3.1.3 Cemented LL-ILW, Domain Insight

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Overview

The cementation of radioactive wastes is a common conditioning technique. It is a largely simple and inexpensive process that is attractive due to the ready availability of the material. The cement is fluid when initially cast and can accommodate a range of waste types, including both solids and liquids. In its hardened state, cement is a hard-wearing solid material that exhibits high compressive strength and low permeability. These properties contribute to its important role in the safe storage and disposal of radioactive waste. The functional requirements of the cemented wasteforms in the storage or disposal environment include: radionuclide confinement - keeping the radionuclides out of the accessible environment; structural integrity – which minimizes the leaching of radionuclides and maintains structural integrity of the storage/disposal infrastructure; and time – the performance characteristics should extend for a time period that reflects the waste management option as determined by the safety assessment.

Keywords

Long-Lived Intermediate Level Waste, LL-ILW, cement, stabilization, retention, radionuclide mobility, sorption, alkaline environments, containment, durability,

Key Acronyms

long-lived intermediate level waste (LL-ILW)

1. Typical overall goals and activities in the domain of Cemented LL-ILW

This section provides the overall goal for this domain, extracted from the EURAD Roadmap goals breakdown structure (GBS). This is supplemented by typical activities, according to phase of implementation, needed to achieve the domain goal. Activities are generic and are common to most geological disposal programmes.

Domain Goal	
3.1.3 Confirm wasteform compositions, properties and behaviour under storage and disposal conditions, including impact on the disposal environment; Cemented long-lived intermediate level waste (Cemented LL-ILW)	
Domain Activities	
Phase 1: Programme Initiation	Conduct initial Cemented LL-ILW inventory analysis, including projections of future LL-ILW generation (incl. waste characterization). Characterization of the different cement matrices (CEM I, CEM V, etc.) used for waste stabilization considering the current best practices in this area and future advances to provide safe long-term interim storage sites.
Phase 2: Deep geological repository (DGR).Site Identification	Update inventory analyses and future waste projections. Evaluate international available information on wasteforms for optimized adaption to national waste inventory. Conduct preliminary waste investigations (radioactive and physico-chemical), for example elements, besides radionuclides, that might interact with the specific DGR site environment (organics, toxic elements, etc.). Investigation of space requirements and disposal options, considering impacts of any delays in the disposal programme.
Phase 3: DGR Site Characterisation	Perform (or use available) studies on Cemented LL-ILW interactions and iterate with engineered barrier systems (EBS) design, waste inventory knowledge and disposal space requirement evaluations; verify interim storage impact.
Phase 4: DGR Construction	Confirmation of models for Cemented LL-ILW packages performance under disposal and EBS conditions to support DGR license application; design and optimization of transport options to the site and internal movements within the DGR.
Phase 5: DGR Operation and Closure	Confirm and preserve documentation for emplaced Cemented LL-ILW inventory for license application for operation/closure, including actual Cemented LL-ILW inventory per container, overall details of the cement matrix used and any other component with might be relevant for ensuring waste stability (organic, metallic components, etc.).

2. Contribution to generic safety functions and implementation goals

This section describes how Cemented LL-ILW and its associated information, data, and knowledge contribute to high level disposal system requirements using EURAD Roadmap Generic Safety and Implementation Goals (see, Domain 7.1.1 Safety Requirements). It further illustrates, in a generic way, how such safety functions and implementation goals are fulfilled. It is recognised that the various national disposal programmes adopt different approaches to how disposal system requirements are specified and organised (IAEA, 2011). Each programme must develop its own requirements, to suit national boundary conditions (national regulations, different spent fuel types, different packaging concept options, different host rock environment, etc.). The generic safety functions and implementation goals developed by EURAD and used below are therefore a guide to programmes on the broad types of requirements that are considered, and are not specific or derived from one programme, or for one specific disposal concept.

2.1 Features, characteristics, or properties of Cemented LL-ILW that contribute to achieving storage safety as well as long-term safety of the disposal system

2.1.1 Primary goal - for safety of many decades of wet and dry storage

EXTERNAL STABILITY: Compressive Strength. The compressive strength of cement-based LL-ILW is one of its key mechanical properties. High compressive strength grants superior long term chemical stability of the cemented waste while ensuring that it is robust enough for handling and transportation operations and that it can endure storage and repository stacking pressures. The compressive strength of cement is principally controlled by type of cement, the water/cement ratio, the cement/waste ratio, the type of waste, and the curing time (Lokken, 1978).

INTERNAL STABILITY: Chemical Tolerance. Cements are tolerant to a wide range of chemical constituents. Accordingly, they are suitable for immobilisation of solid, slurry and liquid wastes. Importantly, the internal chemistry and microstructure of cement-based materials can be controlled through the inclusion of reactive admixtures and by adjusting curing temperatures and water/cement ratios. This means that cement-based material properties can be chosen that optimize the immobilization of a specific waste type (IAEA, 1993).

