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Clay rocks - Characterization of Natural and Engineered Barriers

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Introduction

Clay rock and clay-based materials play an important role in a wide range of geotechnical and environmental applications due to their low permeability, swelling capacity, and favourable thermo–hydro–mechanical–chemical (THMC) properties. In particular, clay formations have been widely investigated as potential host rocks for the deep geological disposal of radioactive waste. In addition, clay-based materials such as bentonite are commonly used as engineered barriers in repository systems [1]. Beyond radioactive waste management, clay rocks also serve as confining units for subsurface energy systems, including geological CO_2 sequestration [2] and hydrogen storage [3]. Furthermore, clay-based materials are widely used in environmental protection systems such as landfill liners, cut-off walls, and containment barriers [4]. However, the mechanical properties of clay-rich materials often present significant challenges for engineering practice. Typically, compared to other geo-materials, clay exhibits relatively low shear strength, high compressibility, and strong sensitivity to water content. These characteristics may lead to excessive deformation, long-term settlement, and potential instability in geotechnical constructions, such as foundations, underground excavations, and slopes.

In addition, the THMC interactions may significantly affect the engineering properties of clay; for instance, volume changes induced by wetting–drying cycles or chemical interactions can further affect the hydraulic and mechanical performance of clay materials. In the context of geological disposal of nuclear waste, such THMC interactions are particularly important. The decay heat released from radioactive waste generates thermal gradients and causes thermal stresses. It also alters pore water pressure and chemistry and triggers clay swelling and shrinkage. Furthermore, an increase in temperature can accelerate mineral reactions and corrosion. Furthermore, introducing engineered barrier materials, such as bentonite, concrete, metals and backfill components, can disrupt the natural geochemical equilibrium by altering pH levels, salinity and redox conditions, which can lead to gas generation. These coupled processes can significantly alter permeability and swelling behaviour, thereby affecting radionuclide retention and the long-term integrity of both natural and engineered barriers.

Extensive research efforts have been undertaken worldwide to improve the understanding of the coupled THMC mechanism governing the performance of clay host rocks and engineered barriers. Both experimental investigations and numerical modelling approaches have been widely employed to characterise the properties and behaviour of clay-based materials under various environ-

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mental conditions. Significant efforts have been devoted to improve the mechanical properties of clay, including soil stabilisation techniques and ground improvement methods. Moreover, novel approaches have been developed to modify bentonite-based materials through chemical stabilisation, polymer amendments, and the incorporation of industrial by-products such as lime, cement, fly ash, and steel slag. These modifications aim to enhance mechanical strength, reduce permeability, and control the swelling behaviour of clay soils. In addition, nanomaterials and advanced composite technologies have been introduced to tailor the microstructure and improve the long-term performance of clay-based systems.

This Topical Collection was established on the occasion of the "9th International Conference on Clays in Natural and Engineered Barriers for Radioactive Waste Confinement" Clay Conference), which was held from 25-28 November 2024 in Hannover. In total, 237 manuscripts were submitted, of which 49 articles were accepted for publication. Figure 1 shows a world map of the geographic distribution of the authors who contribute to this Topical Collection. The most active countries are China, India, Ethopia, Egypt, Iran, Germany and France.

The papers included in this Topical Collection can be broadly grouped into three categories according to their primary research objective, core methodology, and main contribution:

- Geological and geotechnical characterisation
- Process understanding through experiments and computational methods
- Material and engineering innovations

A structured overview of the contributions under each category is provided in Table 1.

Given the important role of clay-based materials in constructing multi-barrier systems for the deep geological disposal of radioactive waste, dedicated sections synthesise the implications of these findings and in the broader context of ongoing international repository research initiatives, particularly EURAD-2 and DECOVALEX. Some works cited in those sections, therefore, serve as background references rather than as contributions to the present Topical Collection.



Fig. 1: Author location map of the manuscript submission to the Topical Collection "Clay rocks - Characterization of Natural and Engineered Barriers"

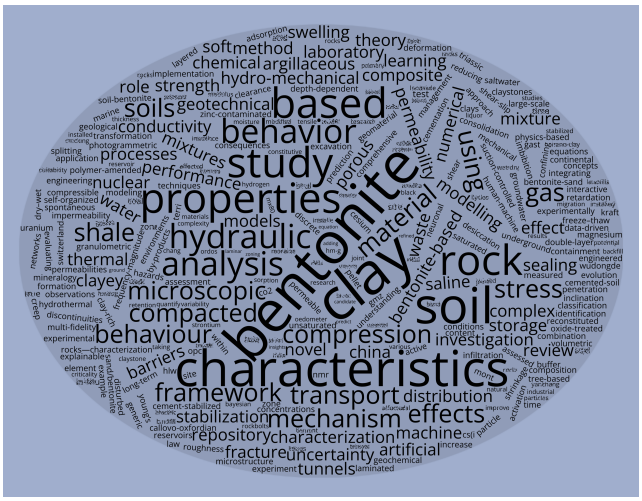


Fig. 2: Word cloud generated from the titles of the published articles (using https://www.wortwolken.com/ software)

