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Impact of weathering on macro-mechanical properties of chalk: Local pillar-scale study of two underground quarries in the Paris Basin

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ABSTRACT

In order to investigate the causes of underground collapse and aid the development of prevention strategies, we conducted a detailed study of the physico-mechanical behaviour and ageing of chalk in underground quarries in the Parisian Basin, France. Core samples were drilled horizontally from pillars at two sites: the Saint-Martin-le-Nœud underground dolomitic chalk quarry (Oise, France) and the Estreux underground glauconitic chalk quarry (Nord, France). Uniaxial tests were performed on dry and saturated cylindrical specimens, extracted perpendicularly to the cores at regular distances along their lengths. The cores were drilled horizontally from the edge to the centre of the pillars. Measurements of both physical and mechanical properties were made. The dolomitic chalk (Saint-Martin-le-Nœud) exhibits variations in mechanical and physical properties with horizontal pillar depth, and both density and compressive strength appear to increase outwards from the core to the wall of the pillar, the opposite of what would be expected from a purely mechanical point of view. Scanning electronic microscope (SEM) analysis revealed progressive degradation and increasing 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, crystals in the inner part of the pillar are finer-grained and anhedral with highly degraded edges. In addition, video logging of the pillar revealed a greater number of fractures in the centre of the pillar than at its edge.

In physico-mechanical tests and SEM analysis performed on the Estreux glauconitic chalk, no significant variation was observed between the pillar wall and the pillar core. However, dissolution marks were observed along the entire length of the half-pillar core.

1. Introduction

Alteration can be defined as a modification of the physico-chemical properties of minerals, and therefore rocks, by atmospheric agents, groundwater, or thermal waters (Winkler, 1975; Foucault and Raoult, 1995). The process is dependent on climate, water and temperature, as well as on the nature and degree of rock fracturing. Alteration generally leads to less-coherent rocks, promoting their deterioration 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 that result from chemical transformations (Norbury et al., 1995; Chigira and Oyama, 1999; Oyama and Chigira, 2000). The alteration of rocks by dissolution (limestones, tuffs, sandstones, crystalline rocks), with or without mineral neoformation, has been studied by numerous authors (Farran and Thenoz, 1965; Auger, 1991; Furlan and Girardet, 1991; Chéné et al., 1999; Chigira and Oyama, 1999; Gupta and Seshagiri Rao, 2000).

The causes of weathering can be divided into two main groups composed of so-called external and internal agents (Javey, 1972). The "external" causes characterize the weathering medium and are exhibited regardless of the actual nature of the rock. The physical processes are strongly linked to air temperature and humidity variations and lead to differing degrees of mechanical disaggregation of the rock. Chemical processes result in variable degrees of mineral attack by aggressive solutions or gases. In some cases, rock weathering is enhanced by biological factors that act either directly, via mechanical action, or indirectly, via an increase in the aggressiveness of the solutions or through decay of organic matter present within the rock material (Fusey and Hyvert, 1964; Winkler, 1966; Pochan and Jaton, 1967; Fassima, 1995; Gomez-Alarcon et al., 1995; Chen et al., 2000; Delatieux et al., 2001; Grgic et al., 2002; Ascaso et al., 2002). The "internal" causes are related to the intrinsic characteristics of the rocks themselves and determine their susceptibility to alteration. For any given set of physico-chemical

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conditions in the medium, the resistance of the rock to weathering agents depends upon a number of characteristics such as chemical and mineral composition, structure and texture, porosity and intrinsic permeability (Ramana and Gogte, 1982; Halsey et al., 1998; Gokceaglu et al., 2000; Jeannette, 2000; Canton et al., 2001; Inigo and Vicente-Tavera, 2001).

The term 'ageing' refers to weathering of a rock within a medium influenced by human activity. In the context of underground structures, the term is used to describe the range of mineralogical and physical modifications of the rock over time. These modifications then lead to a deterioration of the hydraulic or mechanical properties.

The effect of time on the behaviour of an unlined underground structure encompasses various phenomena responsible for the variations in the material properties:

- degradation of minerals in the rock as a result of physico-chemical action, leading to a reduction in the mechanical characteristics (this is the ageing effect, *stricto* sensu);
- deferred deformation due to constant loading (i.e., creep);
- variations in humidity (often linked to the airing conditions in the underground quarry), and thus in the saturation and suction conditions that affect the rock mass, over time. These cyclical variations in the hydric boundary conditions may generate damage due to hydro-mechanical coupling.

The influence of all these phenomena must be taken into account when studying the temporal evolution of underground quarries, with the aim of being able to provide optimum remediation strategies for ensuring the long-term stability of the quarries with regards to public safety and the protection of built resources.

Even though the oxygen content of the quarry atmosphere has been proven to play a key role in the ageing of rocks, other phenomena, sometimes neglected, can occur:

- biological factors have been cited in some very specific cases, such as bacterial activity that has caused degradation of organic matter present in iron ore deposits in the Lorraine region of eastern France (Grgic et al., 2002);
- the role of brine water salts on chalk piles;
- the effects of freezing and freeze-thaw cycles, which are only felt near gallery entrances.

