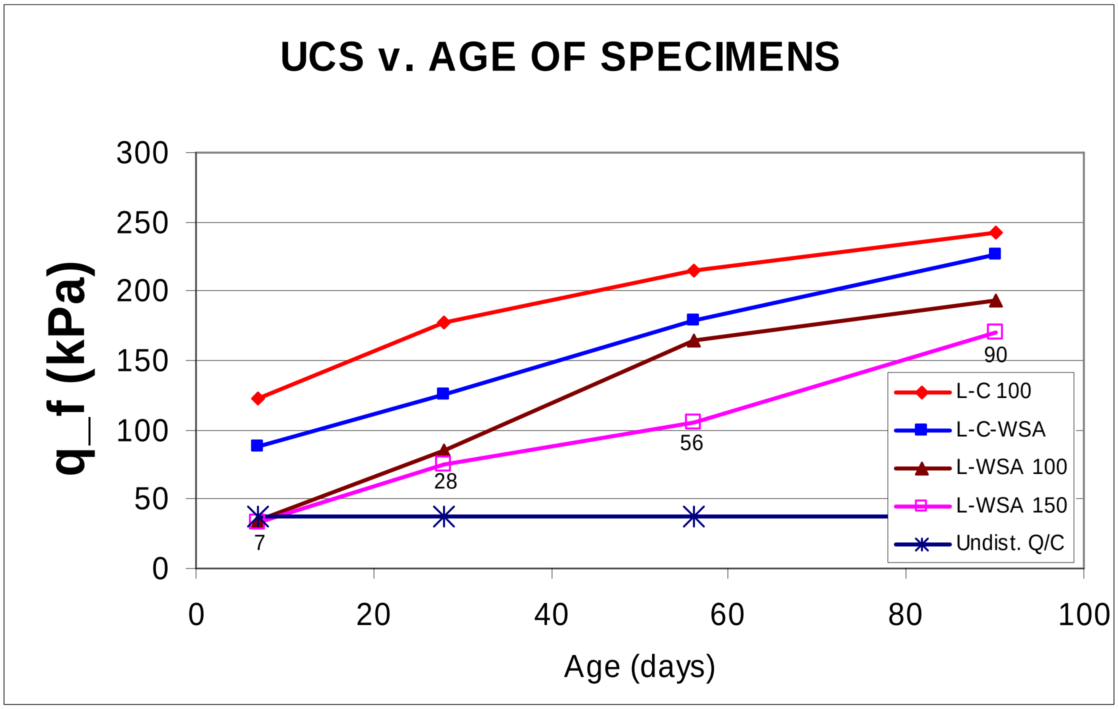


Fig. 5: Variation of compressive strength with sample curing period

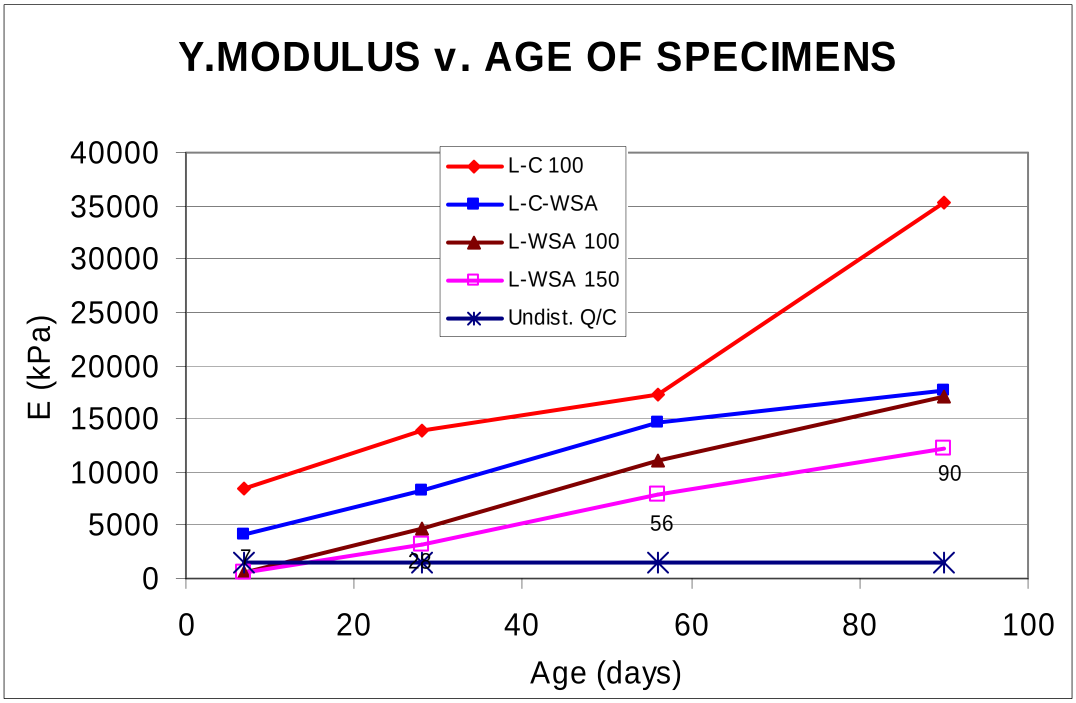


Fig. 6: Variation of Young's modulus with sample curing period

