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REVIEW PAPER

Self-repair of cracks and defects in clay: a review of evidence, mechanisms, theories and nomenclature

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Abstract

Clay minerals and clayey soils have been extensively researched over the last century leading to a rich and still evolving corpus of knowledge on clay chemistry, microstructure and macroscopic behaviour. Clay has the ability, under certain conditions, to spontaneously repair its cracks. However, despite ample evidence, clay self-repair remains understudied and under-theorised. For example, the majority of experimental studies discussing clay self-repair infer its existence from changes to macroscopic properties assumed to be caused by self-repair, and only a small number of studies have attempted to observe self-repair directly. This paper reviews the literature on clay self-repair. First, it situates clay self-repair within the broader context of self-repairing material. Next, *autogenous* self-repair of clay, under wet-dry cycles, freeze–thaw cycles and deep-ground consolidation, is presented focusing on evidence, driving mechanisms and key variables of influence. Next, theories of clay self-repair proposed in the literature are discussed, highlighting their scope and limitations, as well as the extent to which they have been validated by experimental observations. Key gaps in current knowledge of clay self-repair are highlighted and ways in which they can be addressed in future research are proposed. Finally, a nomenclature distinguishing between different kinds of clay self-repair is proposed based on eight different attributes.

Keywords Clay · Clay liners · Desiccation · Montmorillonite · Self-healing · Self-repair

1 Introduction

Undesirable fracturing and fissuring[1] of soil and geotechnical components of major infrastructures may occur as a result of natural and/or anthropogenic factors. These include, amongst others, droughts and floods, over-abstraction of groundwater, overloading and/or excavation of soil, explosions and seismic activity, underground thermal gradients and thermal desiccation.

The development of cracks in soils can reduce their shear and/or compressive strengths (e.g., [56, 119]) increase their hydraulic conductivity (e.g., [10, 50, 140]), reduce their water retention capacity (e.g., [20, 37]) and accelerate erosional processes (e.g., [110]). This can lead to a range of serious problems including slope instability [49, 60, 130, 144], loss of performance of waste insulation systems [54, 82, 98, 109] and mine tailing dams [85], failure of roads, embankments and foundations [2, 71, 114] and a self-reinforcing cycle of decline in soil fertility and desertification [34, 58]. On the other hand, fractures may be desirable and may be introduced deliberately into soils and geological strata. This is what happens, for example, in hydraulic fracturing for the extraction of shale gas [80] and in carbon dioxide geo-sequestration [4].

The capacity of clay to self-repair its cracks is of high relevance in all of the above-mentioned problems: it may

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[1] No clear-cut distinction exists between fracturing and fissuring; however, in this paper, we take fracturing to refer to a pattern of large and spaced-out cracks, while fissuring indicates a denser configuration of smaller and narrower cracks; we will use the term “cracking” when referring generically to both fracturing and fissuring.

be a valuable resource that mitigates the effects of cracking or, in the case of hydraulic fracturing, an impediment that must be overcome to keep the cracks open. Hence, the ability to control and leverage self-repair of cracks in clay is a highly promising pursuit with significant social, economic and environmental stakes. For example, fissures are an important factor in many slope and road surface failures, with the former estimated to cause more than US$20 billion in yearly costs worldwide [18, 70]. In the USA, damage to buildings and infrastructure, part of which is caused by cracks from shrink-swell subsidence, incurs billions of dollars in cost annually [65]. Shale gas extraction is financially and environmentally costly since high pressures need to be maintained to counter the natural tendency of fractures to self-heal—for example, a single-fracture, horizontal well for shale gas requires up to 30,000 m^3 of water and thousands of gallons of chemicals to initiate and keep it open during operations [126].

Despite its importance, clay self-repair remains vastly under-researched and under-theorised—a gap that constitutes a serious impediment to the promise of developing self-repairing soil systems.

Most studies of clay self-repair have inferred its existence through measurements of hydraulic conductivity, usually without direct observation of crack closure at either macroscopic or microscopic scales [42, 115]. While these studies can indicate ‘sealing’ of the cracks, this may not be the same as ‘healing’, which usually (although not always) implies the complete regaining of strength and a loss of memory of the cracks [12]. Bio-cementation of soil, in which the by-product of microbial digestion has a cementing and pore-clogging effect, is a form of healing that has recently received considerable attention in the literature. It also has potential to generate healing and self-healing of geotechnical structures [40]. Although most bio-cementation studies have focussed on sand, some have considered clay as well [22, 59]. However, research on bio-cementation has aimed mostly to identify the best combinations of bacteria and physico-chemical conditions, and the best means of delivery of healing agents, rather than to develop a theoretical understanding of *how* healing and self-healing occurs at various scales [35, 131].

Major breakthroughs in inducing self-repair in cementitious material, paints, coatings and ceramics have been achieved over the last few years, using polymeric hydrogels, reinforcement fibres, fly ash, biological agents or a combination of these [55, 91, 117] but have not, to date, been extended to clay.

Several obstacles to research on clay self-repair are worth highlighting. Our understanding of clay’s chemistry and micro- and macro-structure—a fundamental foundation for research on clay self-repair—is still very much a work in progress, spanning several academic disciplines (e.g., chemistry, soil physics and geomechanics, soil science, hydrology and rheology) and requiring an often-complex combination of analytical, experimental and numerical approaches. Another obstacle is the difficulty of observing clay self-repair in real-time owing to the multiple spatial and temporal scales involved. Adding further complexity is the vast array of clay minerals and clayey soils that exist in nature and in applications in geotechnical, geoenvironmental, cosmetic, pharmaceutical and other industries. Indeed, self-repair in different types of clay minerals, such as kaolinite versus smectite, may be driven by very different mechanisms (e.g., osmotic swelling for smectite and applied pressure for kaolinite) [42]. Finally, there is some confusion in the literature about the definition of self-repair, with multiple terms used by different authors sometimes inconsistently (e.g., healing, self-healing, self-sealing, autogenous healing, natural healing), and no unified nomenclature is widely accepted. This has arguably hampered the synergetic accumulation of knowledge in the field.

The goals of this paper are threefold. First, we present a review of the literature on self-repair of cracks in clay. We discuss evidence for self-repair, our knowledge of the mechanisms that drive it, key variables influencing it, and theories and models currently available for predicting it. Second, based on the review, we identify key knowledge gaps and propose several future research directions. Finally, we propose a taxonomy of clay self-repair, along with a nomenclature for identifying its most critical attributes. While the taxonomy has been developed with clay in mind, it will be relevant to self-repairing material other than clay. Its adoption will allow for a better scientific communication process and a more rigorous exchange of ideas between researchers in a fast evolving field.

To maintain a reasonable scope for the paper, we restrict our investigation to the self-repair of macro- and micro-cracks and do not include repair of other forms of damage (e.g., loss of structure from excavation, liquefaction and thermal exposure). Nor do we discuss the various forms of ground improvement.

In the remainder of the paper, we adopt the term ‘self-repair’ (short for ‘self-repair of cracks in clay’) as the most general designation of the processes discussed. The reason for this choice will be elaborated in Sect. 6 of the paper as part of a proposed nomenclature and is meant to avoid confusion associated with other terms such as self-healing, self-sealing and autogenous healing. We also use ‘clay self-healing’ in some places in the paper, especially when discussing the theoretical literature, because this is the term most commonly adopted, and associated with such concepts ‘damage’ and ‘healing’ variables and ‘healing evolution functions’. However, unless explicitly stated, ‘self-healing’ is assumed to have the same meaning as ‘self-repair’.

2 Self-repairing material

A significant range of self-repairing materials exists, including polymers, metals, ceramics and cementitious-based composites. Self-repair is a property that can occur naturally (natural, intrinsic or autogenous self-repair) or be the outcome of engineered design (engineered or extrinsic self-repair, sometimes referred to as autonomous self-repair). Self-repair can also take place spontaneously or may develop under an external source of energy (e.g., excitation by light, thermal, electrical and magnetic sources). Materials can also be engineered to improve their self-repair ability. For example, resins can be deployed in hollow fibres within a polymer matrix in such a way that they are released to assist in self-repair only when needed [16]. Self-repairing materials can be useful in minimising maintenance/repair costs and reducing risk of failure by damage propagation. Although the above-mentioned materials all exhibit similar self-repair capability, the specific mechanisms, features and applications differ greatly.