Geological and geotechnical characterisation

Geological and geotechnical characterisation aims to identify and quantify the key intrinsic structural, mineralogical, hydraulic, and mechanical attributes of clay-rich geomaterials, clay-bearing sedimentary rocks and related rock masses. The results often provide an essential basis for the subsequent process-specified analysis and engineering assessment. Yang et al. [5] developed a photo–grammetry–based human–machine interactive method for the refined identification of complex discontinuities in rock mass. This study offers a high-resolution and practical approach for characterising fracture geometry in the repository host rock. Standardised cyclic wet–dry tests on several typical clayey soils were carried out in [6]. Based on multiple cracking parameters and entropy weighting, a classification framework was proposed in this work to characterise the cracking potential. Thereby, the conventional geotechnical characterisation was extended from an index properties-based to a crack-related performance. By combining true triaxial compression experiments with numerical simulation, the influence of joint roughness and inclination on the strength, deformation, and fracture

Table 1: Structured overview of the Topical Collection "Clay rocks—characterization of natural and engineered barriers"

Geological and geotechnical characterisation	
Human-machine interactive refined identification of complex rock discontinuities using photogrammetric techniques: Case studies from a candidate HLW repository site in China	[5]
Classification of cracking potential for clayey soils based on cyclic wet-dry tests	[6]
Effects of joint roughness and inclination on fracture behavior of jointed rock under true triaxial compression	[7]
Permeability evolution of claystones and other sealing materials for CO2 storage: role of confining stress and time	[8]
Depth-dependent engineering geological and geotechnical characterization of ankara clay: a study on the effect of consolidation on soil variability	[9]
Influence of osmotic suction on the hydro-mechanical behavior and micro-structure of compacted red clay in contaminated sites	[10]
Distribution characteristics of laminar thickness and spontaneous imbibition law of continental shale – taking the chang 72 shale of the triassic yanchang formation in the ordos basin as an example	[11]
Landslide hazards in the Wudongde Reservoir (China): Analysis of frequency-magnitude characteristics based on self-organized criticality theory	[12]
Process understanding	
Experimental studies:	
Damage behaviour of MX80 bentonite pellet in mixture under suction-controlled oedometer compression	[13]
Tensile behaviour of compacted bentonite assessed by a Brazilian splitting test: role of particle size and water content	[14]
Study on the influence of thermal aging on the swelling properties of GMZ bentonite	[15]
Progressive degradation and performance deterioration mechanisms of the limestone	[16]
Effect of dry–wet cycles on the impermeability of sand bentonite mixtures: A microscopic analysis	[17]
Initial moisture effects on THMC processes in cement-stabilized marine clay	[18]
Desiccation crack and volumetric shrinkage of magnesium oxide-treated compacted soil liner in landfill	[19]
Hydraulic conductivity of compressible clayey soil stabilized with kraft black liquor and composite cement	[20]
Dismantling of the Mock-Up Josef in situ experiment after 10 years of operation – a comprehensive analysis of the bentonite barrier	[21]
Experimental study on Atterberg limits and shear strength properties of saline clay based on microscopic pore characteristics	[22]
Understanding of Cs(I) and Am(III) retention behaviour on Vindhyan argillaceous clay for evaluating its suitability for nuclear waste management	[23]
Impact of varied sodium polyacrylate dispersant conformation on Atterberg limit	[24]
Research on cementation in moraine soils: insights from mineralogy and granulometric analysis	[25]
Laboratory testing of saturated permeability affected by rock swelling	[26]
Investigation of creep characteristics and microscopic mechanism in cemented-soil subjected to freeze–thaw during artificial ground freezing	[27]
Computational methods:	
Geochemical modelling to assess the consequences of an increase in pH for an in-situ experiment at the Mont Terri Rock Laboratory, Switzerland	[28]
Analysis of stress and deformation characteristics of rockbolts installed in layered soft rock roadway of coal mines	[29]
Study on stress distribution characteristics in small clearance tunnels under complex conditions	[30]
Shear-slip and hydraulic fracture penetration in laminated shale reservoirs: discrete element method (DEM) and explainable machine learning	[31]
A numerical large-scale investigation of gas transport processes in a generic nuclear waste	[32]
Hydro-mechanical and gas transport (HM-G) characterization of sand/bentonite mixture within the framework of the Gas Permeable Seal Test (GAST)	[33]
Effect of heating on clay formations: results of a THM modelling benchmark exercise on two heater tests in indurated and poorly indurated clays	[34]
Numerical investigations on buffer-host rock thermo-hydro-mechanical interactions in diverse geological settings: a comparative study	[35]
A physics-based model of soil water adsorption in saline environments: integrating electric double-layer theory with NMR observations	[36]
Constitutive equation for Young's modulus in clay-rich rocks: adding complexity, reducing uncertainty	[37]
Hydraulic modeling of saltwater infiltration with various concentrations into unsaturated bentonite-based buffer material	[38]
Implementation framework for numerical transport models: Application for underground hydrogen storage	[39]
Data-driven modelling of compression behavior of reconstituted clays based on multi-fidelity framework	[40]
Combination of Bayesian and artificial neuronal networks to quantify uncertainty of the short- and long-term behavior of Callovo-Oxfordian claystone	[41]
Assessment of tree-based machine learning models and empirical equations to predict thermal conductivity of bentonite-based backfill material using experimentally measured data	[42]
Review:	
Chemical effects on the hydro-mechanical behavior of compacted bentonite: a review	[43]
Material and engineering innovations	
Hydrothermal stabilization of clay soils using industrial by-products: A comprehensive review of microstructure, chemical composition, and mechanical properties	[44]
Novel approach to improve geotechnical properties of clay soil by nano-clay and OPC particles	[45]
Hydraulic performance of polymer-amended bentonite for containment of zinc-contaminated groundwater	[46]
Retardation mechanism and migration of Cr(VI) by the active porous material in modified soil-bentonite barriers	[47]
Acid activation of bentonite: structural transformation and sorption performance for uranium, cesium, and strontium	[48]
Strength properties of a composite geomaterial for soft soil stabilization	[49]
Novel sealing concepts for landfills: mechanism and prediction of permeabilities of bentonite-sand mixtures	[50]
Study on local primary support method for tunnels based on the zoning results of excavation disturbed zone	[51]