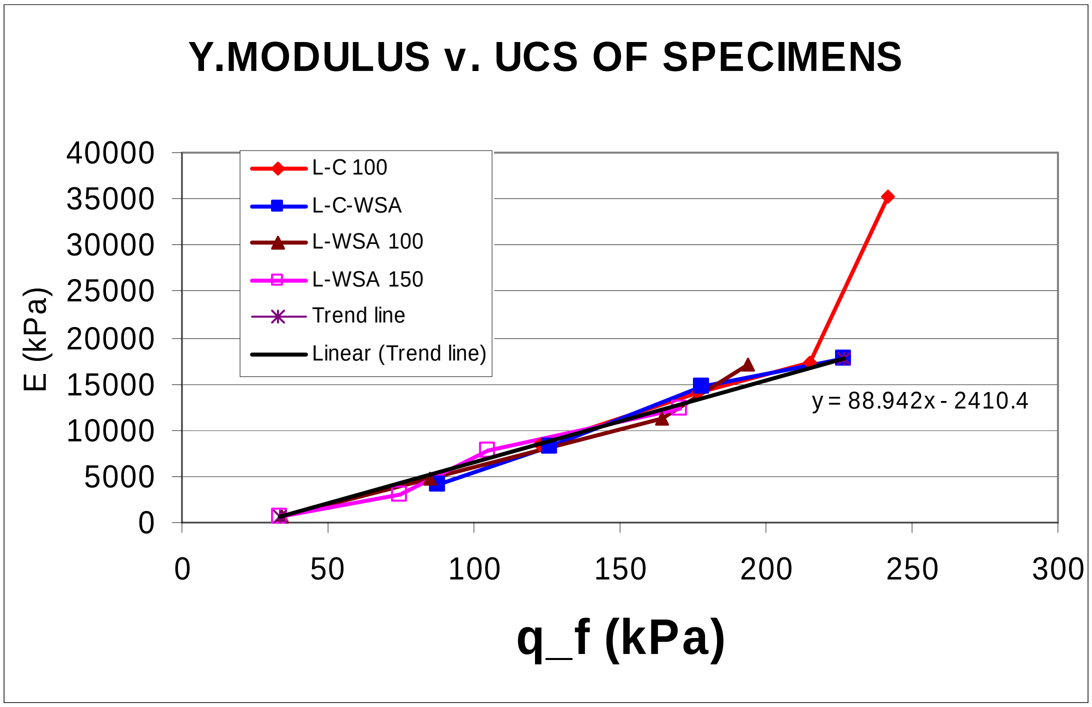


Fig. 7: Variation of Young's modulus with uniaxial compressive strength

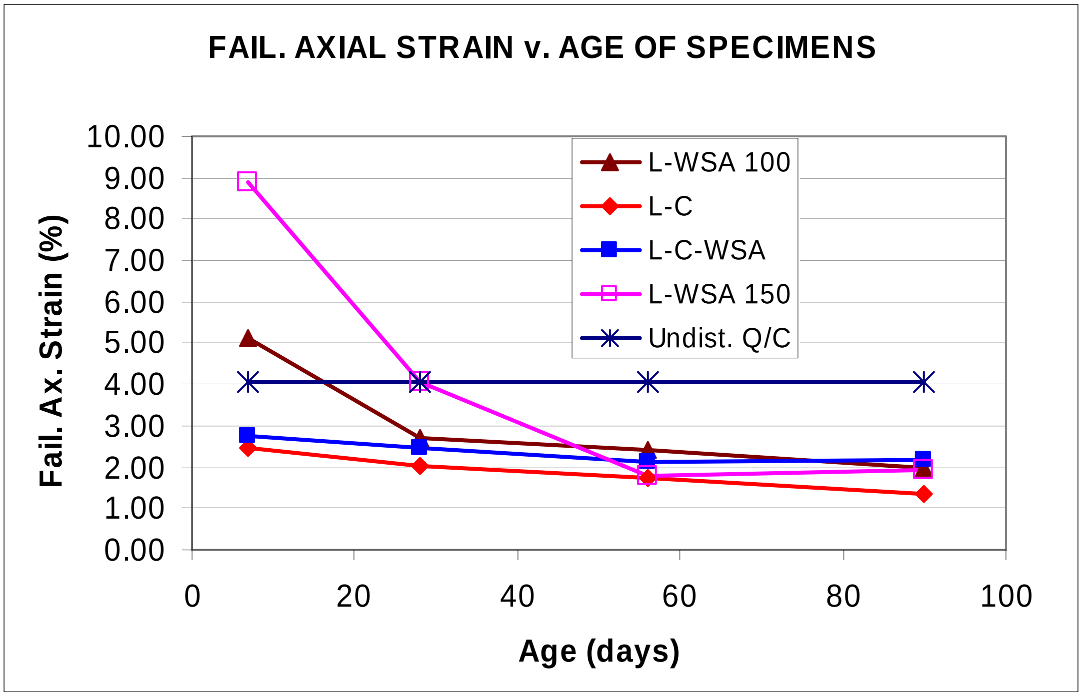