Autogenous self-repair has been reported in many materials and with different levels of efficiency. For example, in the case of concrete, up to about a third of cement remains un-hydrated inside the composite material even after it is in structural use. Therefore, when cracks develop and there is access to water, un-hydrated particles can react and generate a cemented paste to close the cracks, at least partially. The effectiveness of this phenomenon, however, declines significantly with age and crack width [30].

Autonomous self-repair can be promoted by introducing chemical or biological compounds into the matrix of the material. Different options are available for this purpose, including encapsulation and vascular networks and the use of memory shape alloys embedded in the matrix (e.g., [7]). Encapsulation techniques are most common in cementitious and polymeric materials. The main challenge here is to design capsules that can mechanically withstand the process of material mixing and production, but still remain fragile enough to break and release the repairing compound when needed [30]. In the case of concrete, both bacteria and polymers can be embedded in the matrix to help it recover partially, or even completely, from damage. In asphalt, closed fibres (or coils) can be embedded in the mixture; these can later be excited and heated by an alternating electromagnetic induction field that partly melts the binder and causes the cracks to be filled [121]. Dai et al. [28] showed that an optimal strength regain can be achieved for an asphalt mixture with 5.66% steel wool fibres and a temperature of 100 °C, although a temperature range of 60 °C to 80 °C already provides a 50% strength recovery after six fracture-healing cycles.

While there have been significant developments in self-repairing polymers, ceramics and cementitious materials, self-repair in metals poses unique challenges. This is because repair in metals often requires the melting of the damaged substrate and/or the introduction of a liquid repairing metallic component. In addition, oxidation, either by exposure to air or water, or even by the galvanic process, can make bonding difficult and needs to be considered. Nevertheless, different sealing techniques have been explored, which include the embedment of shape memory alloys to counteract the damage suffered by the material and to close cracks if a source of energy can be provided [47].

Despite major advances in self-repairing materials, important gaps remain. No taxonomy for material self-repair and no protocols for the testing of self-repairing materials have yet been adopted [97]. Speed and stability of self-repair are important aspects that remain under-explored. For example, in maritime cementitious applications, the *rate* at which cracks are sealed—and not just the extent of sealing—is of great importance because the aim here is to prevent penetration by aggressive agents that would eventually corrode/damage the structure [41]. There is uncertainty about the stability of self-repair when the material is subjected to cyclic loading or repetitive damage. Questions also remain about the shelf-life of repairing compounds, i.e., how long the bacteria or other repairing agents will endure and still be able to repair the material when damage finally occurs [97].

The above-mentioned research gaps apply to self-repair of clay as well, as will be shown below. Indeed, key attributes of self-repair pertain to all self-repairing material (speed and stability of self-repair, recovery or lack thereof of material properties and retention, or not, of memory of damage in the self-repairing system) and may hence benefit from the development of a common taxonomy. On the other hand, unique challenges exist in the case of clay that are not as relevant for less porous, less reactive material. These challenges include frequently occurring exposure to wet-dry and freeze–thaw cycles, and a range of mechanical loading scenarios that can reach, in the case of deep strata, hundreds of MPa.

3 Autogenous self-repair of cracks in clay

3.1 Evidence for self-repair

Evidence for clay self-repair has been found under conditions of wet-dry cycles, freeze–thaw cycles and deep-ground consolidation. Partial self-repair of desiccation cracks in soils undergoing *wet-dry cycles* has been widely reported, including fast closure of cracks and significant decreases in hydraulic conductivities [19, 87], reopening of cracks upon subsequent dehydration [88], deterioration of soil self-repair capacity with more wet-dry cycles [5, 6, 87], and changes in soil pore structure and density [124, 140]. Self-repair has also been reported in so-called self-mulching soils, usually smectite-rich vertosols, in which swell-shrinkage and re-aggregation occur during wet-dry cycles [8, 11, 52, 129].

Hydraulic conductivity, *k*, is the clay property commonly measured in tests on sealing within cycles of wetting and drying. This is because declines in infiltration rates and hydraulic conductivity during the wetting cycle can be assumed to correspond to partial or complete closure of cracks. Albrecht and Benson [5] have found that the hydraulic conductivity of a high-plasticity clay compacted wet of optimum water content gradually increases with each drying cycle, from an initial value close to 10^{-9} m/s, reaching 10^{-6} m/s by the fourth cycle. Cripps and Parmar [27] have conducted two cycles in a Rowe cell for high- and low-plasticity clays and the hydraulic conductivity of both increase by about half an order of magnitude upon re-saturation at the end of the second cycle. However, more self-sealing—observed by naked eye and inferred from hydraulic conductivity—has been recorded in the high-plasticity clay than in the low-plasticity one [27].

Mohammadi and Choobbasti [95] have performed unconfined compressive tests to study the stress–strain relationship of residual clay soil and compare the behaviour of soils at the time of failure and repair. They have also evaluated the effect of self-repair on ultimate compressive strength.

Research on geosynthetics clay liners (GCLs) made of bentonite has generated evidence of partial repair of damage upon rehydration of a desiccated sample (see Figs. 1 and 2). The degree of repair has been shown to depend on the chemistry of the hydration solution, since the bentonites in GCLs are highly reactive and their swelling upon hydration will be suppressed by exposure to chemical solutions [48, 90, 93]. For example, Petrov and Rowe [101] have reported that NaCl solutions with concentrations of 0.6 and 2.0 mol/L result in notably higher hydraulic conductivities in GCLs than those permeated with water. The presence of divalent cation such as Ca^{2+} in the permeant solution can lead to even more significant hydraulic conductivity increases for GCLs [13, 63, 68, 72]. Lin and Benson [83] have subjected GCL samples to wet-dry cycles using different chemical solutions, then measured their hydraulic conductivity. They have found that bentonite failed to self-heal cracks when hydrated with saline solutions, with the hydraulic conductivity increasing by three orders of magnitude after five to eight cycles. Sari and Chai [112] have introduced holes up to 30 mm diameter into GCLs, as a proxy for mechanical damage, and found that they can heal completely in water but much less so in cation-rich solutions. Salemi et al. [111] have observed that the flow rate of mechanically damaged GCL samples decreases during wetting cycles but is still one-order-of-magnitude higher than its original value prior to the introduction of damage.

Freeze–thaw is another process that can result in crack opening and closures, driven by a two-fold process. When soil temperature drops below 0 °C, some pore water turns to ice while the rest remains unfrozen, resulting in volumetric expansion. The resulting swelling pressures lead to the formation of large voids and cracks in the soil. At the same time, water pressure decreases at the freezing front and pressure differences drive water movement from the unfrozen to the frozen parts of the soil; this desiccation leads to the build-up of frost-induced suction and the formation of shrinkage cracks in the drying parts of the soil [73, 84]. As a result, soils may lose strength and show alterations in hydraulic conductivities. However, unlike under wet-dry cycles where rewetted samples generally experience swelling, thawing appears to lead to consolidation and a denser structure [73, 132, 142]. In addition, in spite of evidence of closure of cracks upon thawing, freeze–thaw cycles have been shown to cause an increase in permeability, due to micro-fissuring and large pores created by frozen water. Gradual changes in other soil properties such as Atterberg limits, grain size distributions, stress–strain relationships, resilient modulus under cyclic triaxial loadings and undrained shear strength can also occur [104].

There is, furthermore, significant evidence of clay self-repair of cracks caused by *excavation in deep ground* which then self-seal over time at least partially [12, 17, 143]. This is consistent with the evidence, discussed later, that confining pressure has a positive effect on the self-repair of clay soils under wet-dry and freeze–thaw cycles [5, 19, 99]. Eigenbrod [42] has suggested that consolidation and creep under high confining pressures can lead to self-repair in natural clay. Several authors have reported on the SELFRAC project, a European initiative for assessing the viability of deep burial of radioactive waste, and analysed fracture opening and closure in an excavation-damaged zone in the vicinity of the prospective waste facility [12, 17, 64]. They have found that under high confining pressures in deep ground, crack closure of fractured tertiary clays occurs with full or partial recovery of hydraulic conductivity.