behaviour of jointed rock was analysed and quantified in [7]. The permeability evolution of claystones and other sealing materials for CO_2 storage was characterised, with particular attention to the effects of confining stress, time, and lithological heterogeneity [8]. The results show that sealing performance varies substantially across and within lithotypes, and that permeability measurements are strongly influenced by stress equilibration. Şahin and Koçkar [9] presented a comprehensive depth-dependent engineering geological and geotechnical characterisation of Ankara Clay based on a large regional database of borehole, laboratory and in-situ test results. The results showed that consolidation history strongly affects soil variability and undrained shear strength prediction. By incorporating the consolidation condition into empirical correlations, the authors improved predictions of undrained shear strength and provided practical equations for preliminary geotechnical design in high-plasticity clay deposits. The hydro-mechanical and microstructural response of compacted red clay under contaminated-site conditions was characterised by Zhang et al. [10]. This study provides useful insight into chemo-hydro-mechanical interactions in clayey soils exposed to saline or contaminated pore fluids, with implications for environmental geotechnics and contaminated-site redevelopment.

Bright and dark laminae in continental shale were distinguished through combined XRD analysis with multi-scale observations [11]. Their mineralogical contrasts, thickness distributions, and imbibition-related heterogeneity were further analysed. In addition, Liu et al. [12] proposed a statistical approach to slope instability assessment by analysing the frequency–magnitude characteristics of reservoir-bank landslides. Although this method was not specifically developed for clay-based materials, it has the potential to be extended to clay-rich slopes, particularly for characterising scale-dependent instability patterns and supporting hazard assessment.

In general, geological observations identify, locate and describe the spatial variability of clay formations, while geotechnical tests investigate how the materials respond to changes in surrounding conditions. Taken together, the contributions reveal that characterising a clay-rich formation and material requires more than assigning a single set of representative properties and a single observation scale. At the site scale, the identification of discontinuities and depth-dependent variations in soil and rock properties leads to define the spatial structure that engineering assessments must account for. At the material scale, wetting–drying tests and experiments with different pore-water chemistries indicate that cracking potential and hydro-mechanical properties are strong dependent on environmental conditions. These findings improve the basis for selecting parameters and identifying potentially vulnerable zones. However, the individual studies often concern on specific materials and setting. Thus, their results cannot be transferred directly among different sites and scales. Moreover, a parameter measured on a specimen, or a relationship established for one clay, may not represent a heterogeneous site or remain valid as conditions change over time. Future characterisation should therefore to systematically link field observations, sampling, and laboratory tests, quantify the uncertainty in spatial and material properties, and provide a defensible basis for parameters for assessment of long-term engineering and barrier performance.

