Ageing-induced deformation of chalk rocks in underground quarries

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AGEING-INDUCED DEFORMATION OF CHALK ROCKS IN UNDERGROUND QUARRIES

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ABSTRACT

Chalk rocks have been used for centuries as a strong building material and for the production of lime. The shallow underground room-and-pillar quarries where the chalk was extracted are now abandoned and endure the effects of time and weathering, increasing their risk of collapse. The risk of instability, involving natural or anthropic underground structures, is an issue for more than 10 000 towns in France.

In order to investigate the causes of underground quarry collapse and to aid prevention strategies, we carried out a study of the physico-mechanical behaviour and ageing of chalk in abandoned pillars in two underground quarries, *in situ*-instrumented by INERIS, in the Parisian Basin, France. Core samples were drilled horizontally from pillars in the Saint-Martin-Le-Noeud dolomitic chalk quarry (Oise, France) and the Estreux glauconitic chalk quarry (Nord, France).

Uniaxial tests were performed on dry and saturated cylindrical plug samples extracted perpendicular to the cores at regular distances along their lengths. Physical and mechanical properties were obtained. The dolomitic chalk (Saint-Martin-Le-Noeud) exhibits variation in mechanical and physical properties with horizontal pillar depth. Both density and compressive strength seem to increase outwards from the pillar-core to the pillar-wall. This is the opposite of that would be expected from a purely mechanical point of view. SEM analysis revealed progressive degradation and homogeneity of the grains from the edge to the inside of the pillar. At the pillar wall, the crystal faces are well-defined, almost euhedral, and the grains are of variable size. In contrast, at the inside of the pillar, crystals are finer-grained and are anhedral with highly degraded edges. In the physico-mechanical tests and SEM analyses performed on the Estreux samples, no significant variation was observed between the pillar-walls and pillar-core. However, dissolution marks were observed along the entire length of the half-pillar core.

KEYWORDS

Chalk, ageing, underground quarries, water, strain, mechanical behaviour

INTRODUCTION

Alteration can be defined as a modification of the physico-chemical properties of minerals and therefore rocks, by atmospheric agents, ground waters or thermal waters (Winkler, 1975; Foucault and Raoult, 1995). The process is dependent on climate, water temperature, the nature of the rocks, and their degree of fissuration. Alteration generally leads to less-coherent rocks, facilitating their disintegration, rupture and eventual failure (Kasim and Shakoor, 1996; Gupta and Seshagiri Rao, 2000; Massuda, 2001). Macroscopic signs of alteration include the appearance of cracks, microfractures and macroporosity, as well as the presence of hard deposits resulting from chemical transformations (Norbury et al., 1995; Chigira and Oyama, 1999; Oyama and Chigira, 1999). The alteration of rocks by dissolution (limestones, tuffs, sandstones, crystalline rocks), with or without mineral neoformation, has been studied by a number of authors (Farran and Thenoz, 1965; Auger, 1991; Furlan and Girardet, 1991; Chêne et al., 1999; Chigira and Oyama, 1999; Gupta and Seshagiri Rao, 2000).

The term 'ageing' refers to alteration of rocks as a result of human activity such as mining or quarrying. In the context of underground works, the term is used to describe the totality of mineralogical and physical modifications of the rock over time, leading to deterioration of the hydraulic or mechanical properties of the rock. The effects of time on the behaviour of an unprotected underground site consist of different phenomena responsible for degradation of the material properties: (i) degradation of constituent minerals by physico-chemical processes, leading to diminished mechanical characteristics (this is 'ageing' in its stricto sensus); (ii) deferred deformation under a constant load i.e., creep; and (iii) variations in humidity, and therefore in saturation and suction, in zones within the rock that experiences variable ventilation (these cyclical stresses can induce damage through hydromechanical coupling). The influence of each of these processes must be fully taken into account in any assessment of the temporal evolution of an underground quarry in order to provide appropriate recommendations for the solutions that should be implemented to ensure the long-term stability of a site, without endangering the safety of the public or property.