Cracks develop upon excavation in tertiary clays (high density, high strength and low hydraulic conductivity) as a result of stress reduction and subsequent redistribution of stress and pore water pressure under poorly drained conditions. Over time, the full or partial recovery of low hydraulic conductivity, indicating crack sealing, has been

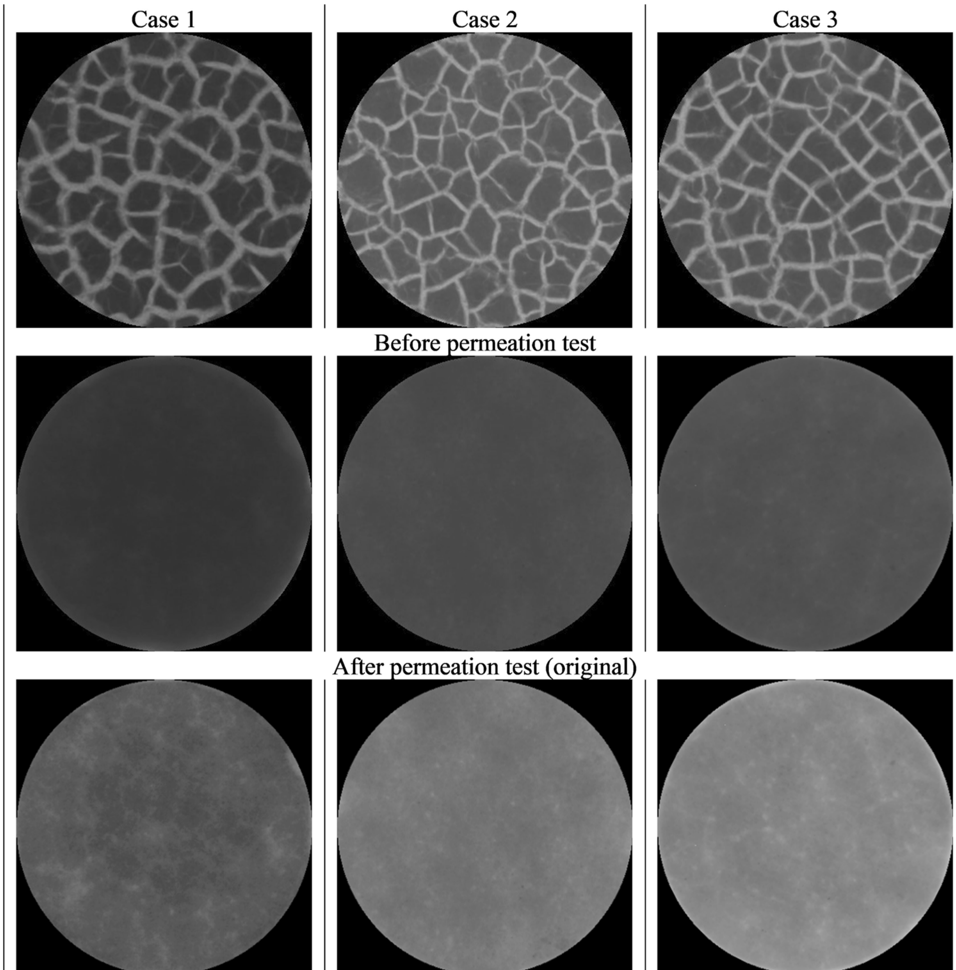


Fig. 1 X-Ray for 3 different test cases of sodium-bentonite in GCLs after undergoing thermal desiccation (topmost images) followed by rehydration (middle and lowermost row of images); the lowermost images, with contrast enhanced, show traces of the sealed cracks; the 3 test cases have different average width and length of cracks before rehydration (see Yu and El-Zein [140] for more details)

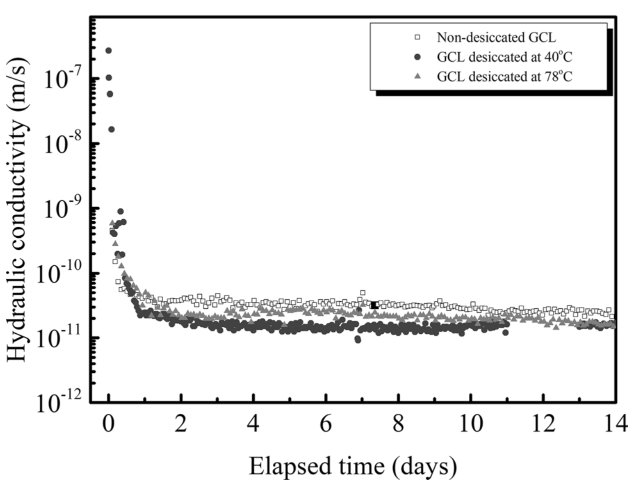


Fig. 2 Recovery of hydraulic conductivity upon rehydration of desiccated GCL: conductivity drops from $\approx 10^{-7}$ m/s at time = 0 days (cracked GCL) to 5×10^{-10} m/s within 2 days of rehydration (see Yu and El-Zein [140] and Yu et al. [141] for more details)

observed, but the fractures tend to reopen when disturbed or dried again, hence retaining crack memory. The processes driving crack closure are believed to be: a) swelling of the crack faces during pore water redistribution; b) consolidation under high confining stresses; and c) long-term creep [12, 17, 143].

Jobmann et al. [64] have studied the sealing of an Opalinus clay drilled from 200 m depth, using gas permeability to evaluate the closure of artificially introduced cracks under different confining stresses (from 0.25 to 5 MPa). Results indicate that, even without an external water supply, the sealing process occurs when confining pressure is applied. Further reduction of the permeability is achieved by maintaining the confining pressure for a long duration, hence demonstrating the role of creep in closing fractures. Several authors report that, even without the supply of external water, the sealing process continues, as evidenced by changes in permeability for at least one year or two [89, 143].

Zhang [143] has conducted gas permeability and wave velocity tests on Opalinus clay under 15 MPa confining stress and has found strong evidence of self-sealing behaviour. Fractures close faster at large apertures in the initial loading stage, with the closure rate subsequently decreasing. Assessing the influence of external water supply, Zhang [143] also reports that it enhances clay self-repair, hence lowering permeability and reducing the likelihood of the reappearance of cracks when the sample is unloaded.

3.2 Key variables in self-repair

The extent of self-repair is influenced by several soil properties (e.g., fine content, plasticity, shrinkage potential), environmental variables (e.g., overburden stress, chemical composition and mode of application of the permeant solution, extent of drying and wetting, presence of plant roots, thermal conditions) and the initial state of the soil (e.g., width and number of cracks, initial water content of soil). These are discussed next.

Soils with *higher fine content, higher plasticity* and *higher shrinkage potential* are more likely to experience both cracking and sealing [6, 27, 87, 106]. It has been proposed that the drying of soils containing a high proportion of fines creates shrinkage stresses which lead to desiccation cracks that may or may not heal upon rehydration [83, 98, 139]. Working with two kaolinite-bentonite–sand mixtures, Cripps and Parmar [27] have found that, while the soil with higher plasticity is more prone to cracking, it exhibits more self-repair. They have concluded that, although recovery of hydraulic conductivity is not complete upon wetting, the self-repair capacity of bentonite can be relied on to relax the limit of 4% on linear shrinkage usually set for compacted liners in landfills. This, however, is contingent on the presence of sufficiently high confining pressures and full rewetting under each cycle. In bentonite GCLs, higher montmorillonite content of bentonite, higher bentonite mass per unit surface area, sodium rather than calcium cations in the interlayer space, as well as fibre inclusion in the process of binding the bentonite to the geotextiles all seem to enhance self-repair upon rehydration [100, 107].

Several studies have shown that a minimum *overburden stress* is required, below which self-repair does not occur [5, 19]. For example, Boynton and Daniel [19] have reported that the desiccated cracks in a CH clay close upon permeation with water under effective stresses higher than 56 kPa, with a ratio of healed to original (before cracking) hydraulic conductivities of 2—compared to 17 under smaller effective stresses. It is notable, however, that most studies on crack self-repair under wet-dry cycles have been conducted for compacted clay motivated by considerations related to base and cover liners for waste insulation. The self-repair capacity of soils reconstituted from slurry, on the other hand, has been far less investigated.

Similar to wet-drying cycles, it has been found that when frozen soils are rehydrated by an external source of water, a higher confining pressure improves self-repair of cracks [99]. However, the same authors suggest that increasing confining pressure *after* the freeze–thaw cycle is not as effective as increasing it *during* the cycle, as the latter case prevents the formation of ice lenses and consequent expansion of soil [99].

