Durability of lime treated soil in coastal environment: Methodology for a laboratory study and first results

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ABSTRACT: In order to study lime-treated soil durability, a method of accelerated aging is proposed. This method reproduces the environmental stress applied on a marine dike. Mechanical properties, microstructural properties and resistance to erosion are parameters followed on lab samples during aging. Destructive and geophysical tests have been performed.

1 INTRODUCTION

Lime treatment of fine soil is a tried and tested material improvement technique on earthwork field. However, it is not a common used technique on hydraulic structures because of a lack of knowledge about long term durability of lime treated soil on these structures.

The material durability study is based on the evaluation of the kinetic of properties changes in a well defined environment. In coastal and marine environments, the seawater and immersion-emersion cycles are the two major causes of material degradation. In literature, works about lime treated soil durability focuses on the curing time impact and sometimes hydraulic solicitations on mechanical and hydro-mechanical material properties. Other properties also have to be considered, like the resistance to internal and external erosion. These phenomenons are the cause of 98% of embankment dam failures and accidents (Foster et al. 2000; Mehenni 2015). Moreover, there are not many publications treate salt influence on long term behavior of lime treated soil.

With the aim of building an experimental marine platform using lime treated soil (Digue 2020 French project), a work about material durability has been performed in the lab.

The aim is to accelerate the material’s aging by cyclic reproduction of environmental conditions, and characterize material properties at different stages of deterioration. The influence of initial material properties on the long term behavior is studied to establish criterions for durability.

Raw soil characteristics and blend formulation are presented in the first part; the second part concerns the reproduction of environmental conditions. These ones are simplified and limited to the impact of salt water and wetting-drying cycles on the material properties. The last part presents the characterization tests (erosion, mechanics, microstructure, geophysics) and the first results.

2 MATERIAL

2.1 *Natural soil*

The soil used in this study is a silt from the Salin de Giraud (France), located near the Grand Rhone mouth. The material was homogenized on site, and then stored in big bags in the open air. The soil use is the same with all the Digue2020 partners.

Geotechnical and physic-chemical features were determined using earthwork standards (XP P94.041; XP P94.057; NF P94-052-1; NF P94-068). Some results are presented in table 1 and figure 1.

Table 1: Some properties of Salin de Giraud soil

Soil pH	Ionique concentration on the interstitial water	Liquid limit	Methylene Blue value
8,6	1,6 g/L	26,2	1,10g/100g

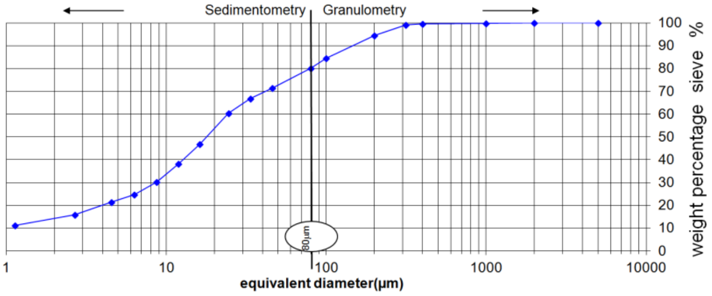

Figure 1: Size distribution of the silt from Salins de Giraud. The clay part is 15% of the mass.

2.2 *Lime*

The quicklime used (Proviacal DD) complies to NF EN 459-1 standard (building lime). The characteristics are detailed in Table 2.

Table 2 Characteristics of the quicklime

free CaO	Reactivity (t_{60})
>80%	<10min

2.3 *Blend formulation*

In order to demonstrate the influence of lime content on the material durability, lime treatment is done using two different lime contents: 1 and 2% of the dry mass.

The 1% lime content conforms the soil-lime proportion requirement for soil stabilization (=PFC). This value was determined using the ASTM D6276 standard (figure 2).