For centuries, chalk has been used as an easily-crafted and building material. The shallow underground room-and-pillar quarries where the chalk rocks were extracted have since been abandoned and now endure the effects of time and weather, potentially increasing their risk of collapse. In order to prevent this risk, INERIS, using *in situ* instrumentation implemented in 2004 and 2009, has been studying the behaviour of the rock in two partially flooded (subject to water table fluctuations) underground chalk quarries at Estreux and St-Martin-Le-Nœud in northern France (Gombert et al. 2010). The two quarries, located at an average depth of 30 m, were exploited by the room and pillar method, with an extraction rate of 60-75%. The quarries were abandoned over a century ago. The original goal of the *in situ* characterization was to determine the impact of water-table fluctuations on their stability. These fluctuations lead to chemical interactions between the chalk and the water and affect the mechanical behaviour of the chalk due to changes in weathering conditions. Laboratory characterization was also undertaken. Nevertheless, the hydro-chemo-mechanical behaviour of the chalk remains poorly understood, despite a number of earlier studies. Due to complex interlocking phenomena acting on the mechanical behaviour of chalks, it remains necessary to address this issue in the framework of multi-scale and multi-physics approaches.

The present study is devoted to experimental characterization of the effects of ageing on the hydro-mechanical behaviour of chalk from underground quarries. The experimental tests were complemented with scanning electron microscope observations in order to identify characteristic signs of ageing in the rock.

MATERIALS AND METHODS

The Saint-Martin-le-Nœud quarry is located to the south of Beauvais, on a hillside in the town of Saint-Martin-le-Nœud. The chalk was quarried by the room-and-pillar method (overlying rock thickness ≈25m, estimated vertical stress ≈1 to 1.5 MPa), leaving galleries greater than 1.60 m in width and irregular pillars of between 2 and 4 m width. The estimated rate of extraction is 50% to 67% (Gombert et al. 2010). The stratigraphy of Saint-Martin-le-Nœud has a near-tabular profile, with a gentle dip (≈4-10°): due to this dip, the lower parts of the quarry reach the shallow aquifer and induce several "underground lakes". The Santonian-age chalk is notable for its relatively high dolomite content (14%). The porosity - which the range of pores is tight - is on the order of 42%. The mineralogy is presented in detail in Table 1.

The Estreux quarry is situated in the town of Saint-Saulve, close to the city of Valenciennes in the North of France. Like the Saint-Martin-le-Nœud quarry, it has also been exploited by the room-and-pillar method and contains galleries of 2 to 3 m width supported by rectangular pillars measuring 1.5 to 4.5 m from side to side (rate of extraction ≈78%, overlying rock thickness ≈20 m, estimated vertical stress ≈1.8 MPa according to Nguyen, 2010). The stratigraphy has a tabular profile. The Turonian-age chalk has a relatively high glauconite content (24%), a clay mineral of the muscovite family and is not as homogenous as the dolomitic chalk in its structure.. The tight-range-of-pores porosity is around 35%. The detailed mineralogy is presented in Table 1.

Table 1 – Mineralogical compositions of chalk from the two quarries.
(Spa: sparite; Mic: micrite; Qtz: quartz; Glau: glauconite; Dol: dolomite; Opq: opaque minerals)

	Spa (%)	Mic (%)	Qtz (%)	Glau (%)	Dol (%)	Opq (%)
Saint-Martin	17	68	0	0	14	1
Estreux	24	50	2	23	0	1

At each of the two sites, chalk samples were collected by drilling 120-mm-diameter, 2- to 4-m-long boreholes horizontally into the pillars. Cylindrical plugs (20 mm diameter, 40 mm height) were then taken from each of the cores at intervals of approximately 10 cm. The longitudinal axis of a plug sample is therefore parallel to the axis of the pillar (Figure 1). The samples were then used to determine the physical and mechanical properties of the chalk as a function of horizontal pillar depth. The same sampling approach has been successfully applied to gypsum in previous studies (Auvray et al., 2004; Grgic et al., 2001; Grgic et al., 2013).