The extent of drying, means of rehydration and *presence of plant roots* can affect self-repair. Malusis et al. [87] have shown that, for cracked bentonite–sand mixtures, the dryer the sample, the less crack closure occurs, and hence the higher the post-closure hydraulic conductivity. Miller et al. [92] have found that the erosional effects of high-intensity rainfall can cause widening (rather than closure) of surface cracks. Li et al. [77] report that plant roots in compacted clay liners operating as cover for a landfill reduce both the formation of desiccation cracks (by acting as reinforcement which increases the tensile strength of the soil, especially in early cycles) and their closure under subsequent wetting, with a net effect of higher hydraulic conductivities compared to non-vegetated liners.

Another important factor in the self-repair of clay under wet-dry cycles is the *chemistry of rehydration water*. Lin and Benson [83] report that self-repair of an Na-bentonite is inhibited when it is permeated with a calcium-rich solution because of cation exchange that prevents osmotic swelling, in comparison with rehydration with tap, distilled or deionised water (see our earlier discussion of self-healing of bentonite in GCLs). Julina and Thyagaraj [67] report that permeation with 1 M NaCl solution inhibits self-repair of compacted clay and leads to the reappearance of cracks at the same location upon re-drying.

When drying is driven by thermal gradients [27, 45, 140], *thermal history* (e.g., how high the temperature and temperature gradients, for how long has the sample been exposed to thermal gradients) is found to be important. Studies have revealed that the swelling capacity of bentonites decreases slightly at high temperature [133, 134]. Villar et al. [133] have observed an increase in the permeability of water-saturated bentonite with temperature. They have pointed out that the increase of permeability cannot be attributed solely to water viscosity changes and that loss of clay swelling at high temperature is probably involved. Earlier studies have also found that elevated temperature may result in the alteration of clay fabric and intra-aggregate fluid, and may eventually affect clay swelling and permeability [108]. In addition, particle charge and diffuse double layer thickness may be influenced by high temperatures [44]. A recent study by Yu and El-Zein [140] reports that traces of incompletely sealed cracks, after thermal dehydration of a sodium bentonite in a GCL, can still be observed by a high-contrast X-ray photo. On the other hand, the study has also found that, at low surface temperature (40 °C), there is complete recovery of hydraulic conductivity upon rehydration with water despite significant desiccation cracking at the end of the drying cycle.

Moulding water content (i.e., water content at which soil is compacted prior to undergoing wet-dry or freeze–thaw) has also been shown to have an influence on crack development and hence the hydraulic conductivity. The different microstructures resulting from compacting wet or dry of optimum have been long established [74], and these are associated with increases in crack density on drying as water content reduces [25]. The influence of moulding water content on hydraulic conductivity after wet-dry cycles has been less studied, but microscopic studies have shown that microstructural differences reduce after wetting [21, 120, 120]. Thus, it can be inferred that provided sufficient stress is provided [19] sealing and repair on wetting should occur irrespective of the moulding water content. Similar effects of microstructure have been reported for compacted samples subjected to freeze–thaw cycles, with samples compacted wet of optimum water content (ω_{opt}) exhibiting smaller cracks and more microcracks [69]. With increasing numbers of freeze–thaw cycles, it has been reported that stable crack patterns develop indicating the presence of crack memory and incomplete repair during thawing [84].

Initial conditions (i.e., the hydro-mechanical, chemical and thermal states of the soil at the start of the repair process) are another important factor in the self-repair of clay, the effects of which are poorly captured by most studies. For example, fracture size, fracture distribution and water content at the start of the hydration-driven repair process have a significant influence on the extent and pace of self-repair. However, in laboratory studies representing wet-dry cycles, it is very difficult to control the exact shape and size of fractures at the end of a drying cycle. Consequently, experimental comparisons of the effects of a given variable on self-repair can be somewhat misleading because the control case has different initial conditions to the study case. The conclusions of these studies are often pertinent to net cracking (developed cracks minus closed cracks) rather than self-repair per se (e.g., [32, 140]). To address these issues, artificial cracks have been introduced into the soil in some studies and the repair process observed (e.g., [48, 100]).

Several authors have found that various *additives* can have significant impact on the self-repair capacity of clay [33, 95, 122]. De Camillis [32, 33] has found that, compared to untreated bentonite, bentonite amended with Sodium Carboxymethyl Cellulose polymer (Na-CMC) is more likely to retain high swelling and low hydraulic conductivity, even when in contact with strong electrolyte solutions (e.g., seawater) under wet-dry cycles. Mohammadi and Choobasti [95] have reported more recovery of unconfined compressive strength under wet-dry cycles of a clayey soil amended with nano-clay, compared to unamended samples. Tabassum and Bheemasetti [122] have found that a polydimethylsiloxane polymer and nano-montmorillonite (MMT) can mitigate desiccation cracks during wet-dry cycles. Here again, in assessing the effects of additives on self-repair, it is important to bear in mind the point made earlier about the different initial conditions in experiments and the fact that the experimental design of most studies seems to allow investigators to observe net cracking but not sealing per se.

3.3 Crack observation and crack memory

3.3.1 Observational techniques used in studies of clay self-repair

As mentioned earlier, most studies on clay self-repair infer its presence and/or extent from the recovery of material properties, such as hydraulic conductivity and compressive strength [42, 95]. Some studies couple the measurement of these properties with naked-eye observation and/or digital photography of surface cracks. In some cases, X-ray and scanning electron microscopy (SEM) of the sample have been conducted at the end of a given wet-dry or loading–unloading cycle [23, 67, 123].

In some studies, crack closure has been observed with the naked eye and measured with gauges or callipers [23, 24, 29, 36, 46, 78, 79, 103]. Favre et al. [46] have conducted experiments at a vertosol site, with changes in the dimensions of artificially introduced cracks measured by a swelling gauge at different wetting times. Didier et al. [36] have reported that defects of up to 30 mm in diameter, artificially introduced into GCL samples, can completely close within 15 days under a low hydraulic head. Chai et al. [24] and Prongmanee and Chai [103] have investigated the healing extent of holes in GCL samples, which is calculated as the healed area divided by total area of the hole. Li and Rowe [78, 79] have measured the evolution of crack sizes with a Vernier calliper. Direct measurement of cracks is simple and low-cost but limited in its accuracy and only relevant to aspects of the cracks visible from the surface.

Several studies have captured the evolution and self-repair of surface cracks through *digital photography*. The technique has been used mostly to observe cracking [25, 53, 89, 105, 107, 123, 137] and, occasionally, sealing as well. The camera and sample are typically fastened, providing a consistent shooting angle to facilitate interpretation of results [123]. Photographs of cracks are usually processed with image analysis software and quantitative parameters describing the extent of cracking, such as the crack intensity (CIF) and/or crack density factors (CDF), are calculated [116]. Digital photography is non-destructive and easy to conduct, but it is restricted to changes visible at the surface and unable to capture changes to micro-cracks below a given size. Figure 3 shows an example of crack quantification by digital photography.

X-ray computed tomography (XCT) has been used to visualise cracking and sealing at resolutions up to 1 μm [128], including the capture of crack changes at different self-repair times [38, 51]. Di Donna et al. [38] have introduced an artificial crack in clay samples and saturated the cracked samples with vapour or water. After various wetting times, the samples have been scanned by X-ray and the cracks observed at different resolutions. They report that cracks close faster when saturated with water compared to vapour [38]. Among the limitations of the XCT when it comes to self-repair are a ceiling on the maximum sample size (depending on instrument resolution) and the time it takes to complete the scan (in the order of one or more hours). Figures 1 and 5 show examples of X-Ray imaging of self-sealing.

SEM can be used to visualise changes in the microstructure of a clayey soil during the self-repair process. For example, authors of this paper have conducted hydration tests on an artificially introduced hole in a quasi-saturated bentonite sample, using XCT and SEM (see Figs. 4, 5 and 6). Repeated XCT scans over three days have allowed the size and shape of the hole to be monitored in real time as it undergoes self-repair. At the end of the tests, the authors have conducted SEM imaging on specimens taken from the sealed hole as well as away from it (Fig. 6). The images show that the specimen from the sealed hole has more micro-voids and a less dense structure than its counterpart from the un-damaged part, hence suggesting that density may be (a) an explanatory factor in self-sealing with only partial recovery of material properties, and (b) a way in which memory of the crack is preserved by the sealed material.