INTERNAL STABILITY: Low Voidage. Void spaces decrease the strength of the waste package, making it more susceptible to damage from mechanical impact. Further, their presence can result in locally enhanced corrosion of the package. As cements are free-flowing viscous liquids when freshly mixed, they will fill voids in the waste package. The reduction of voids in the waste package improves its structural integrity (Glasser, 2011).

INTERNAL STABILITY: Radiation Tolerance. Cement-based materials can endure substantial doses of radiation (of the order of 10^8 Gy) without significant reduction in the mechanical strength of the cement compound and their morphology. This is a key advantage of cementitious materials as ionising radiation from the radioactive components of the waste as well as surrounding waste packages may contribute to the chemical breakdown of materials through radiolysis (IAEA, 1993, Craeye et al., 2015).

CONTAINMENT: Low Permeability. In their hardened state, cement-based materials typically exhibit low permeability to water, specifically for low Water/Cement ratios. This limits the ingress of chemically aggressive water into the waste package, lowering the degradation rate of the cement. Permeability values of 10^{-13} m/s can be achieved in conventional cements. The permeability is dependent on factors such as w/c, additives or water saturation. In principle the water permeability of a mortar is lower than that of a concrete (Glasser, 2011).

2.1.2 Primary goal - relied upon for long-term repository safety

RETENTIONS AND RETARDATION: Cement Chemistry. Cement-based materials will evolve following contact with groundwater, buffering porewaters to high pH levels and having the capacity to maintain these conditions for an extended period of time. High pH values can slow corrosion rates of metallic materials and limit the solubilities of some radionuclides (IAEA, 1983).

RETENTIONS AND RETARDATION: Cement Chemistry. The cement hydrates (hydration products) favour sorption and substitution of cationic, anionic and neutral radioactive waste species into cement solids (Ochs et al., 2015). The inclusion of additives such as clays can act as adsorbents for species such as Cs which may otherwise demonstrate limited adsorption on cementitious phases (Evans, 2008). In contrast certain (mostly organic) compounds in the waste (for example, cellulose) or additives in the cement (for example, superplasticizers) can negatively impact sorption of radionuclides on cement (IAEA, 2013).

CEMENTED LL-ILW EXTERNAL STABILITY: Limiting Microbial Activity. Microbial activity can play a significant role in the degradation of cement-based materials and subsequent structural deterioration. Typically, degradation results from mineral or organic acids produced by microbial metabolism that can dissolve the cement hydrates. However, the high pH environment expected following contact of groundwaters with cement-based materials will limit microbial activity which is typically inhibited above pH 10 (IAEA, 1993).

2.1.3 Illustrative requirements of critical information for both extended storage and long-term disposal safety

Critical radiological information for cemented LL-ILW includes knowledge of:

- Total activity
- Radionuclide composition
- Surface dose rate
- Surface contamination
- Thermal power
- Radiation stability
- Fissile content

This ensures the cemented waste complies with the licensing limit of the storage or disposal facility, that it meets transport regulations, helps define handling conditions, and prevents inadvertent criticality.

The following are illustrative critical physical and chemical information requirements for cemented long lived intermediate level waste:

- Mass and weight
- Structural and dimensional stability
- Permeability and porosity
- Density
- Voidage
- Mechanical Strength/ Load Resistance
- Impact resistance
- Chemical stability (leachability)
- Chemical composition
- Corrosivity
- Explosiveness
- Gas generation
- Toxicity
- Fire resistance

This information ensures that the chemical and physical integrity of the cemented waste during handling, transportation, storage, and disposal is maintained.

2.1.4 Illustrative requirements of critical information for storage

The most frequently used cement composition for waste conditioning is ordinary Portland cement (OPC). When cured, its most important phase is the calcium-silicate-hydrate (CSH), although other phases such as ettringite are present in lower quantities. The pH of a normal OPC system varies between 13 and 14. When contacted with (ground-)water, it starts to degrade due to leaching. This can be described as a four stage degradation process in which the end member is calcite (for a detailed explanation the reader is referred to Taylor (1997)). This degradation of course can impact its goals as described in (§2.1.1-2.1.3). To ensure the correct cement formulation, it is necessary to know the container material as well as the waste contents. The formulation is selected to prevent a negative impact of the degradation processes on the safety requirements and handling of the waste containers during storage (and later). Examples of degradation processes include chemical reactions between the wasteform and the inner surface of the waste container and expansive phenomena resulting from corrosion of the waste components which could induce stress on the waste container itself.