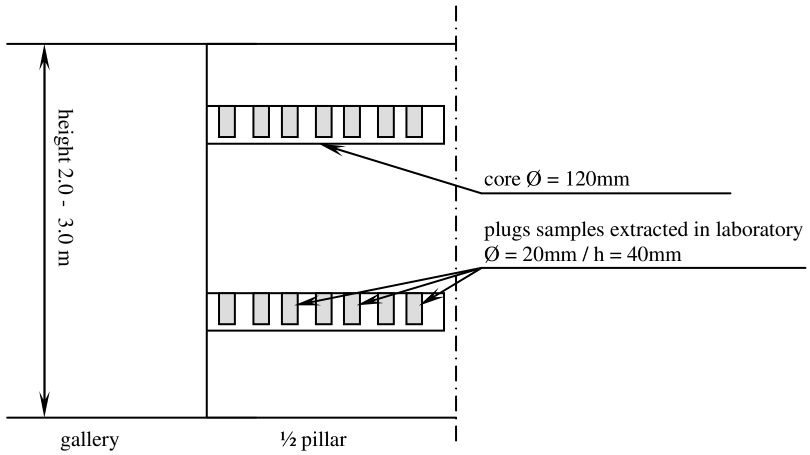

Figure 1 – Sampling method.

PHYSICO-MECHANICAL CHARACTERIZATIONS

Different physical and mechanical parameters were determined for all cores of up to 2 m length: rock density (dry and at saturation) ρ_d / ρ_{sat}; porosity accessible to water, n_w; water content at saturation, W_{sat}; compressional ultrasonic wave velocity under saturated conditions, Vp_{sat}, and; uniaxial compressive strength under dry / saturated conditions, RC_{sec} / RC_{sat}. The water used to saturate the samples was saturated (in reference to calcite) prior to the experiments in order to avoid any dissolution of the rock. The compression tests were performed using a hydraulic press of 5 kN capacity, operated at a deformation velocity corresponding to a displacement rate of 30 µm/min. Beyond the variability of results obtained from laboratory tests performed under dry and saturated conditions, we can discuss the main trends.

The results of the tests on samples from the Saint-Martin-Le-Nœud quarry are presented in Figure 2. The key findings include:

- The evolution of the four physical properties (densities, water content and porosity) clearly shows two distinct domains of variations: one defined between the wall and the depth of 75 cm, the second from the depth of 75 cm to the middle of pillar. In the first domain, wet and dry densities decreases with depth while the water-accessible porosity and water content increase. In the second domain, given the variations, a plateau can reasonably be considered for all these physical properties.
- Despite showing large variation, compressional ultrasonic wave velocity generally decreases with horizontal core depth.
- For mechanical characteristics (uniaxial compressive strength in saturated and dry conditions), there are also two domains of variations, with a limit of 50 cm deep against 75 cm for physical properties. In the first domain, there is no evolution of strengths: they can be considered as constant with approximately the same mean value for both states (dry and saturated). In the second domain, the dry uniaxial compressive strength increases with depth unlike the strength in saturated conditions remains on a plateau whose value is 2-3 times less than that obtained on the edge of the pillar (domain 1). Thus, for the saturated uniaxial compressive strength, the transition between the two domains is sudden.

Results for the tests on samples from the Estreux quarry are presented in Figure 3. Despite systematic undulations that we do not explain:

- The evolution of all the physical and mechanical properties are monotonous except for the compressional ultrasonic wave velocity. The latter increases with depth in the first 50 cm, and decreases between 50 cm and the middle of pillar . The other physical properties decrease with distance from the outer edge of the pillar
- The resistance of dry and saturated samples under uniaxial compression shows some variations, without a clear overall trend with core depth. It is nevertheless noted that the evolution of uniaxial compressive strength is identical to that shown in the second domain for Saint-Martin-Le-Nœud chalk, that is to say an increase from the wall to the middle of pillar for dry state and almost a plateau for satured uniaxial compressive strength.
- Overall, the trends are clearer for the chalk of Estreux compared to that of Saint-Martin-Le-Nœud, but with lower changes.