Process Understanding

Most papers in this collection contribute to improving the understanding of the complex mechanisms governing the micro- and macroscopic properties, as well as the geological and coupled THMC behaviour of clay-based materials and rock mass under various environmental and engineering conditions. For this, primarily, experimental and numerical studies were conducted.

This section summarises laboratory-based and field-supported experimental investigations in the Topical Collection mainly focusing on the hydro-mechanical, thermo-hydraulic behaviour, and chemo-environmental interactions of clay-based barriers and related fine-grained geomaterials. A major focus is the quantification of key barrier functions under repository- and geoenvironment-relevant conditions. Regarding the bentonite material, Yang et al. [13] carried out suction-controlled oedometer tests together with micro-CT and MIP to investigate wetting- and loading-induced damage in MX80 bentonite pellet/powder mixtures. Their results revealed that crack development strongly depends on both suction and loading level. The tensile behaviour of compacted bentonite was further examined using the Brazilian splitting tests combined with the Digital Image Correlation (DIC) and pore structure analysis [14]. The roles of particle size and water content were highlighted in this work. Thermal effects of compacted GMZ benonite were further analysed through long-term thermal aging tests [15]. In addition, the swelling pressure under constant-volume conditions were measured. The results showed a clear reduction in swelling capacity after prolonged heating, which was linked to microstructural changes. Liu et al. [16] examined the progressive degradation of limestone-concrete interfaces under coupled sulfate attack and dry-wet cycling through compression-shear tests combined with DIC, acoustic emission monitoring, MIP and SEM observations. The

study showed that the interface degradation follows a two-stage mechanism, with early pore-filling enhancement followed by crystallisation-induced cracking and mechanical deterioration.

Several studies focused on the durability and sealing performance of clay as barrier materials. Hu et al. [17] combined permeability, SEM, and CT tests, indicating that repeated dry-wet cycles reduce the impermeability of sand-bentonite mixtures by loosening the microstructure and changing pore characteristics. Huang et al. [18] investigated the coupled THMC behaviour of cement-stabilised marine clay with different initial moisture contents through column tests and microstructural observations. Their results showed that moisture content strongly controls hydration, strength development, hydraulic conductivity, and internal thermal-hydraulic evolution, with an optimum construction moisture content of 22%. Al-Soudany et al. [19] investigated MgO-treated expansive soil as an alternative liner material for landfill applications. Based on hydraulic, shrinkage, cracking, and microstructural tests, the study showed that MgO treatment can reduce free swelling, hydraulic conductivity, volumetric shrinkage, and desiccation cracking, thereby improving liner stability and integrity. The experimental results in [20] showed that black liquor, especially when combined with CP II-F-32 cement, can remarkably reduce hydraulic conductivity and improve chemical stability. This work highlights the potential of the application of these mixtures for landfill liners. Vašíček et al. [21] reported the dismantling and post-test analysis of the Mock-Up Josef in situ experiment after nearly ten years of operation under repository-relevant thermal and hydration conditions. The study provides a comprehensive assessment of compacted Na_2CO_3-activated Czech bentonite, including its dry density, saturation state, mineralogical and geochemical evolution, and microbiological activity.

Other contributions also examined chemically affected soils and retention behaviour. He et al. [22] performed volumetric flask tests, triaxial shear tests, NMR, and SEM, and revealed that salt type and concentration influence Atterberg limits, bound water, pore structure, and shear strength. Kar et al. [23] combined sorption experiments with mineralogical characterisation. The experimental observations demonstrated the retention capacity of Vindhyan argillaceous clay for Cs(I) and Am(III), which indicates its relevance for nuclear waste management. Based on laboratory experiments, Li et al. [24] investigated how sodium polyacrylate dispersant (PAANa-D) affects the Atterberg limits and compaction characteristics of clay minerals. Using Ca-montmorillonite, kaolinite and illite as representative clay minerals, the study showed that PAANa-D modifies clay index and compaction properties by shifting from particle dispersion to agglomeration with increasing concentration.

Several contributions used experimental approaches to improve the understanding of natural and artificial clay-rich soils and rocks. Lu et al. [25] combined field surveys, XRD, SEM/EDS, and pretreatment-based granulometric analysis to identify widespread clay-carbonate cementation in moraine soils. A novel flow-through swelling test on Opalinus Clay was proposed in [26], which enable the simultaneous observation of saturated permeability, swelling stress, and swelling strain while accounting for anisotropy. In addition, Zhou et al. [27] investigated the creep behaviour of cemented soil before and after freeze–thaw through triaxial creep tests, SEM observations, and PFC simulation. The results indicated an increased creep deformation, especially at lower freezing temperatures, while cement reinforcement still works to reduce the overall creep response.