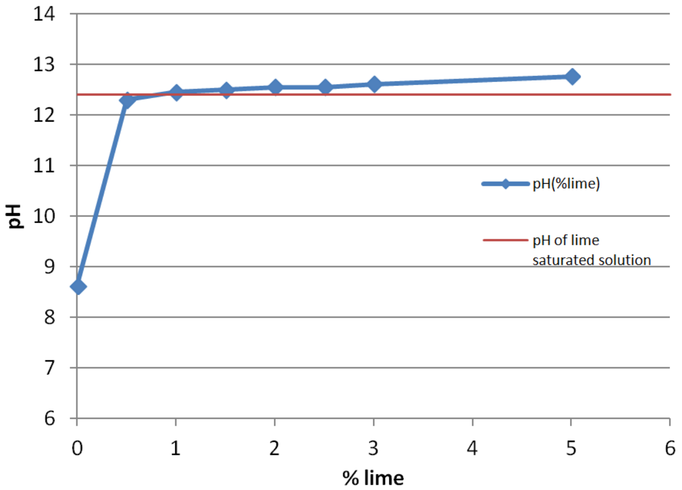

Figure 2. pH versus lime mass content on the soil+water+lime solution. The lime content corresponds to a 12.4 pH. It is the soil-lime proportion requirement for soil stabilization.

Short term improvements of mechanical properties are at a maximum for a lime content equal to the PFC (Le Roux & Rivière 1969; Bell 1996; Mehenni 2015). However, long term performance can be improved using more lime than the PFC concentration. (Locat, et al. 1990; Nguyen 2015).

For earthworks, the lime content has to be of PFC+1% to ensure that the lime content is sufficient anywhere despite the heterogeneities due to the mixing methods.

A batch of samples is prepared using 2% of lime. This choice corresponds to the standard recommendation.

Some specimens are reconstitued using only natural soil in order to discriminate the performance linked to the soil and those linked to the lime treatment.

2.4 *Compaction properties*

Proctor density and optimum water content are determined on soil without treatment, on soil treated with 1% (in mass) of lime, and on soil treated with 2% in mass of lime. We notice that optimum water content is 2 points lower for the natural soil than the treated soil (Figure 3).

Samples reconstituted for our study were dynamically compacted on seven 20mm thick layers. Samples diameter is 70mm. The density target is 98% of the Proctor density, and the water content is equal to the optimum water content +1. These compacting conditions allow the lowest permeability rate (Le Runigo et al. 2011; Cuisinier et al. 2011; Herrier et al. 2013). Gamma densimetry measurements confirmed that the density is the almost same in each layer with a relative accuracy of about 0.06 g/cm^3.

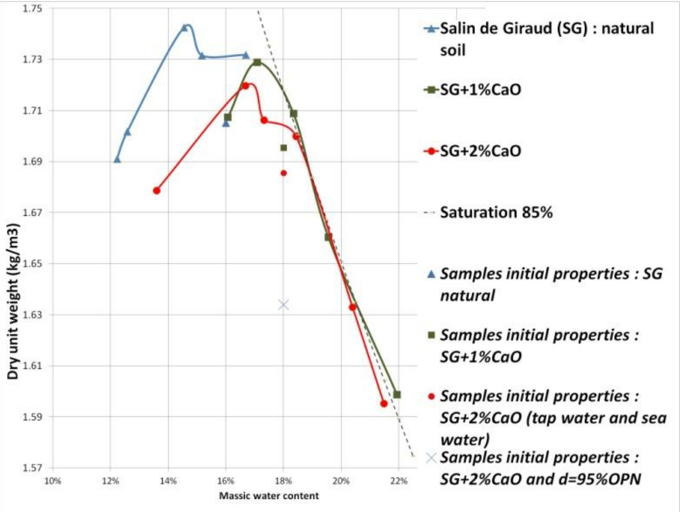

Figure 3. Proctor curves for natural and treated Salin de Giraud silt, and characteristics of the five different samples properties.

3 ACCELERATED AGING

In this part, the word « aging » describes the material fatigue created by the environmental stress (salinity and emersion-immersion periods)

3.1 *Evaluation of environmental stress and consequences on material properties*

The aim is to replicate the characteristic environmental stress applied on marine dikes (protection against marine submersions) and look for the consequences on the material. Dike monitoring, using punctual sensors or geophysical surveys, is recent and only limited data is available. Therefore it is difficult to know the relationship between the intensity and frequency of weather conditions (rain, sea level, waves, temperature…) and the consequences on material properties, in particular on the water content. One of the most recent data is from the TerDOUEST French project (ANR-07-PGCU-0006). Volumic water content was recorded on a lime treated embankment at different depths, and correlated with weather conditions. The 4 years data collection shows that at a few centimeters under the embankment surface there is daily high frequency water content variation (±5%) but the annual mean is stable at 30%. The particular geographical position of the dike, in a place with the stable weather condition could explain the weak water content variations. In the case of the Digue2020 marine dike, the geographic position (South-East of France) and the seawater closeness, allow to make the hypothesis of higher water content variation in comparison to the TerOUEST embankment. Hence, in lab condition we chose to study the consequence of intense massicwater content variation and salinity induced by seawater.