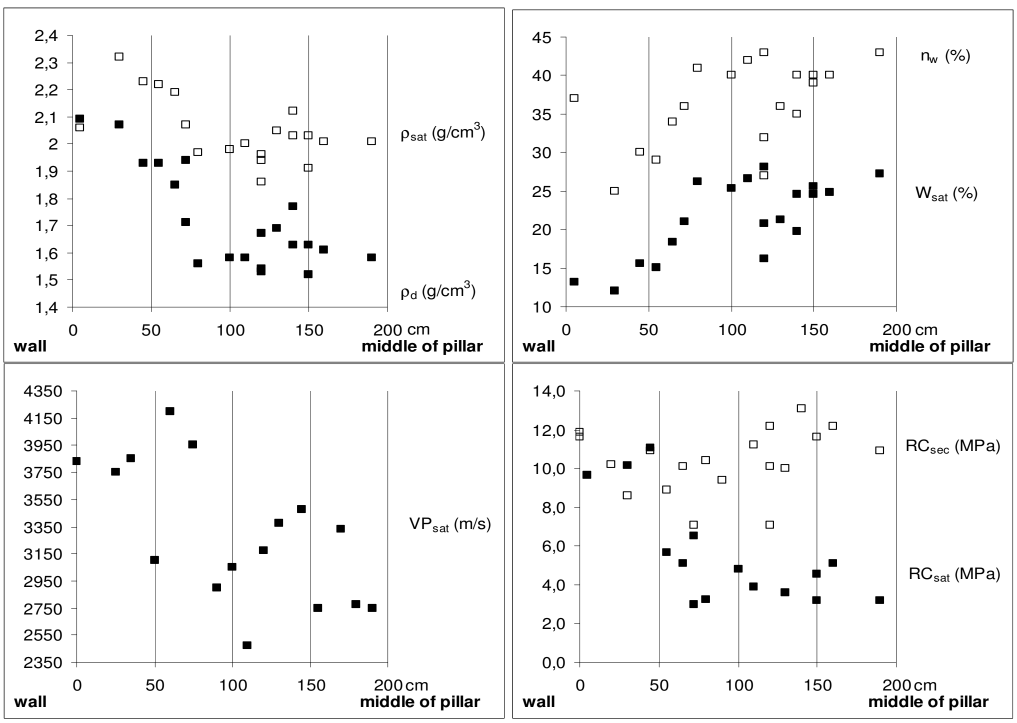

Figure 2 – Variations in physico-mechanical parameters with horizontal core-depth, Saint-Martin-Le-Nœud quarry.

