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Experimental investigation of the effects of fatigue on caprock materials in H_2 storage projects

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The intermittent nature of renewable energy sources unavoidably limits their application as primary power supplies. In this sense, balancing the production/demand cycles over seasonal and annual timescales is essential for decarbonizing our economy. An effective long-term solution is represented by hydrogen underground storage in depleted hydrocarbon fields [1]. During overproduction periods, extra power is stored in the form of hydrogen in a porous reservoir formation, surrounded by a low-permeability caprock. Ensuring the integrity and the sealing efficiency of such material over the fatigue loading induced by storage/withdrawal cycles is thus fundamental for preventing hydrogen from escaping into the surrounding formations.

A substantial amount of research has been conducted in the past to define the impact of fatigue on the response of either hard or soft rocks (e.g. [2]). Nevertheless, very few studies focused on the cyclic behaviour of caprock-like materials, i.e. structured stiff clays subjected to large confining pressures. Those are characterized by the distinctive stress-strain behaviour of clays together with a significantly larger undisturbed shear strength. When subjected to cyclic loading, progressive destructuration takes place, leading to softening of the response and eventually to fragile failure. This research fits within this context, focusing on the development of an effective methodology to assess fatigue-related risks in H_2 storage projects. To this end, a series of monotonic and cyclic triaxial tests were performed to investigate the influence of loading frequency f (or, equivalently, the period $T = 1/f$), maximum deviator stress q_{max} and loading amplitude A on the response of the material. The latter is a stiff clay with silt (clay fraction, $d < 2\mu m$, is equal to 50% and the silt fraction, $d < 60\mu m$, is 49%) with an average carbonate content of 40%. The liquid limit is $w_L = 43\%$ and the plastic limit is $w_P = 25\%$. Specimens were consolidated under K_0 conditions to an effective stress state consistent with its lithostatic value (namely, $q = 6.3$MPa and $p' = 8.1$MPa). Monotonic and cyclic shearing were applied through loading-compression paths under undrained conditions.

A preliminary summary of the results of the cyclic tests is presented in Figure 1a, where the fatigue life N_f is plotted against the corresponding q_{max}. Only two tests (represented as triangles in the plot) were interrupted before failure, due to their excessive duration. Most of the tests were conducted employing $A \approx 5.3$MPa, except for two tests imposing $A = 3.25$MPa. The tests were carried out either with $T = 5$min ($f = 3.3 \cdot 10^{-3}$Hz) or $T = 250$min ($f = 6.7 \cdot 10^{-5}$Hz). Consistently with previous findings (e.g. [2]), N_f decreases with increasing q_{max}. In particular, N_f seems to be well predicted by a linear regression (in logarithmic scale) when the tests are conducted at consistent A and f values. The influence of A is instead somehow counterintuitive as decreasing A implies a reduction of N_f. Such a result is in contrast to what has been observed for other materials (e.g. [3]), for which a larger amplitude A causes a faster degradation. Viscous effects might explain the observed behaviour. For a given q_{max}, adopting a smaller A implies oscillating around a larger mean deviator stress q_{mean}. Assuming that the creep strain rate increases as the stress state approaches the limit state surface [e.g. 4], smaller A values would also imply summing larger creep strains to those induced by cyclic degradation.