Other techniques, such as synchrotron [15, 86, 102] and neutron radiography [118, 125], have been employed for soil crack quantification and could in principle be useful for

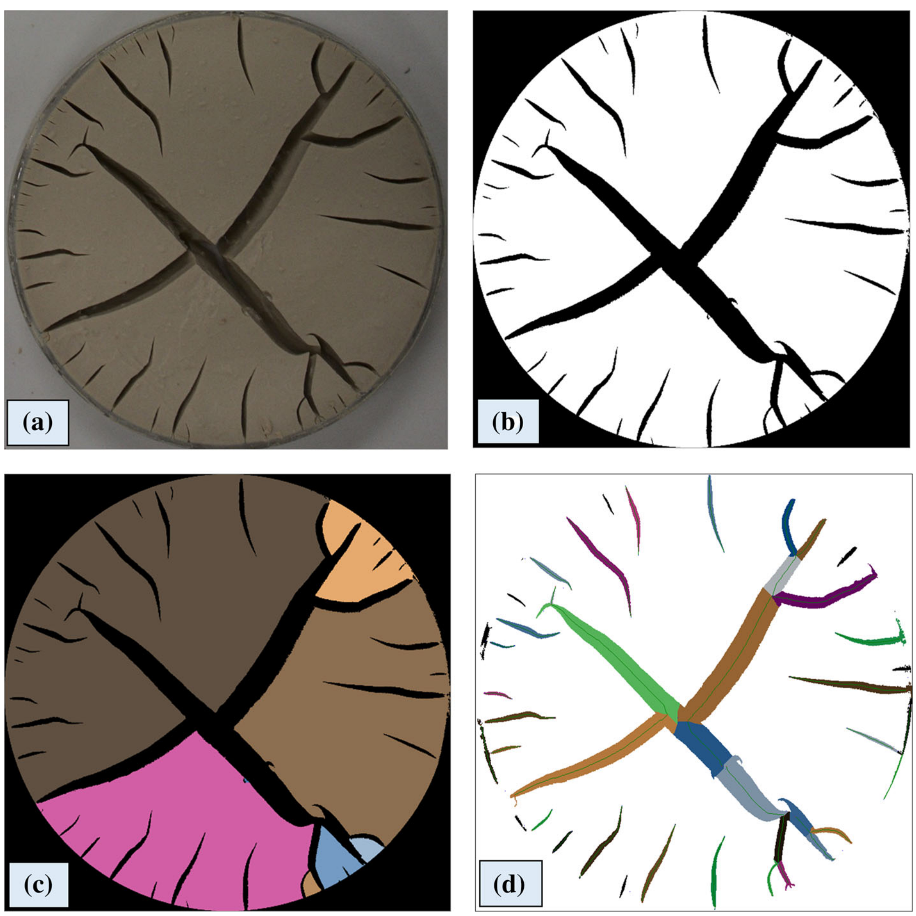


Fig. 3 Crack monitoring by digital photography: **a** original image; **b** binarized image after noise removal and crack restoration; **c** cell details; **d** crack quantification (see Mohammad et al. [94] for more details on digitisation methodology)

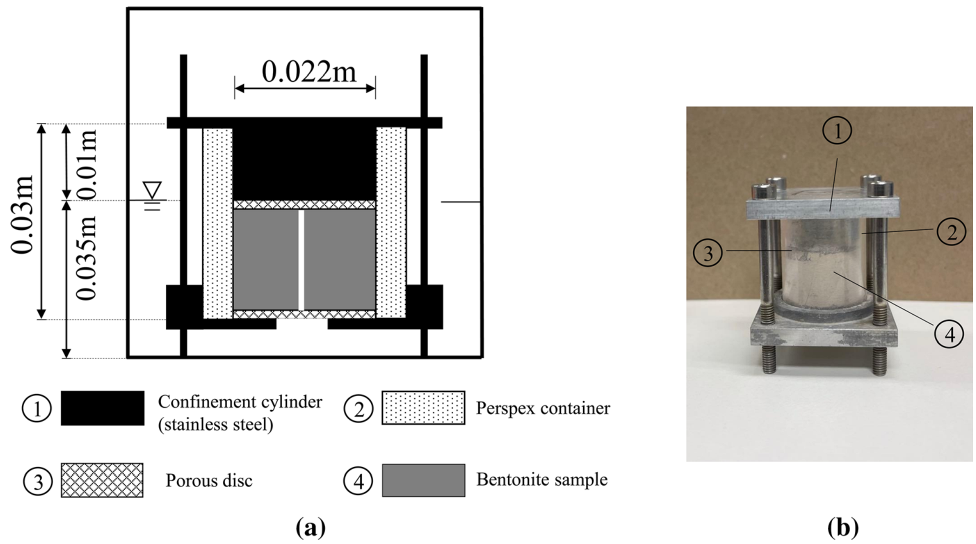


Fig. 4 Apparatus for visualising self-repair in a bentonite sample, with an artificial hole, undergoing hydration, using X-Ray computed tomography and SEM (see Gao et al. [48] for more details)

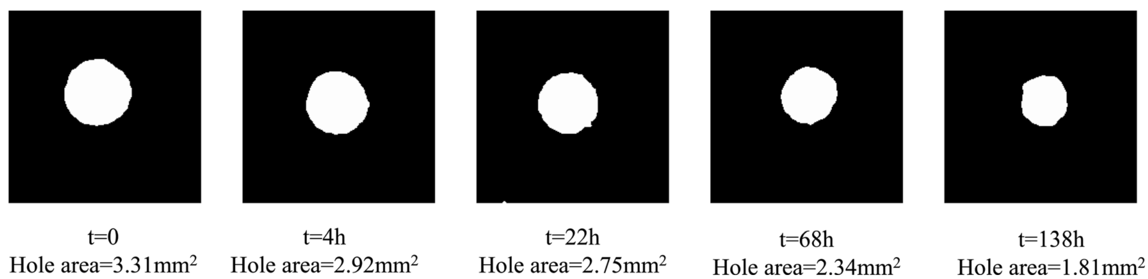


Fig. 5 X-ray images of sealing of hole during self-repair driven by hydration and osmotic swelling (see from Gao et al. [48] for more details)

observing crack sealing. The synchrotron has been found to be able to effectively characterise crack initiation and propagation [86]. It can be applied to develop XCT, enhancing the scanning efficiency and providing spatial and temporal (4D) information on crack propagation. Stavropoulou et al. [118] have stated that neutron imaging techniques could provide and explain cracking characteristics seen by X-ray scans. Water fills cracks, which can then be detected by neutron radiographs, providing a clearer view of the waterfront compared to X-ray scans alone [118].

3.3.2 Crack memory

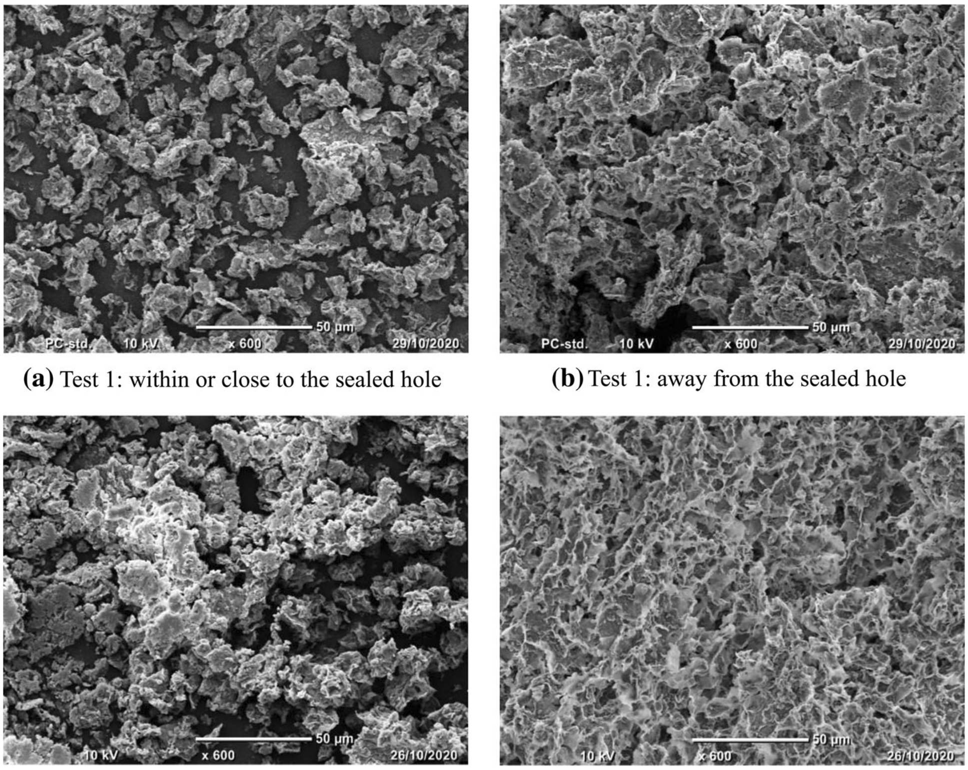
Some wet-dry cycles studies have assessed the presence of crack memory after self-repair ('recurrence' or 'repeatability'), i.e., the extent to which the same cracks are likely to reopen upon re-drying [67, 81, 88]. For example, McBrayer et al. [88] have shown that cracks in kaolinite do not close fully and readily reopen in subsequent drying cycles.