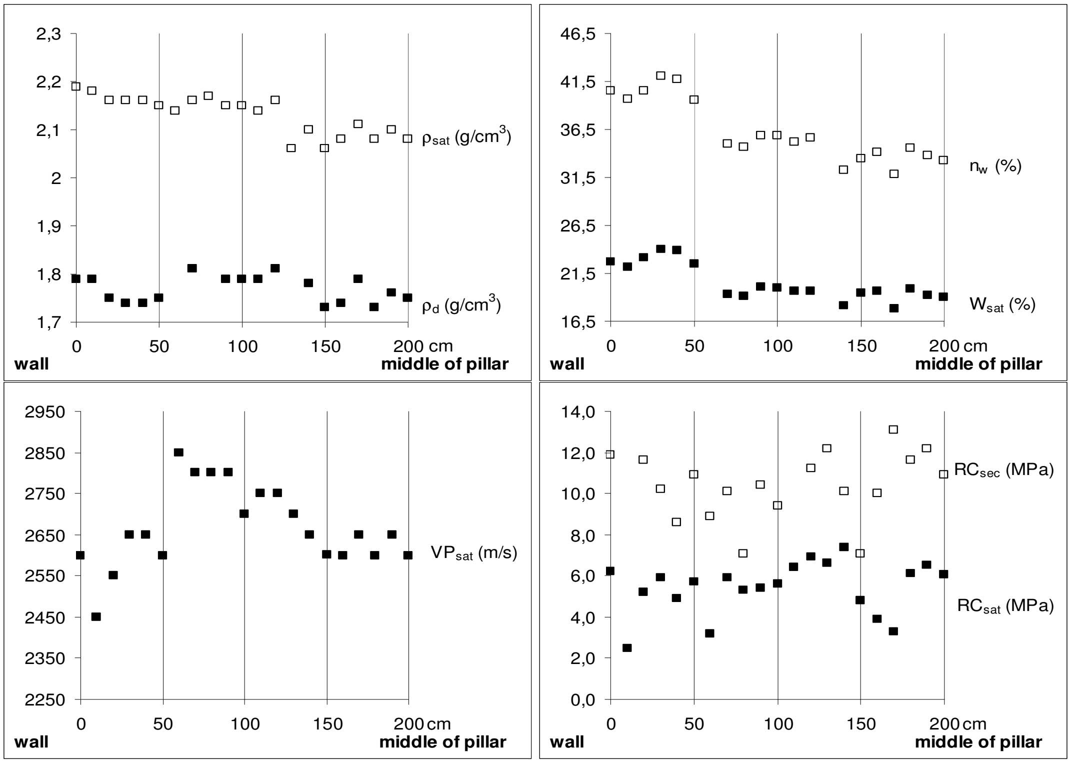

Figure 3 - Variations in physico-mechanical parameters with horizontal core-depth, Estreux quarry

MICROSCOPIC OBSERVATIONS

Samples from both quarries were examined by scanning electron microscopy (SEM). In samples of the Saint-Martin-Le-Nœud chalk, structural differences were observed between samples collected from the pillar-walls and those taken from the middle of the pillars. At the pillar walls, we observed euhedral multimetric-sized crystals of micro-calcite that presented no signs of neo-precipitation (Figure 4a). In contrast, at the centre of the pillars, crystals were micro-to infra-metric in size and xenomorphic (anhedral) (Figure 4e), probably due to partial dissolution. It was not possible to identify any zoning of these differences, and the decrease in crystal size and change from euhedral crystal shape both appeared to be continuous from the walls to the centres of the pillars. It was not possible to distinguish or measure the dimensions of a dissolution fringe.

In contrast to the Saint-Martin-Le-Nœud chalk, no variation in crystal size with depth was observed in the Estreux chalk pillars. However, a number of crystals in each sample plug exhibited clear dissolution marks (Figures 4g and 4j).