3.2 *Drying-wetting protocol*

The parameters of the drying-wetting cycles are chosen to reproduce the most adverse condition for the material. During the curing time and cyclic water content variations, samples are not confined. They represent the surface dike material.

The drying phase is controlled in a climatic chamber (set point**:** T=20°**C,** hygrometry 60%). The drying time is of 48 hours, and the water content obtained is 5% higher than the minimum water content possible in these drying conditions (part of the water is trapped in the small pores).

Sample wetting is made by capillary rise. Samples are put on filter paper and porous stone on water (figure 4). This phase take 24h. To accelerate the wet homogenization, samples are switch at half-time.

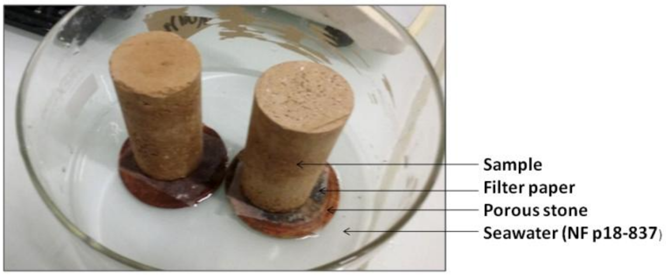

Figure 4 : wetting configuration

To simulate seawater immersion during storm, artificial seawater (NF P18-837 standard) is used during the wetting phase. The same water is used for all the laboratory works in the Digue2020 project. Salt content in samples is followed by electrical resistivity measurements.

A posteriori, the lab results will be compared with the data obtained by monitoring on the full-scale dike Digue2020. The dike is planned to be built in spring 2018.

4 MULTI-PHYSICAL MATERIAL CHARACTERIZATION: EXPERIMENTAL DEVICE FOR THE DURABILITY STUDY

The study is focused on material resistance to erosion, mechanical performance, microstructure and geophysical properties.

4.1 *Resistance to erosion*

Internal resistance to erosion is characterized by the Hole Erosion Test (HET) (Figure 5). This test aims to replicate and model hole erosion on hydraulic structures. Parameters determined are the critical tangential stress where the erosion is initiated, and the erosion rate (Chevalier et al. 2012; Chevalier et Bonelli 2016; Haghighi 2013; Mehenni 2015). the erosion law is determined at different curing times and after one to eight drying-wetting cycles.

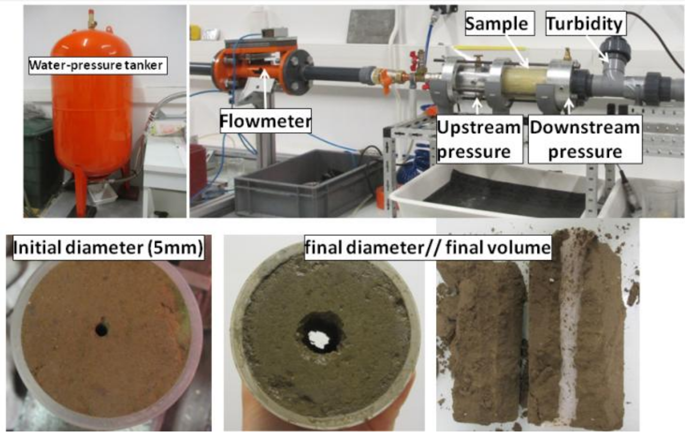

Figure 5: HET device and example of a sample before and after the test.

The external erosion is characterized using the mobile jet erosion test (MoJET) device (Chevalier et al. 2012; Haghighi 2013). This test can be made both in lab and in situ. The eroding unit projects water in 0.5 mm diameter nozzles perpendicular to the soil (Figure 6). Effluent collected at different times are placed in the drying oven and measured to determine the mass of dry material eroded (Pham, 2008, Reiffsteck et al., 2012). This solid load (i.e. eroded mass as a function of time) is used to perform qualitative evaluations of erosion, to establish correlations between the amount of eroded soil and geotechnical properties. The test is performed on samples after zero to eight drying-wetting cycles.