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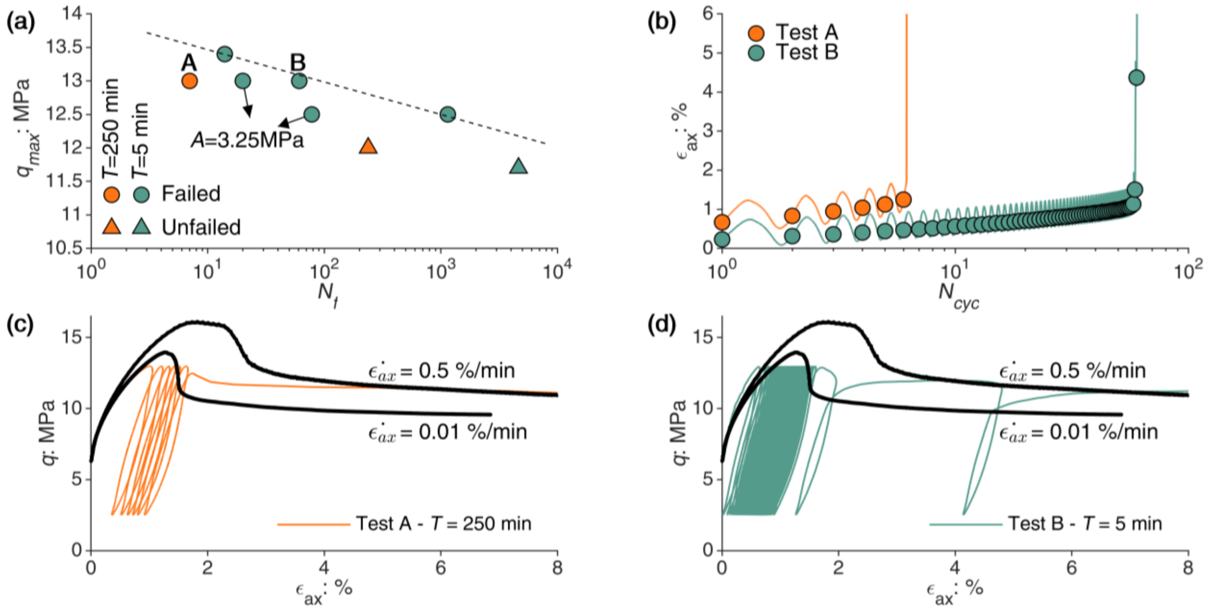

Figure 1: Results of cyclic triaxial tests: (a) N_f as a function of q_{max} for the entire dataset; (b) influence of f on the evolution of ϵ_{ax}; and comparison between monotonic and cyclic stress-strain responses obtained for different f (c-d).

The dependency of the mechanical response on the strain-rate $\dot{\epsilon}_{ax}$ applied at shearing provides further evidence of the relevance of viscous effects. Figure 1b reports the comparison between two cyclic tests (A and B in Figure 1a) conducted applying the same stress history, but different f (and, thus, average $\dot{\epsilon}_{ax}$). The specimen sheared with a lower f (test A) presents a significantly larger accumulation of ϵ_{ax} with increasing loading cycles N_{cyc}, leading to failure after few cycles. Conversely, slower destructuration takes place in test B, which requires a larger number of cycles to fail. Figure 1c-d compare the cyclic stress-strain responses observed for tests A and B with the monotonic curves obtained employing strain-rates which are consistent with the equivalent average ones implicitly adopted in the cyclic tests ($\dot{\epsilon}_{ax}$ equal to 0.01%/min and 0.5%/min). The cyclic response observed in test A is well-enveloped by the monotonic curve obtained for $\dot{\epsilon}_{ax}$ = 0.01%/min. Destructuration takes place with cyclic loading, inducing progressive softening of the material response, so that, during the 7th cycle, the strength reduces below q_{max}, leading to sudden failure. Conversely, about 60 cycles are needed in test B before approaching the monotonic resistance characteristic of $\dot{\epsilon}_{ax}$ = 0.5%/min.

The relevance of the strain rate on the material response suggests that laboratory tests should be used with care for boundary value problems having very low loading frequencies, such as hydrogen storage. As those frequencies are not compatible with feasible experimental times, a viable testing procedure might require monotonic and cyclic tests at different strain rates. The cyclic tests shall be done at frequencies larger than the field ones. The monotonic tests shall instead be run at both the strain-rate of the field and the one of the cyclic tests. This would allow rescaling the cyclic response of laboratory tests to the one of the field frequency.

Contributor statement

All authors contributed to the study conception and design. Material preparation, data collection and experimental tests were performed by Andrea Ciancimino. The first draft of the manuscript was written by Andrea Ciancimino and all authors commented on previous versions of the manuscript.

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