Fig. 8: Variation of the failure axial strain with sample curing period

C: Results form Field Samples

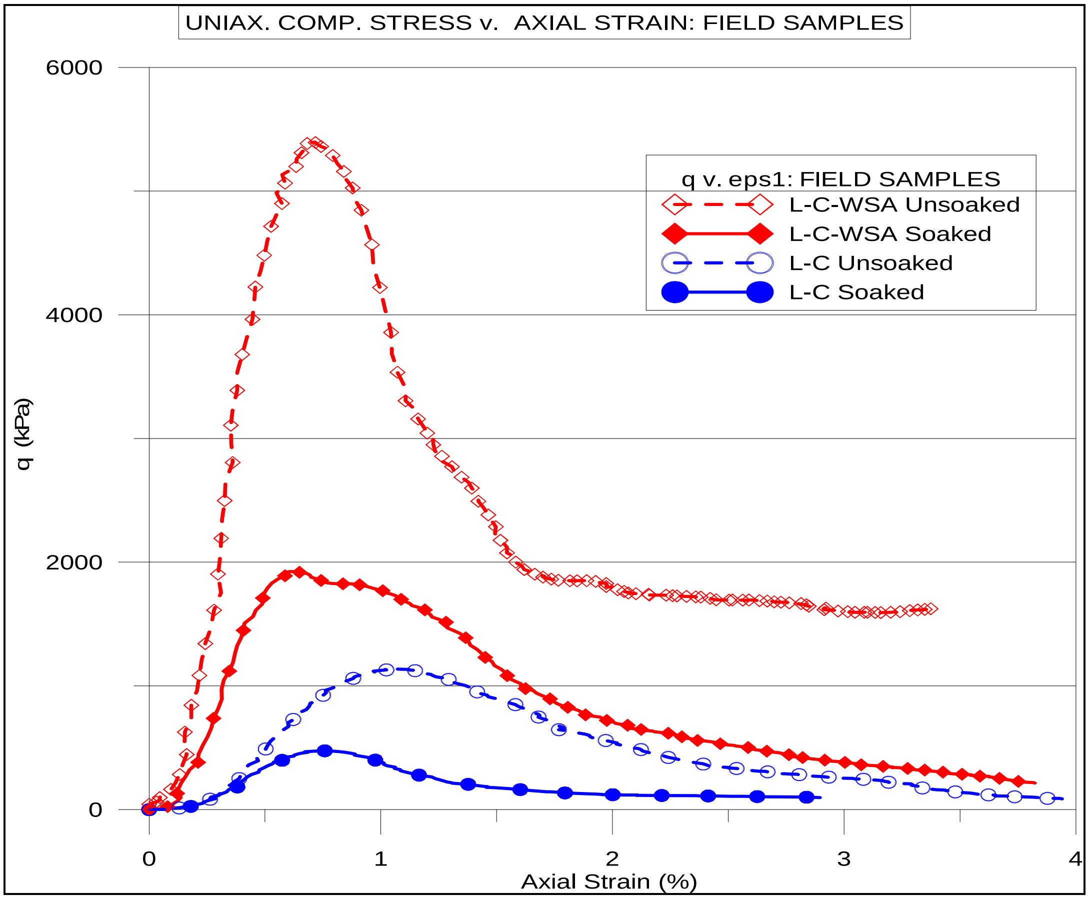


Fig. 9: Stress-strain curves for uniaxial compression of stabilized field samples