Li and Zhang [81] have compared snapshots of the same plot in an excavated area after two different drying cycles and found the same cracks reforming. A similar observation has been made by Julina and Thyagaraj [67], working on samples of compacted natural clay soil. Note that 're-peatability' is sometimes used to indicate reopening of cracks at the same location, while at others, it refers to the reoccurrence of desiccation generally, though not necessarily the reopening of the same cracks (e.g., Li and Zhang [81] describing the work of Rayhani et al. [106]).

4 Theories and models of clay self-repair

4.1 Approaches to damage and repair modelling

Porous media may contain cracks of various sizes which can be considered from both macroscopic and microscopic perspectives. In continuum mechanics, cracks are often conceptualised as 'damage', which causes changes to macroscopic properties of the material (e.g., stiffness, strength and permeability). Damage is a phenomenological variable that refers to the amount of energy dissipation at the macroscopic scale of a representative volume element (RVE) (see Fig. 7) or the smaller scale of the cracks [9]. If



(a) Test 1: within or close to the sealed hole **(b)** Test 1: away from the sealed hole

(c) Test 2: within or close to the sealed hole **(d)** Test 2: away from the sealed hole

Fig. 6 SEM of specimens taken from the self-sealed hole and away from it at the end of the hydration process; test 2 is a repeat of test 1; note the difference in microporosity between samples taken from the sealed hole and those away from it indicating incomplete recovery of porous structure after self-repair

S is the total cross section of an RVE defined by the normal, $\mathbf{L}$, S_D is defined as the cracked area of the RVE on the same plane that the stress is applied to ($\mathbf{L}$ plane). The actual resisting area is therefore taken as the total area (S) excluding the surface areas of the cracks. The damage variable (D_L) associated with $\mathbf{L}$ direction, as shown in Fig. 7, has been defined by Lemaitre [76] as follows

$$D_\mathrm{L} = \frac{S_D}{S}. \tag{1}$$

Damage can be represented by a tensor $\mathbf{D}$, which, under conditions of isotropy and homogeneity, can be reduced to scalar D [76]. (Note that tensors and vectors are shown in bold characters; also note that, in this section, we use the term "healing", rather than "repair" or "sealing", because the models we are discussing are concerned with crack closure, strength recovery and, potentially, recovery of permeability).

Continuum damage mechanics (CDM) for macroscopically homogenous materials has been first described in the framework of mechanics of continuous media and thermodynamics of irreversible processes without any consideration of the microstructure of the material [66]. Wilkins [138] has been among the first to show that progressive deterioration of the material can be related to a variable prior to failure. CDM has been improved in the 1980s by considering thermodynamics and micromechanical laws when deriving the damage formulation. In the early 2000s, continuum damage mechanics has been combined with Biot theory and extended to unsaturated soils to account for hydro-mechanical couplings [39]. The effect of soil plasticity has been added later as well by using elastoplastic constitutive models.

Healing can be described as a reversal of damage. There is strong evidence that damage in some material such as polymers, concrete, rocks and cohesive soils can be reversed and can, therefore, lead to the recovery of all or part of the lost mechanical and hydraulic properties through chemical, physical or biological changes [31]. Voyiadjis et al. [135] have been among the first to present a theory of continuum damage including healing mechanics.

In phenomenological models assuming isotropic behaviour, a net damage (D^*) variable is usually defined as a function of damage (D) and healing (ϕ) parameters that affects the stiffness matrix. For instance, Abu Al-Rub et al. [1] have presented the following equation for net damage in cohesive geomaterials:

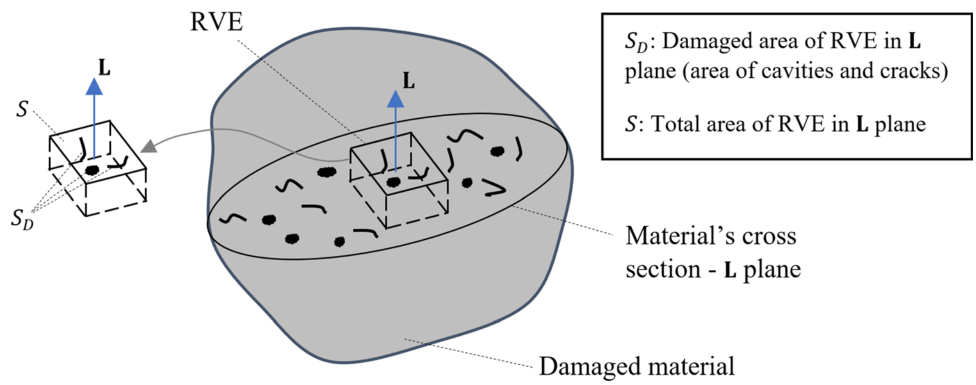


Fig. 7 Schematic illustration of damage in an RVE; damage variable associated with L direction is defined as the ratio of the cracked area to the total area of an RVE in L plane (see Esgandani and El-Zein [43] for more details)

$$D^* = D(1 - \phi) \quad (2)$$

While there is generally agreement in the literature about the definition of the damage parameter [76], different researchers have defined the healing parameter somewhat differently. For instance, Esgandani and El-Zein [43] have defined ϕ as the ratio of the surface area of healed cracks to the surface area of cracks prior to healing. In this case similarly to D, the healing parameter, ϕ, ranges between 0 when no healing has occurred and 1 when the whole damaged area is healed. Ju et al. [66], on the other hand, have defined ϕ as the ratio of healed cracks to the total surface area, which allows the material to gain more strength than the amount it lost during the previous damage cycle.

The changes in damage and healing variables are determined by evolution laws expressed at the RVE scale. These are commonly described with phenomenological equations without relating them to the microstructural physical processes driving the repair [43, 113]. Thermodynamics laws, stiffness positiveness, symmetry, and constitutive requirements should be satisfied in such phenomenological models when defining the Helmholtz free energy (ψ) at RVE scale as a function of D, ϕ, elastic and plastic strain components:

$$\psi = \psi(\boldsymbol{\varepsilon}^e, \boldsymbol{\varepsilon}^p, D, \phi) = \psi^e(\boldsymbol{\varepsilon}^e, D, \phi) + \psi^p(\boldsymbol{\varepsilon}^p, D, \phi) \quad (3)$$

To define thermodynamically consistent damage and healing evolution laws, damage and healing conjugate forces are defined by differentiating the expression of free energy with respect to its corresponding variable (D or ϕ). This is to enforce the positiveness of the second law of thermodynamics which states that energy is dissipated during irreversible processes. Hence, the rate of damage is assumed to be non-negative [113]:

$$\dot{D} \geq 0. \quad (4)$$

The same approach can be used to derive the healing evolution requirement [43]:

$$\dot{\phi} \geq 0. \quad (5)$$

Therefore, healing and damage are treated as separate processes. In fact, a common simplifying assumption is that damage and healing are opposite processes and cannot happen simultaneously in the same spatial unit.

4.2 Models of damage-healing for clayey soils

Several constitutive models based on continuum damage healing mechanics have been presented in recent years to capture the self-healing behaviour of geomaterials, including rocks [118], asphalt material [121], and cementitious materials [61]. In contrast, there are very few damage-healing models in the literature that can be applied to clays.