Generally, experimental investigations and measured data form a robust foundation for the development and validation of numerical modelling, enabling the underlying mechanisms and coupled processes to be interpreted in a more systematic and predictive manner.

Computational methods: Complementing the experimental investigations, several contributions in this collection employ computational methods, including theoretical, numerical and physics-based modelling to further deepen the understanding of the multiphysical and multiscale processes in clay-based material. Among those contributions Weyang et al. [28] applied geochemical modelling to evaluate the consequences of alkaline perturbation in Opalinus Clay. This work shows the effects of mineral precipitation and cation exchange on the control of risks in the in-situ repository experiments. Chen et al. [29] developed a nonlinear theoretical model for rockbolts installed in layered soft rock, which can be used to clarify the load transfer mechanism, stress and deformation characteristics, and the dependence of effective anchorage length on the properties and thickness of soft rock layers. A related theoretical and numerical study by Chen et al. [30] analysed the stress distribution in shallow-buried, biased, staggered small-clearance tunnels. Equations for surrounding rock pressure and revealing the effects of excavation sequence, burial depth, bias angle, staggered height, and tunnel spacing have been provided.

At the fracture scale, Li et al. [31] combined three-dimensional DEM simulations with mechanistic analysis to investigate hydraulic fracture penetration in laminated shale. This research highlights the dominant role of bedding-plane shear strength in controlling fracture

deflection or vertical propagation. At the repository scale, Pitz et al. [32] carried out a large-scale coupled thermo-two-phase-flow-mechanical (TH^2M) simulation of gas migration in a generic nuclear waste repository in argillaceous porous media. The properties of gas transport resulting from advection and diffusion over a large spatial domain and over long temporal durations were quantified. Further, Toprak et al. [33] investigated the coupled hydro-mechanical and gas transport response of sand/bentonite mixtures within the Gas Permeable Seal Test framework. They calibrated porosity- and strain-dependent constitutive relationships to analyse the behaviour of gas-permeable seals under sequential hydration and gas injection. de Lesquen et al. [34] presented the results of THM modelling benchmark on two full-scale in-situ heating experiments in clay host rocks. Far-field temperature and pore-pressure evolutions were generally well captured using anisotropic poro-elastic approaches, whereas near-field behaviour required more advanced models accounting for excavation-induced damage, strain-dependent permeability, and stiffness degradation. Bhukya et al. [35] present a systematic numerical investigation of coupled THM interactions in nuclear waste repositories by analysing twelve buffer–host rock combinations under consistent boundary conditions using OpenGeoSys (OGS). A key contribution of the study is the identification of thermo-hydraulic decoupling, where peak temperatures occur early, whereas buffer saturation evolves over much longer timescales controlled by host rock properties. The results show that host rock permeability, porosity, and stiffness govern hydration, stress evolution, and sealing behaviour, with distinct responses between FEBEX and MX-80 bentonites. By translating these THM insights into design-oriented guidelines for buffer selection and repository layout, including canister spacing, the study provides a comparative framework linking material-scale behaviour to repository-scale design. In addition, by integrating the electric double-layer theory with pore structure analysis, a physics-based model was proposed in [36] for soil water adsorption in saline environments. This model has been validated against Nuclear Magnetic Resonance (NMR) observation and improved the quantification of adsorbed water film thickness and adsorbed water content.

Schumacher et al. [37] advanced constitutive equation for Young's modulus in clay-rich rocks based on long-term triaxial experiments on Opalinus Clay and Passwang Marl. Their results showed that stiffness depends on both effective mean stress and true axial strain. This work was estimated to be able to better capture the variability in experimental data and reduce the uncertainties in numerical modelling. Tabkubo et al. [38] developed a simplified PFLOTRAN-based hydraulic model to investigate the infiltration behaviour of saltwater into the unsaturated Kunigel V1 bentonite. Their results show that intrinsic permeability and water retention function are key parameters that control the resaturation process. This work also highlights the importance of dry density and salinity-dependent hydraulic properties in the assessment of repository performance. Navarro et al. [39] proposed an implementation framework for numerical transport models aimed at underground hydrogen storage in porous media. Rather than using COMSOL Multiphysics only as a simulation tool, the study demonstrates its use as a flexible implementation platform for developing conceptual and numerical models.