In the present study, we restrict our assessment of ageing to two types of chalk sampled in two different underground quarries. The study reinforces the fact that when dealing with chalk, the potential phenomena involved cannot be extrapolated from other types of chalk/from other rock types and the results will depend entirely on the intrinsic properties and environmental conditions in play during the evolution of the chalk. Following a short description of the quarries and the sampling methodology, we describe/discuss the results obtained from mapping of the fractures inside the pillar. Then, we discuss the scanning electron microscope (SEM) observations of the chalk samples in detail. Finally the trends in a number of physico-mechanical parameters (mass density, velocity of ultrasonic P waves, uniaxial compressive strength) are highlighted.

2. Description of the underground quarries

2.1. General framework

Chalk is an easily-crafted material that has been used for centuries in building and construction. 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 weathering, potentially increasing their risk of collapse. In order to prevent this risk, INERIS has been studying the behaviour of the rock in two partially-flooded underground chalk quarries that are subjected to water table fluctuations, at Estreux (EX) and Saint-Martin-le-Nœud (SM) in the Parisian Basin (Fig. 1) in northern France (Gombert et al., 2013). These quarries, located at an average depth of 20 to 25 m, were exploited by the room-and-pillar method, with an extraction ratio of 60–75%. The two quarries were abandoned at approximately the same time over a century ago, but they were active for very different lengths of time: around twenty years for the first and several centuries for the second. In situ instrumentation was implemented in these quarries in 2004 and 2009, with the aim of determining the impact of water-table fluctuations on their stability. These fluctuations lead to chemical interactions between the chalk and the water, thereby affecting the mechanical behaviour of the chalk through changes in the weathering conditions (Brignoli et al., 1994; Talesnick et al., 2001; Schroeder, 2002, 2003; Mortimore et al., 2004; Risnes et al., 2003, 2005; Duperret et al., 2005; Nguyen, 2009; Mortimore, 2012; Gombert et al., 2013; Lafrance et al., 2014). Preliminary laboratory characterization (e.g., mineralogical studies and uniaxial and triaxial compression tests) has also been undertaken (Gombert et al., 2013; Lafrance et al., 2014). Nevertheless, the hydro-chemo-mechanical behaviour of the chalk remains poorly understood due to complex interrelated phenomena that act on the mechanical behaviour of chalk. It therefore remains necessary to address this issue in the framework of multi-scale (microscopic, laboratory and in situ scales) and multi-physics (mechanic, hydraulic and chemical) approaches.

2.2. The Saint-Martin-le-Nœud underground quarry (SM)

The Saint-Martin-le-Nœud underground quarry is located on a hillside to the south of Beauvais (Oise, Picardie, France) within the northern flank of the Bray anticline and near the Bray fault (Barhoum, 2014). The material extracted from this quarry is a white to grey homogenous chalk containing dolomite (14%) and was used to build Beauvais Cathedral in the 12th century. The quarry was closed in 1830 by Royal decree. The chalk has a wackestone texture and is Santonian-Coniacian in age. The average total porosity is about 42%, with a tight range of pore-size distribution. Chalk porosity was determined by comparing the saturated and dry density (ISRM standard procedure) of 40 samples taken from blocks using mercury porosimetry. The mineralogy of the chalk, presented in detail in Table 1, was obtained using a semi-quantitative method based on the microscopic study of thin sections. According to Faÿ-Gomord et al. (2016), this chalk can belong to the micritic chalk group. The chalk was quarried by the room-and-pillar method, leaving behind 3 to 5 m wide galleries, originally 4 m in height, and irregular pillars of between 2 and 4 m width (Fig. 2). The estimated ratio of extraction is 50% to 67% (Gombert et al., 2013). Based on the overlying rock thickness (25 to 30 m), the average vertical stress in the pillars is about 1 to 1.5 MPa. The stratigraphy (Fig. 3) of Saint-Martin-le-Nœud has a near-tabular profile with a gentle dip (≈4–10°). Due to this shallow dip, the deepest parts of the underground quarry reach the shallow aquifer, resulting in the formation of several "underground lakes" (Mary and Mary, 1907).

2.3. The Estreux underground quarry (EX)

The Estreux underground quarry is located in the town of Saint-Saulve, close to the city of Valenciennes in northern France near the northern boundary of the Parisian Basin. The quarry opened in 1850 and closed in 1870. The material extracted from the quarry is a green to grey homogenous chalk with a high glauconite content. It has a packstone texture and is Turonian in age. The chalk (exploited levels shown in Fig. 4) contains a relatively high amount (24%) of glauconite, a clay mineral of the muscovite family, and is not as homogenous as the Saint-Martin-le-Nœud dolomitic chalk in terms of its structure. The total porosity of the chalk is around 35% and displays a tight range