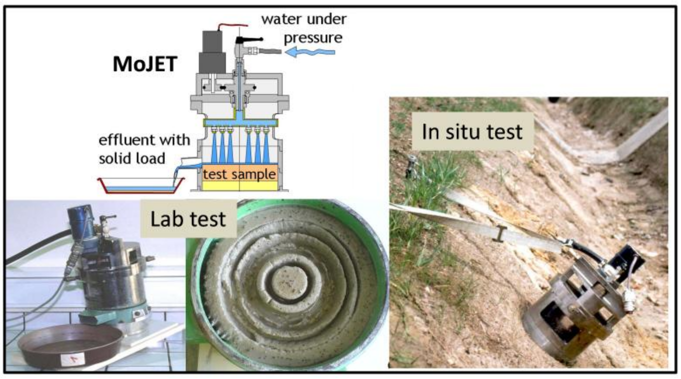

Figure 6: MoJET device

4.2 *Mechanical behavior: unconfined compression test*

Unconfined compression strength (Rc) is a easy obtained parameter with many references in literature about lime treated soil. (Le Roux et Rivière 1969; Bell 1996; Nguyen 2015; Mehenni 2015).

The test is done at different curing times and after zero to twelve drying-wetting cycles. Compressive stress values are compared with micro structural and geophysical data.

4.3 *Micro structural study*

Pore size distribution is determined during the curing time and after drying-wetting cycles using the mercury porosimetry method. Pore distribution is used to model permeability and study relative permeability variations between materials after different numbers of drying-wetting cycles.

4.4 *Geophysical study: geoelectrical and seismic methods*

The DC-resistivity measurement device consists of a resistivity meter (Syscal Pro DM, IRIS Instruments), and a cylindrical cell with annular electrodes (figure 7). Electric current (I) is injected through the sample and potential drops (U) are measured between each pair of annular electrodes. The resistance U/I mutiplied by the geometrical factor gives us apparent resistivity of each investigated volume (Du Plooy et al., 2013).

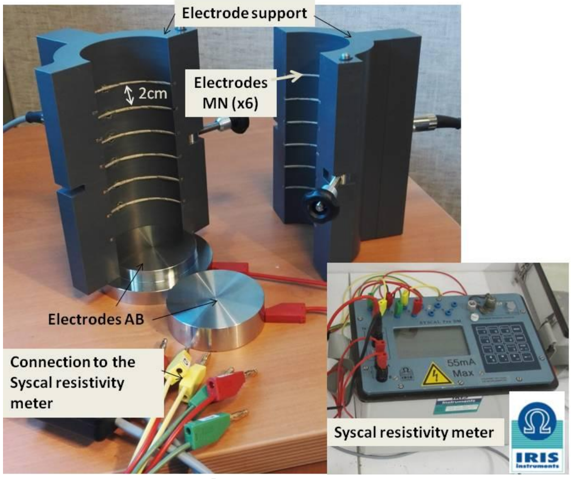

Figure 7: Restivity device

The velocity of P and S waves in material is measured using the piezoelectric transducer. S waves velocity is linked to the G modulus (small deformation). The aim of the measure is to detect structural modifications on material linked to salinity and cyclic water content variations.

5 SOME RESULTS

5.1 *Unconfined compression strength function of composition and hydraulic solicitation*

After 28 curing days the samples treated with 2% of lime and seawater present the highest value, but after two drying-wetting cycles this value decrease by 130 kPa whereas for the 2% lime treated soil strength decrease by only 25kPa (figure 8). After four cycles the strength value is quite the same (view error bar).