Ju et al. [66] have presented a coupled elastoplastic damage-healing model for cohesive granular soils. The damage-healing model is based on a continuum thermodynamics framework with an associative flow rule used to describe plastic behaviour and the strain equivalence hypothesis relating undamaged to damaged-healed configurations. It is assumed in the model that damage and healing are caused only by mechanical loading. Therefore, a change in the hydraulic conditions does not affect the damage or healing processes.

Parastar et al. [100] have extended the theory presented by Wang and Li [136] and suggested a physical model to analyse the effects of the structural properties of GCLs on their self-healing behaviour. Their focus is on the effect of water content on physico-chemical interaction between particles. Their model can calculate the force and water volume between particles by considering the fusion of the liquid bridge. Liquid bridges are allowed to form between particles and the liquid bridge force is used for predicting

SWCC and hydraulic conductivity. The self-healing capacity of needle-punched GCLs is not computed directly, but rather through the proxy of changes in hydraulic conductivity. Furthermore, the authors have mainly focused on the structural properties of the GCLs such as type of geotextile and needle punching density rather than properties of the bentonite clay. Their results show that needling or fibre inclusion in bentonite reduces the size of cracks and results in reduced hydraulic conductivity and better self-healing capacity [100].

Jia et al. [62] have presented a coupled hydro-mechanical model for creep and seepage in clayey rocks by using a rheological constitutive model which accounts for plastic damage and self-healing. The constitutive model is developed based on modified Mohr–Coulomb yield criteria. The damage evolution law is similar to the one suggested by Chiarelli et al. [26]. Jia et al. [62] assume that damage behaves elastically before yielding, becoming plastic after yielding. A creep damage criterion is also defined to consider the effect of internal cracking during creep. As a result, total damage is a combination of elastic, plastic and creep damage. The healing parameter adopted in their model is a function of hydrostatic and deviatoric stresses and has a direct relationship with hydrostatic pressure and inverse relationship with deviatoric stress. On the other hand, the damage parameter does not have any direct effect on the determination of healing parameter and permeability is defined as a function of total damage and healing. The proposed model has been implemented in a finite element framework and used to simulate the behaviour of clayey rocks during excavation and construction of a radioactive waste repository [62].

Esgandani and El-Zein [43] have presented a coupled elastoplastic-damage-healing constitutive model at a continuum scale. The damaged-healed configuration in their work is defined using the complementary energy equivalence hypothesis. The effect of plastic hardening, strain rate, stress ratio, suction hardening and confining pressure are taken into account in the evolution laws. The elastoplastic response of the soil is also captured using a bounding surface plasticity constitutive model from critical state soil mechanics. The model has been validated by comparing its predictions to existing experimental observation data.

Modelling healing in clay is hampered by two current limitations of the literature. First, few experimental datasets exist that can be used to conduct ‘blind’ validation of damage-healing models of clayey soils. This is largely due to the fact that none of the experimental studies generating these datasets was designed for the purpose of validating the models. Moreover, it is difficult to design an experiment to determine strength recovery of clays during healing. In particular, the shrinkage of clays during the desiccation process, and its swelling upon wetting, can cause changes in sample geometry (dimensions and effective area over which the load is applied) which makes it difficult to infer the strength of the damaged/healed material. In addition, application of load during the test may add to damage and/or healing hence compounding interpretation challenges. Second, evolution laws based on the micromechanical and microstructural understanding of damage and healing are needed with models currently using over-simplistic phenomenological laws that are either lacking in empirical evidence or limited to a narrow range of cases.

5 Knowledge gaps and future research

While several knowledge gaps have been identified in the discussion above, we focus here on four key areas—site studies, clay mixtures and reconstituted soil, observational studies under controlled initial conditions of repair, and development of predictive models.

5.1 Site studies

Studies of self-repair are dominated by laboratory experiments on compacted soils and much less effort has been expended towards understanding *in situ* opening and closure of cracks over both short and long-time scales (e.g., crack dynamics in response to diurnal and seasonal cycles, as well as long-term droughts). Early work by Morris et al. [96] has related the observed depth of cracking in drying soils to suction profiles using linear elastic fracture mechanics and shear and tensile failure criteria. Experimental research programs associated with deeply buried nuclear waste repositories, reviewed earlier in this paper, have also produced a significant body of literature, recording and interpreting cracking in high-density clay (e.g., [12, 17, 143]). However, there is a dearth of in situ geotechnical studies, particularly given the widespread existence of cracking, self-sealing and self-healing, in a range of geotechnical engineering structures. For example, slickensides, encountered relatively frequently in geological formations, including natural and oil reservoirs, have received very little attention in the literature [e.g., 79.]

While site monitoring has traditionally been expensive and highly time-consuming, several new technologies offer promise in this space. In situ Transmission Electron Microscopy (In situ TEM) and In situ Scanning TEM (In situ STEM) allow for better control of environmental conditions and hence better approximation of site conditions (e.g., [57]). Relatively inexpensive and mature remote-sensing technologies, such as Interferometric Synthetic Aperture Radar (InSAR) and 3D laser scanning

(LIDAR) have now been applied in studying soil settlement and other geophysical hazards (e.g., [127]) and can potentially be deployed for the monitoring of cracking and self-sealing of clayey soils in the field, especially if combined with artificial intelligence for better data mining and interpretation [75].

5.2 Clay material studied

The swelling-clay fraction of a given soil has been shown to be an important variable determining the extent of cracking, sealing and healing [27, 83, 98, 139]. Much work has been done on the sealing of swelling clays, such as bentonite (with a predominant montmorillonite fraction) and to a lesser extent kaolinite, because of the importance of the former in barrier systems, and the latter in a range of geotechnical and geoenvironmental applications. On the other hand, our understanding of the cracking-sealing-healing behaviour of soil mixtures remains incomplete, especially the effects of the coarse-grained fractions and non-swelling clay. In addition, very little work can be found on the healing capacity of soils reconstituted from slurries.

5.3 Direct observation of sealing under controlled initial conditions

A substantial number of studies in which sealing of cracks is observed and measured (as opposed to inferred from changes in material properties) can be found in the literature, as shown in the discussion above. However, most studies either compare images of cracked to sealed or partly sealed samples or, more commonly, provide observations at different points in wet-dry cycles. However, a drawback of these studies lies in the difficulty of controlling the initial conditions prior to the sealing process. This is due to the fact that, under wet-dry cycles, a network of cracks is typically generated at each dry cycle, which depends on local heterogeneities in the sample and will be different in each test. Hence, it is difficult to study the effects of different variables on sealing, and to separate constitutive processes operating at the level of a single crack from those pertaining to the interaction between cracks. These studies provide important insights but need to be complemented by studies with better control of initial conditions. The creation of artificial cracks which are then allowed to seal (e.g., by hydration or loading) offers one possible approach to this problem, as shown by Gao et al. [48].

5.4 Predictive models and healing evolution functions

Models incorporating self-repair of clay must be able to predict the evolution of cracks, as well as the effects of cracking on the hydro-mechanical behaviour of clay, with the two endeavours ideally coupled in real-time. This can be achieved in principle through thermodynamically consistent models and/or heuristic sealing/healing evolution functions. Cohesive crack models have been shown in the past decade to allow better predictions of cracking in concrete and, more recently, in soil (e.g., compared to linear elastic fracture mechanics). Hence, they provide a possible avenue for developing numerical models that incorporate sealing/healing as well. A key obstacle to the development of such models is the lack of experimental data—both site and laboratory-based—specifically derived to validate sealing/healing evolution outcomes and research is needed in this space.

6 A proposed nomenclature of self-repair in clay

Even a brief review of the literature on clay healing reveals a certain level of confusion about the terms adopted. For example, 'healing' has sometimes been used to denote any closure of crack, partial or total, while for others, it is used to refer to full closure of cracks (e.g., [14]) More generally, is 'self-healing' the same as 'autogenous healing'? Does 'self' in self-healing refer to a 'natural' aptitude of a material or the self-triggering nature of the process, even when it is engineered? What is the difference between 'healing' and 'sealing', and do experimental procedures allowing us to distinguish between the two actually exist? How do we characterise healing when full closure of crack is observed but not a full recovery of macroscopic properties under study (or vice-versa)? In fact, the term 'self-healing' is often used to denote both aspects of self-repair—crack closure and property recovery. Clearly distinguishing between these two aspects is an important first step towards better understanding the relationship between them.