Apart from the traditional theoretical and numerical modelling work, machine learning (ML) and data-driven techniques have recently been increasingly applied in geotechnical engineering to capture and predict the complex material behaviour. In this Topical Collection, Song et al. [40] developed a multi-fidelity neural network to describe the compression behaviour of reconstituted clay. In this work, synthetic low-fidelity data generated from empirical equations were combined with high-fidelity data obtained from oedometer tests. The results show that the model can accurately reproduce full compression curves even with sparse experimental datasets. The prediction of the time-dependent behaviour of repository drifts is often challenging, as the repeated numerical simulations are usually computationally expensive. To address this issue, Hieu et al. [41] developed a hybrid data-driven framework that combines Artificial Neural Network (ANN) and Neural Basis Expansion Analysis for Interpretable Time Series (NBEATS) within an updated Bayesian inference scheme. In this framework, ANN was used to learn the short-term drift response, while NBEATS is used to extrapolate its long-term evolution over time. The results demonstrated that this hybrid surrogate improves both the time-dependent prediction and the uncertainty quantification of the behaviour of Callovo–Oxfordian claystone. In a more application-oriented context, Sah et al. [42] assessed several tree-based machine-learning models to predict the thermal conductivity of bentonite-based backfill materials based on the experimental dataset. The gradient boosting decision tree model is found to have better performance compared to the other tested ML models, as well as the empirical equations. Further, the conducted SHapley Additive exPlanations (SAHP) analysis in this work identified the importance of the input variables such as degree of saturation, sand content, and silt content in the controlling of model predictions.

In addition, Lu et al. [43] critically reviewed experimental studies and modelling approaches for the effects of saline and alkaline environments on the hydro-mechanical behaviour of compacted bentonite. The review relates changes in water retention, hydraulic conductivity, swelling pressure and compression behaviour to mechanisms including ion exchange, diffuse-double-layer modification and mineral transformation. However, differences in bentonite type, dry density, stress history and testing method lead to partly inconsistent findings, particularly regarding shear strength. The review also highlights the need for development of experimentally validated, multiscale chemo-hydro-mechanical frameworks that incorporate the relevant chemical and microstructural processes.

The Process Understanding section brings together roughly 30 contributions that advance the mechanistic understanding of clay-based barriers and clay-rich host rocks through coupled experimental and computational work. Experimental studies span suction-controlled oedometer and Brazilian splitting tests on bentonite, thermal-ageing and dry–wet cycling effects on swelling and permeability, THMC behaviour of stabilised and contaminated clays, retention of radionuclides such as Cs(I) and Am(III), and novel testing concepts (e.g. flow-through swelling tests, the Mock-Up Josef dismantling in an URL). Computational contributions range from geochemical and DEM/THM modelling to emerging data-driven and machine-learning surrogates for parameter identification and uncertainty quantification, generally validated against or informed by the parallel experimental work. Together these studies strengthen the mechanistic basis linking micro-scale processes (pore structure, mineralogy, particle interactions) to macro-scale hydro-mechanical, thermal and chemical barrier performance.

Despite the progress made, further research is needed. The main research gaps lie in bridging multiple scales: connecting mineralogical/microstructural evolution to constitutive response and repository-scale performance remains underdeveloped, and long-term experiments under representative, repository-relevant boundary conditions are still scarce relative to short-term laboratory tests. Extrapolating laboratory observations to field- or repository-scale timeframes, and quantifying uncertainties from material heterogeneity and coupled-process interactions across scales, remain largely unresolved. AI/ML-based approaches are promising but still at an early, exploratory stage and require further validation against experimental and field data before they can reliably support long-term predictive modelling.

Material and Engineering Innovations

Material and engineering innovations focus on the modification of clay-based materials, often through the incorporation of sustainable substitutes or additives, to enhance their barrier, sealing, stabilisation and support performance. A review provided in [44] synthesises hydrothermal stabilisation strategies using industrial by-products such as fly ash, lime, steel slag, and cement kiln dust, highlighting their role in forming cementitious phases that can enhance strength while reducing plasticity, shrinkage, and swelling behaviour. This theme was further advanced by experimental studies with innovative material design. Soltani et al. [45] proposed nano-clay and ordinary Portland cement (OPC) mixtures that can remarkably improve compaction and strength and introduce the idea of nano-clay as a self-curing agent for self-compacting clay (SCC). The study reported in [46] shows that polymer-amended bentonite, particularly with Carboxymethyl Cellulose (CMC), can significantly reduce hydraulic conductivity and improve the performance of bentonite in vertical cutoff walls for containing heavy-metal-contaminated groundwater. In addition, the study identified a negative correlation between the free swelling index and hydraulic conductivity. Luo et al. [47] demonstrated that active carbon- or zeolite-modified soil-bentonite barriers significantly enhance the ability of Cr(VI) adsorption and retardation. Particularly, active carbon-modified barriers provide the best long-term protection. The study in [48] indicates that acid activation can transform bentonite into a more porous and selective sorbent for radionuclide removal. Nguyen et al. [49] developed a composite geomaterial from river dredged soil, Ground Granulated Blast Furnace Slag (GGBFS), and waste fishing net, where an optimal GGBFS content improves strength, and the fishing net enhances ductility. Xu et al. [50] proposed a stone chip-bentonite liner system for landfills, achieving low permeability with a practical predictive model for design. Furthermore, Zhang et al. [51] developed a local primary support method for tunnels based on excavation damage zone (EDZ) zoning results. Combining model tests with Finite-Discrete Element Method (FDEM) analysis, a refined support strategy was proposed, in which different support measures were assigned according to the disturbance degree of the surrounding rock. The results showed that this zoned support concept could effectively restrain crack propagation and deformation, increase the ultimate bearing capacity by 38.3%, and enhance construction economy.