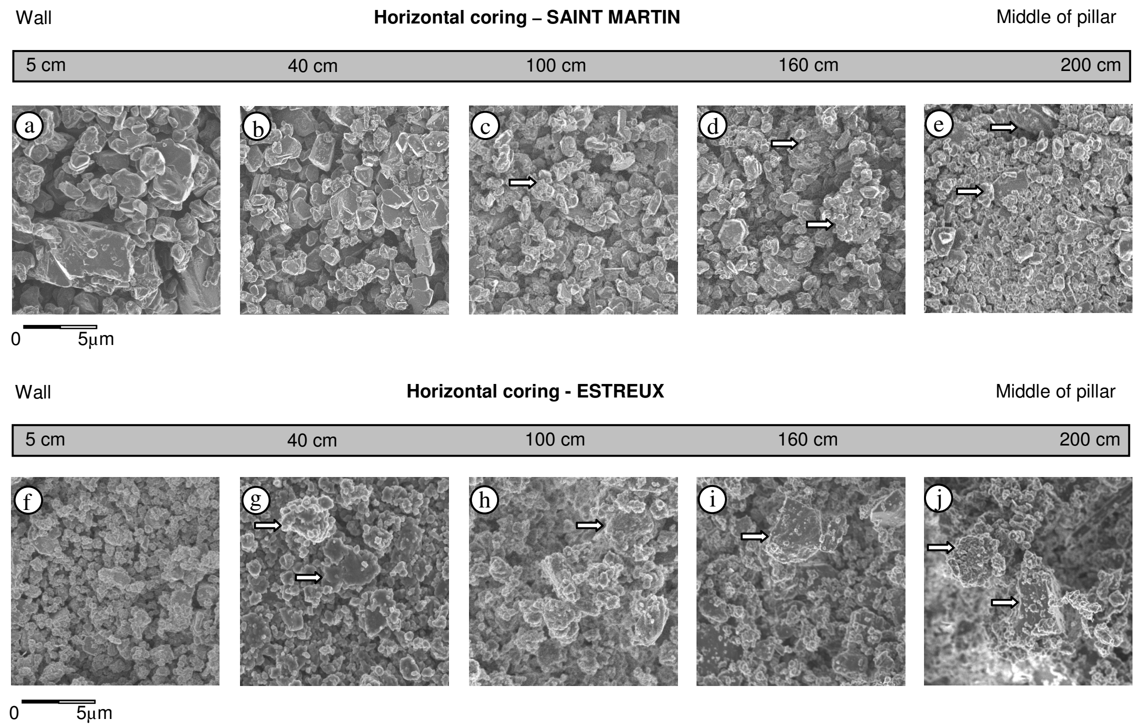

Figure 4 – Structural and morphological variations (⇨ : dissolution marks) in the Saint-Martin-Le-Nœud and Estreux chalks as a function of horizontal pillar depth (Lafrance et al., 2014).

INTERPRETATION-DISCUSSION

The effects of alteration on the physico-mechanical parameters studied here have previously been defined in samples of different rock types: charnockite (Ramana and Gogte, 1982), granite and marble (Jeannette, 2000) and clays (Canton et al., 2001). However, only a few studies have examined these parameters in the context of ageing (Auvray, 2003; Auvray et al., 2004; Grgic et al., 2001; Grgic et al., 2013). Crystal dissolution and the observed variations in certain physical parameters should be closely related.

In the Estreux quarry chalks, the intensities of the dissolution tracks do not vary along the length of the core (Lafrance et al., 2014). However, porosity accessible to water decreases from the pillar-wall to the middle of the pillar. Water (vapour and/or liquid) will progressively dissolve crystals and penetrate a pillar towards its centre. An increase in porosity accessible to water is therefore a direct effect of dissolution. This means that the amount of empty space, such as cracks and pores, should be greater at the pillar walls than in the middle of the pillars. From the SEM observations, these empty spaces appear to be in the form of dissolution cavities. The dissolution does not appear to be zoned however, and in fact, the entire pillar appears to have experienced partial dissolution. According to these hypotheses then, the resistance of the material should increase towards the centre of a pillar (the edges of the pillars being more damaged than the centres and being composed of more porous material). However, the data obtained from the uniaxial compression tests suggest that resistance is in fact highly variable, masking such a trend if it exists. It is possible that the anthromorphic changes, synonymous with ageing, are too advanced in these pillars to allow either a dissolution fringe or progressive degradation to be distinguished. Investigation of samples from a longer, horizontal borehole drilled into the rock face could shed further light on this.

In the Saint-Martin-Le-Nœud quarry samples, no dissolution marks were observed at the edges of the pillar at the scale of our observations (Lafrance et al., 2014). However, marks became apparent towards the centres of the pillars. In addition, a large decrease in the size of calcite crystals was observed from the edge to the centre of the pillar. The explanation put forward for the Estreux chalk does not hold for the Saint-Martin-Le-Nœud chalk, however. Even though the density of the rock decreases from the pillar wall to its centre, the other parameters - water-accessible porosity, water content at saturation and resistance under uniaxial compression in saturated conditions – all show an overall decrease towards the centre of the pillars. In other words, the centres of the pillars are apparently more damaged than their walls. In an attempt to explain these variations, we can put forward a number of hypotheses:

- The pillar may act as a vertical drain. As a result, a greater vertical flux of water the middle of the pillar would cause massive dissolution.
- Dissolution under strain would have more significant effect at the core of the pillar than at its edges.
- A mechanism of aggrading neomorphism or Ostwald ripening may be involved, which would correspond to the dissolution of fine-grained crystals in the presence of an under-saturated fluid. Such dissolution would allow the simultaneous growth of larger crystals due to a phenomenon related to the surface energy of particles. Consequently, crystal sizes would be homogenized and the final size attained would be greater than it was in the initial rock. This is one of the criteria that support the aggrading neomorphism hypothesis (Morse and Casey 1988). However, with the means of observation available to us, we were unable to observe any large subhedral crystals that cover the vestiges of small rounded crystals.
- A combination of the three hypotheses described above.

A dataset of measurements of resistance under compression is currently available for horizontal boreholes drilled into a phosphate chalk quarry (Malogne quarry at Cuesmes), near Mons in Belgium (Funcken 1996). The resistance values measured in the Malogne chalk appear to decrease towards the interior of the pillar (Figure 5), thus supporting the findings of our study and allowing us to favour a hypothesis of preferential vertical drainage down the middle of a pillar. We can therefore infer that ageing of the chalk also occurs at Estreux, but it is not possible to identify the mechanism or mechanisms responsible.

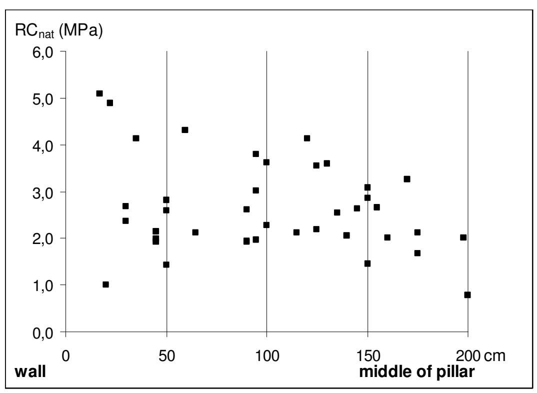

Figure 5 - Variations in uniaxial compressive strength (natural water content) as a function of horizontal pillar depth (Funcken 1996) Mons quarry

CONCLUSIONS

At the quarry at Saint-Martin-Le-Noeud, we have observed evidence for temporal changes to the chalk due to human activity, changes which can therefore be defined as ageing. The intensity of dissolution marks in calcite grains appears to decrease outwards, from the inner-core of the pillar towards the pillar walls. However, rock density decreases in the opposite direction, from the wall towards the centre, and parameters such as water-accessible porosity, water content at saturation and resistance to uniaxial compression under saturated conditions also present an overall decrease from the wall towards the middle of the pillars. Four hypotheses can be put forward to explain the observed variations: (i) vertical drainage that is greater in the interior of the pillar than at its edges; (ii) a higher degree of dissolution under strain down the middle of the pillar; (iii) aggrading neomorphism or Ostwald ripening; (iv) a combination of the three.

At the site at Estreux, ageing of the glauconitic chalk already appears to be at an advanced stage. This may explain why we were unable to distinguish zoning of either dissolution marks or resistance to uniaxial compression. To test this hypothesis, a long horizontal borehole could be drilled in the chalk face, thus allowing us to investigate the nature of the chalk at depths beyond those regions affected by ageing and to reach areas of intact 'healthy' chalk.

The paralleling of SEM analysis and various physico-mechanical properties has permitted us to probe into the ageing-induced changes of different chalks with efficiency and little material. However, a certain amount of time is required just for preparing the samples which might increase because of rocks variability. It may not be wise to apply this method in too much non homogenous rocks, especially if a global geological study (dip, thickness of the geological disposal, global rheology…) was not made prior. From a broader perspective, the distribution of mechanical stresses inside the pillar must be raised in parallel of this method, especially when dealing with soft, complex and as easily deformable as chalk material. It may therefore provide a part of explanation to the variations encountered in the decrease of the parameters from wall to centre of the pillar.

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