Very few papers define the terms 'healing' and 'sealing' and rather assume that the meaning is unambiguous. Two papers that have offered a definition are by Bastiaens et al. [12] and Blumling et al. [17]. They understand 'sealing' as a reduction in fracture permeability only, without regaining mechanical properties, and 'healing' as the sealing with loss of memory and recovery of intact mechanical properties whereby a '*healed fracture will not be a preferred site for new fracturing just because of its history*' [12].

However, Bastiaens et al. [12] also use the term partial 'healing' to indicate, rather inconsistently, a full closure of cracks in some cores; hence, while these authors define 'healing' in terms of memory, they assert its presence based on morphological closure of the cracks (and presumed recovery of mechanical properties) without reference to memory.

We argue that the ambiguities and inconsistencies discussed above have made it more difficult for a coherent body of knowledge on the self-repair of clay to emerge. Here, we propose a set of definitions, and associated nomenclature, which can help in enhancing consistency in scientific communication on clay self-repair. Evidently, as with all conventions, other ways of describing the field are possible, and the only merit of any system is internal coherence and the extent of its adoption.

We start by defining the generic term 'self-repair' as *the capacity of any material to totally or partially remedy morphological defects through a process that is at least partly autonomous*. In the case of clay, we understand this definition to apply to clayey soils, clay materials and/or clay minerals.[2] According to the proposed definition, a process can be engineered, externally triggered and dependent on external assistance to occur during part of the process, and still be called self-repair because it proceeds autonomously during another part of the process.

The basis of our proposed nomenclature is a set of four distinctions. The first distinction is between the *process* of self-repair and its *outcomes*. Within process, we then distinguish between what *triggers* self-repair and what *propels* it. Under outcomes, we separate *morphological* from *physical* effects of self-repair; by physical effects, we mean the influence of self-repair on selected physical properties of the material in question. Finally, we introduce an element of time, subsequent to self-repair, which allows us to characterise *stability* and *memory* of self-repairing material. Based on these four distinctions, we propose a classification structured around seven attributes of self-repair. The attributes are shown in Table 1 and articulated as questions.

The second attribute is related to the 'trigger' of self-repair (spontaneous/self-triggered versus non-spontaneous), while the third, 'propulsion', refers to whether self-repair proceeds autonomously or not, regardless of whether it is engineered and/or spontaneously triggered or not. Under outcomes, two of the four attributes are morphological, i.e., related to changes in the shape and dimensions of the defects. The other two are physical, referring to selected physical properties affected by self-repair. Under 'morphological outcome', self-repair can be either partial or complete. Full self-repair has sometimes been designated as self-sealing in the literature (although not consistently).

The next attribute is 'morphological memory'. Self-repair is said to carry morphological memory if some or all of the same defects, at the same locations in the material, re-emerge after self-repair. This can happen either spontaneously or if the original conditions that had led to it are reinstated (e.g., repeated dehydration or freeze; removal of overburden load).

Finally, the effect of self-repair on selected material properties is accounted for by the last two attributes. 'Physical outcome' depends on whether there is partial or total recovery of properties, and 'physical stability' refers to whether the recovery is stable or not (i.e., prone to be spontaneously reversed or not).

An important observation here is that some of the attributes depend on the scales of observation. For example, a crack might appear to have completely closed under one scale of observation, but not under another, finer scale. Another crack will close fully, but only if the observation is maintained for a long enough period of time. Hence, both spatial and temporal scales of observation are pertinent to the classification of self-repair by outcomes (though not by a process)—and have been added to the last column of Table 1 under 'Co-Variables of Definition'.

In addition, explicit in the definition of morphological memory above is the identification of the conditions that have led to the emergence of the defects in the first place. This may not always be easy or even possible and may hence hamper the practical use of this definition (e.g., an incomplete understanding of the genesis of a defect might lead to a self-repair process being classified as memory-free when it is not). Finally, both attributes relevant to physical outcome depend on the selection of material properties of interest. A self-repair process might lead to full and stable property recovery for one set of properties (e.g., permeability and water retention) but to partial and unstable recovery for another set (e.g., compressive and shear strength).

Note that the proposed taxonomy does not refer to whether agents involved in self-repair (e.g., water, polymer, bacteria) are intrinsic or extrinsic to clay—such distinction would be difficult to draw in reality and would therefore be of little practical usefulness.

Table 2 presents three examples of common self-repair situations and how they are classified within the proposed

[2] *'Clay minerals'* are chemically defined compounds belonging to one of several clay mineral groups such as kaolinite, illite, vermiculite and smectite, which are found in soils; *'clayey soils'* are defined differently by different soil classification systems but, in this paper, we generally understand them to be soil containing significant amounts of clay minerals; *'clay materials'* are industrially manufactured/processed substances that contain refined forms of clay minerals for specific applications such as china clay (kaolinite) or bentonite for waste barrier systems (montmorillonite).

Table 1 Proposed nomenclature for clay crack self-repair

	Attribute of self-repair	Key question	Types of self-repair		Co-variables of definition
			Yes?	No?	
Process	Overall process	Is self-repair autogenous (i.e., non-engineered)?	Autogenous self-repair	Engineered self-repair	
	Trigger	Does the process of self-repair start without requiring an external trigger?	Spontaneous self-repair	Non-spontaneous self-repair	
	Propulsion	Does the process of self-repair proceed in real-time without intervention by an external agent or not?	Autonomous self-repair	Non-autonomous self-repair	
Outcomes	Morphological outcome	Are defects completely closed?	Full self-repair	Partial self-repair	STSO*
	Morphological memory	Is the material immune to redeveloping the same defects in the same locations (e.g., either spontaneously or if self-repairing conditions are reversed/changed?)	Memory-free self-repair	Self-repair with memory (morphologically stable or unstable)**	STSO* + relevant conditions
	Physical outcome	Does self-repair lead to complete recovery of target properties?	Full property-recovery self-repair	Partial property-recovery self-repair	STSO* + properties of interest
	Physical stability	Is recovery of properties stable or is it partially or totally lost over subsequent time?	Property-stable self-repair	Property-unstable self-repair	STSO* + properties of interest

**STSO* Spatial and temporal scales of observation

**If reappearance of defects is spontaneous (unspontaneous), self-repair is said to be morphologically unstable (stable)

Table 2 Examples of self-repair

	References	Hydration of geosynthetics clay liners subject to wet-dry cycles Azad et al. [10] Yu and El-Zein [140] Ghavam-Nasiri et al. [50]	High pressure applied to fractured strata Bastiaens et al. [34] Blümling et al. [27] Jobman et al. [93]	Bio-cementing of soil (urea) Van Paassen et al. [131] Dejong et al. [35]
Process	Overall process	Autogenous	Engineered	Engineered
	Trigger	Non-spontaneous	Non-spontaneous	Spontaneous
	Propulsion	Autonomous	Autonomous	Non-autonomous
Outcomes	Morphological outcome	Full or partial	Full or partial	Full
	Morphological stability	Unstable	Stable	Stable
	Morphological memory	With memory	With memory	With memory
	Physical outcome	Partial	Partial	Full
	Physical stability	Unstable	Stable	Stable

taxonomy, namely hydration of GCLs, high-pressure applied to fractured media and bio-cementing of soils. Note that the last example has been applied to sand rather than clay and the proposed nomenclature, although occasioned by our work on clay, has broader applicability to soils and materials other than clay.

7 Conclusions

Evidence for self-repair in clay is widely reported in the literature, including significant effects of healing on key hydro-mechanical properties and behaviour of clayey soils and materials. In this paper, we have systematically reviewed this evidence as well as the current state of knowledge on influencing variables. We have also reviewed existing theoretical and numerical models of damage that incorporate self-repair in one form or another. In addition, we have proposed, for the first time, a systematic approach to nomenclature in the study of clay self-repair.

Despite significant advances in recent years, key questions remain about driving processes and the relative importance of material and environmental variables in clay self-repair. Furthermore, there is a scarcity of site studies on the healing of clay soils and self-repair of soils reconstituted from slurries. The mischaracterisation of volume change behaviour of expansive soils causes multi-billion dollars in damage to civil infrastructure all over the world annually, while cracking of clay-based materials compromises the performance of waste barriers. A better understanding of the self-repair of clay can help in addressing both problems. We have proposed a set of research directions that we believe can lead to a consistent, experimentally based, theoretical account of self-repair in clay and therefore pave the way towards incorporating self-repair in geotechnical and geoenvironmental design.

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