The collected contributions on material and engineering innovations demonstrate promising improved strength, swelling behaviour, and hydraulic performance

of clay-based material. The studies on polymer-amended bentonite, bentonite-based composites, and engineered seals show that material innovations can significantly improve the integrity of the complete barrier system [46, 50]. However, the performance of the modified material must be assessed in relation to its intended function and its interactions with the adjacent barriers. For example, a material formulation that reduces liquid permeability, may not meet the different requirements of a gas-permeable seal. Moreover, improvements and performance observed in laboratory tests do not guarantee long-term stability especially under lasting changing in groundwater chemistry, mechanical loading, and repeated wetting–drying conditions. Therefore, future work should focus on the investigation of durability and chemical compatibility of modified materials, and their interactions with adjacent barriers, and the resulting effects on system-level transport and containment through longer-term and larger-scale tests combined with numerical modelling.

Clay research in EURAD

EURAD (European Joint Programme on Radioactive Waste Management) is a European collaboration for safe radioactive waste management (RWM). It implements a joint Strategic Programme of research and knowledge management activities at the European level, integrating EU Member State efforts to generate and preserve knowledge for safe, sustainable and publicly acceptable radioactive waste management across Europe [52]. EURAD supports national programmes by complementing them through shared Research, Development and Demonstration efforts and improved access to existing knowledge for end users. It covers the principal scientific and technical areas relevant for the implementation of waste management solutions, including the programme implementation, radioactive waste characterisation, engineered barrier performance, geoscience, facility design, siting and licensing, and safety assessment.

In the EURAD first implementation phase (2019 – 2024), several scientific and technical research activities were conducted on clay-related topics, including gas transport mechanisms [53, 32], radionuclide retention and migration [54], and thermo-hydro-mechanical coupled behaviour in clay buffers [55, 56, 34, 9]. In this collection, the work by [34] directly contributed to the HITEC work package in EURAD by comparing THM simulations of heating experiments in clay formations. Other collection papers also address related questions pursued by EURAD work packages. In particular, the study of radionuclide retention by [23], is closely related to the objectives of FUTURE, whereas the repository-scale gas-transport studies [32, 33] address key questions investigated within the GAS work package.

In the current following project EURAD-2 [1], clay research remains a central focus, particularly for engineered barrier systems (EBS) and clay host rocks. Among the identified EURAD-2 work packages, ANCHORS (Hydraulic Mechanical Chemical evolution of bentonite for barriers optimisation) focuses on the hydro-chemo-mechanical (HCM) evolution and optimisation of bentonite barriers. HERMES (High fidelity numerical simulations of strongly coupled processes for repository systems and design optimisation) addresses high-fidelity modelling of strongly coupled processes for repository analysis and design optimisation, in close connection with on going in-situ experiments at Mont Terri, such as CD-A (Influence of Humidity on the Cyclic and Long-Term Deformation Behavior of the Opalinus Clay) experiments, where measurement data are used for model calibration and validation [57]. Current activities in EURAD-2 also include computational efficiency, software development [58, 39] and benchmarking platforms (Model-Hub) [59].
The collection also provides results related to ongoing EURAD-2 priorities. The investigations of bentonite damage, thermal ageing, saltwater infiltration and chemical effects [13, 15, 38, 43] are closely aligned with ANCHORS priorities regarding hydro-chemo-mechanical evolution and heterogeneity. The coupled buffer–host-rock simulations [35] and data-driven modelling studies [40, 41, 42] address methodological questions pertinent to HERMES, particularly the integration of process models, efficient computation and uncertainty analysis.

Clay research in DECOVALEX

DECOVALEX (DEvelopment of COupled models and their VALidation against EXperiments) is an international collaborative project focusing on modelling and understanding coupled processes in geological systems, particularly in relation to the disposal of radioactive waste [60, 61, 62]. DECOVALEX's primary goal is to improve our understanding of, and ability to predict, how gas- and heat-generating radioactive waste (such as spent nuclear fuel) interacts with the surrounding host rock. Host rocks used for deep geological disposal include clay, salt and crystalline rocks. There is a long tradition of research on thermo-hydro-mechanical-chemical (THMC) processes in clay rocks.