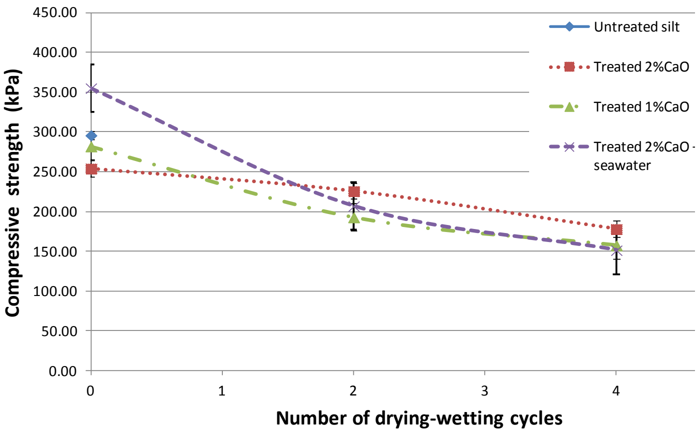

Figure 8: Compressive strength after 28days of curing and different number of cycles. Each point is a three values average, and the error bar corresponds to the standard deviation.

After 90 days of curing, the strength of the 1% lime treated soil is the same as the one obtained at day 28. In the case of the 2% treated soil, the value increases by half. We can conclude that in the case of the 1% treatment, the lime is completely consumed whereas with the 2% lime treated soil, the reaction between lime and clay continues at least until 90 days of during (figure 9).

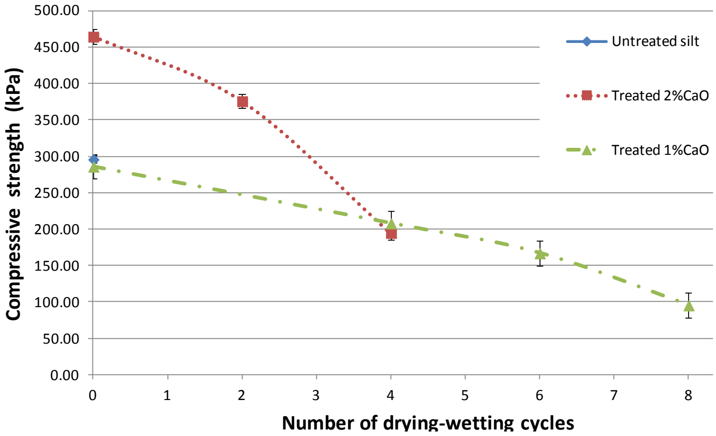

Figure 9: Compressive strength after 90 days of curing and different number of cycles

However the strength value drops by 50% between 0 and 4 cycles. The hypothesis is that the 2% lime treated soil has a high stiffness that induces fracturing during the drying phase. Microstructure analysis could confirm this hypothesis.

The experimentation is still in progress, with an increasing number of cycles to know if compressive strength stabilizes.

5.2 *Resistivity*

During the curing period the resistivity of the sample was studied. For the 2% lime treated sample, the resistivity increased from 2.45Ωm at 18 days to 2.75Ωm at 85 days (Figure 10).The water content is constant. The resistivity depends both on the water content and free ions content in solution. This result shows that part of the free ions precipitated to form new cement compounds. This hypothesis is consistent with the compressive strength results.

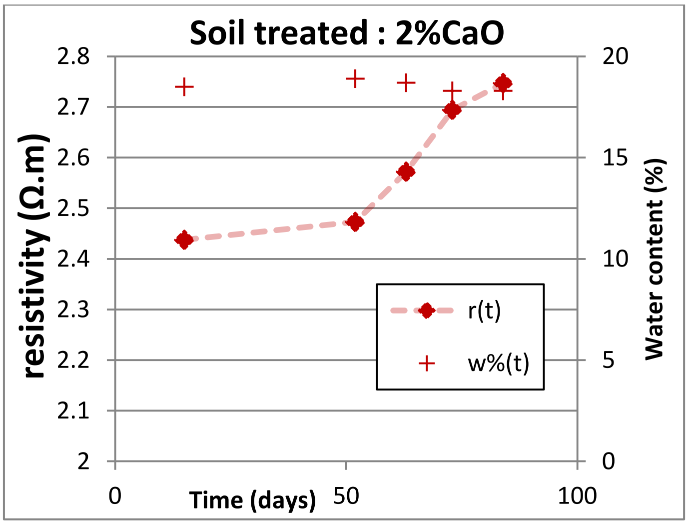

Figure 10 : Evolution of the material electrical resitivity. The sample studied is treated with 2% of lime.

5.3 *Mercury Intrusion Porosimetry*

The figure 11 presents the pore size distribution for the natural compacted soil and the 1 and 2% treated (and compacted) soils before and after 2 drying-wetting cycles. The natural soil presents two pore families, centered at 600nm and 12µm. The total porosity is 35.5±0.5%. The lime treated soils (1% and 2%) also present two pore families. The smallest family (micro-porosity) is different from the natural soil micro-porosity. This difference can be explained by the formation of porosity in clay aggregates which are formed because of lime treatment (Cuisinier et al. 2011). The second family from 8 to 13µm (macro-porosity) seems to be linked to the nature of soil. This macro-porosity is present whatever the formulation, but the total volume of these macropore is higher in the case of natural soil. Based on these observations we can make the assumption that the cement compounds grow in this macro-porosity. However, the addition of lime from 1 to 2% does not induce the diminution of the number of macro pore, contrary to the expected result. Either another physical-chemical phenomenon comes into play with the addition of lime, or this result is linked to the experimental protocol. This question needs more data to be answered.

The effect of the drying wetting cycles is the same whatever the quantity of lime (1 or 2%) : the micro pore size increases and the quantity of macro pore increases. The total volume of pores is constant at 36±0.5% for both compositions. The drying wetting cycles modify the pore size distribution but not the total porosity. This result will be used on a permeability model, and completed with the study of lime treated soil after 90 days of curing (with and without drying-wetting cycles).

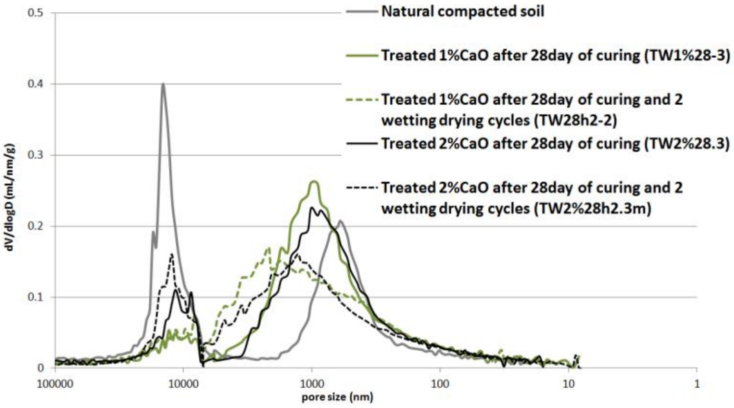

Figure 11 : interpretated porosimetry curves

5.4 *Hole Erosion Test and MoJET test*

The erosion test campaigns are still in progress, results are not yet available. Results will be presented during the conference.

6 CONCLUSION

The lime treated soil durability study is based on reproduction and acceleration of real environmental stresses. These environmental impacts cause modification on material properties which are followed over time.

During the curing time mechanical performances increase provide that the lime content be at least 2% of the total dry mass (in the case of this specific soil). This improvement is due to pouzzolanic reaction triggered by the addition of lime. This result shows the importance of the curing time on material performances. In-situ it should be crucial to protect the dike surface during an initial period (duration have to be determined) to let pouzzolanic reactions append.

Electrical resistivity measurement is an accurate approach in lab to follow the evolution of pouzzolanic reaction during the curing time provides that salinity and water content stay constant during this time.

The drying-wetting cycles modify the samples structure and composition, with consequences on mechanical property. Whatever the initial formulations, the compressive strength decreases. A higher number of cycles will applied to correctly define the kinetic of material properties degradations.

Accelerating aging in lab has limitations in terms of real environmental stress representativeness (immersion frequency, temperature, relative humidity, etc.). Therefore lab material properties and in situ material properties could be different. To quantify this difference, in situ material characterization will be done using sample collected on the full scale experimental dike (Digue2020) just after the construction work, and at different times in the lifetime of the structure (meteorological data, water content and suction values will be recorded by sensor on the dike).

7 ACKNOWLEDGMENT

Digue 2020 is funded with the participation of the European Union. The Europe commit in Provence-Alpes-Côte d'Azur with the *European Found for Regional Development (FEDER).*

Digue 2020 is funded as a part of *CPER 2015-2020*, with the participation of the French Government, PACA region and French department council 13.

A Syscal Pro Deep Marine was used courtesy of IRIS Instruments.

Staff from SRO, GMG and GeoEND labs for their assistance.

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