In the previous DECOVALEX 2023 phase, the focus of clay research was on fundamental studies of gas-

[1] https://www.ejp-eurad.eu/

and thermally-induced damage, pathway dilation, and the self-sealing properties of clay materials [63, 64], behaviour of bentonite buffer under saltwater attack The FE (full emplacement) experiment at the Mont Terri underground research laboratory in Switzerland served as an ideal test case for validating coupled process models based on in situ data [65, 66, 67].
Within the present collection, the gas-transport studies at repository and seal scales [32, 33] address questions related to Task B, which examined numerical descriptions of gas flow in clay-based repository systems. In Task C of DECOVALEX 2023, the experimental data from the Monte Terri Full-Scale Emplacement (FE) experiment was used to validate the THM models. In this context, the heating benchmark [34] and comparative buffer–host-rock study [35] likewise speak to the modelling and upscaling challenges illustrated by Task C, although they investigate different experiments and configurations.

Three tasks in the current DECOVALEX 2027 phase[2] are dedicated to clay research. The HyMar teams are developing new constitutive models to predict the long-term deformation and damage behaviour of argillaceous rocks. Meanwhile, Sandwich and BaSISS are addressing sealing systems based on clayey materials for use in the Swiss and French repository concepts involving Opalinus and Callovo-Oxfordian clay, respectively. Gas migration into clay rock and engineered barrier systems [68, 69], as well as barrier integrity [70], are of most concern for safety cases. Alongside process research, simulation workflows, digitalisation and machine learning methods are becoming increasingly important for unifying and accelerating modelling of complex multi-physics tasks related to safety analyses [59].

Relating to the contributions in the collection, HyMAR's focus on long-term constitutive behaviour is relevant to the stress- and strain-dependent stiffness formulation examined in [37]. The sealing-system questions pursued in Sandwich and BaSiSS also connect with the hydration and gas-transport behaviour of bentonite–sand mixtures studied in [33], although the respective seal designs and boundary conditions differ.

Lessons learned and outlook

The contributions in this Topical Collection highlight the relevance of clay-based materials as well as clay-rich soils and rocks in both geological disposal and wider geoenvironmental applications due to the key features such as low permeability, swelling capacity and retention behaviour.

The research presented in this collection emphasises that understanding the complex long-term behaviour of these materials demands a multi-scale, multi-property framework, given that the relevant engineering properties — swelling, sealing, retention, strength, and long-term stability — are governed by the intricate interplay of coupled hydraulic, mechanical, thermal, and chemical processes across multiple scales. Moreover, microstructure plays a central role in affecting macroscopic behaviour, as changes in pore structure, mineralogy, fabric, and interparticle bonding directly influence permeability, crack development, swelling, and retention performance. Furthermore, uncertainties arising from material heterogeneity, coupled-process interactions, scale effects, and the challenge of extrapolating laboratory observations to long-term field or repository conditions remain relatively unexplored.

From the engineering perspective, innovation is continuously taking place not only through new materials but also through improved barrier concepts, support strategies, and stabilisation methods. Modified bentonites, blended barrier materials, and alternative sealing concepts show clear promise, but their long-term behaviour under realistic coupled conditions remains a key issue.

The on-going EURAD and DECOVALEX research initiatives show that international, multi-partner programmes have become the main vehicle for advancing coupled THMC understanding of clay-based barriers, moving beyond single-study contributions toward coordinated, repository-relevant research.

Looking ahead, future work should move further toward integrated and multiscale approaches. More attention is needed to connect mineralogical and microstructural evolution with constitutive response and large-scale system performance. Furthermore, long-term experiments under representative boundary conditions complemented by laboratory tests are needed. Development of numerical modelling remains essential for describing and understanding multiphysical and multiscale processes, linking laboratory observations to field-scale behaviour, and improving long-term predictive capability. The rapid development of computational methods based on AI, machine learning, and data-driven approaches offers new opportunities for parameter inference, uncertainty quantification and development of computationally efficient surrogate modelling for multi-scale and multi-physic processes in clay-based materials. However, the performance of such approaches depends strongly on the quality and representativeness of the available data. They should therefore be evaluated alongside process-

[2] https://decovalex.org/

based models in shared intercomparison exercises, using independent laboratory and in situ datasets. In particular, the conservation-law and physical consistency must be assessed. In the context of geological disposal, the process prediction and transferable across clay materials, boundary conditions and scales remain challenge. Because available observations span only a small fraction of the timescales, relevant to repository performance, long-term extrapolation remains uncertain. Data-driven predictions should therefore be supported by mechanistic models and tested against experimental evidence wherever possible.

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