The impact of extended storage periods on the integrity of the cement wasteform must be assessed by using the models available. This will include assessment of the hydration of the cement encapsulant. Hydration results in changes to the microstructure of the cement-based materials that can continue for several years after casting. This process can affect the immobilization properties of the resulting wasteform and must be considered in understanding its long-term performance.

Information about the effect of atmospheric corrosion processes, e.g., carbonation, on the selected cement type, is also needed. In the case of carbonation, the carbon dioxide may be present in the atmosphere, it may be formed from the degradation of organic materials in the waste, or it may be naturally present in the porewater of the host-rocks. Again, this means that knowledge of the waste contents is critical. As carbonation reduces the alkalinity of the cementitious environments, this can impact the expected behaviour of the radionuclides. The carbonation rate is limited by diffusion through the cementitious matrix which, being related to the porosity of the solid, is ultimately controlled by the formulation of the cement-based materials.

2.1.5 Illustrative requirements of critical information for long term disposal safety

The availability of robust geochemical models that can predict the geochemical evolution of the cementitious material as well as their interactions with the environment (e.g., the atmosphere, groundwater, clay or other geological barriers). The models should be designed to capture both equilibrium and kinetic processes. The results provide key information about pore water and mineral compositions, porosity distribution and the distribution of radionuclides between solution and solid phases.

2.2 Features, characteristics, or properties of Cemented LL-ILW that contribute to achieving long-term interim storage stability and feasible implementation of geological disposal

PRACTICABILITY – Cement-based materials are simple to use, are abundant, are low-cost and can be processed at ambient temperature.

FLEXIBILITY - Encapsulation with cementitious mixes can be applied to a wide range of waste constituents and the mix composition can be optimized easily to suit specific waste streams.

OPERATIONAL SAFETY - The flow properties of some cement-based materials and the time for which they are reliably maintained means that they can be pumped over long distances. This ensures that it is possible to minimize contact between operatives and radioactive components during the production of the cemented LL-ILW reducing potential health and safety hazards.

OPERATIONAL SAFETY – Cement-based materials are the most common construction material in the world with a long history of use. For waste management practices, many cementation processes have achieved a high degree of acceptance and are now regarded as technically mature. The study of natural cement analogues (e.g., Maqarin, Jordan), the experience of the civil engineering of concrete with codified practices and specification, combined with results from laboratory and modelling studies indicate that the cemented waste can reliably meet expectations for its performance requirements.

3. International examples of Cemented LL-ILW

As mentioned before, Portland cement is the most common type of cement and is typically categorized as ordinary (CEM I), modified (CEM II), high-early-strength (CEM III), low-heat (CEM IV), and sulfate-resistant (CEM V). The specific formulations chosen by each country will vary based on the characteristics, features and design requirements of the storage and disposal concepts. For example, in the UK, cement-based materials for the conditioning of radioactive waste are typically based on formulations containing blast furnace slag (BFS) or pulverized fuel ash (PFA), mixed with ordinary Portland cement (OPC). In France, CEM I, CEM III, and CEM V are considered for conditioning of radioactive waste.

Other examples of cements used include:

Calcium sulphoaluminate (CSA) cement. CSA has been used in China to encapsulate borate-contaminated ion-exchange resins and evaporator concentrates arising from pressurized water reactor power plants, since borate inhibits the curing of OPC cements.

Geopolymers, including SIAL®. These are made by mixing sodium silicate (hydrate) with metakaolin. Used in Slovakia to treat radioactive sludges and sludge/resin mixtures from four nuclear power stations.

Chemically-bonded phosphate ceramics (CBPCs). CBPCs are used in South Africa for the immobilization of wastes containing radionuclides such as iodine isotopes and ^{14}C.

Specific examples of cemented LL-ILW include packages of cemented hulls and end caps from Orano/La Hague (CEC) (COG-040) in France, and RECOND-SCK-LOW-400 in Belgium, a reconditioned waste in which corroded 220 L drums were placed into 400 L drums with the annular space filled with cement grout.

4. Critical background information

The suitability of cemented LL-ILW for use in geological disposal depends primarily on the physical and chemical nature of the waste and the acceptance criteria for the storage and disposal facilities to which the waste will be consigned. Some of the key factors to consider include (IAEA, 2017):

Waste Loading: The wasteform should be able to accommodate a significant amount of waste (typically 25–45 weight % in homogeneous cemented wasteform). This minimizes the total volume of waste and thus the space needed for transport, storage, and disposal.

Waste Chemistry: The cemented LL-ILW will need to accommodate a mixture of radioactive and chemical constituents. Knowledge of the chemistry of the waste is needed to ensure that the appropriate cement formulations are used to minimize the formation of secondary phases that can compromise the durability of the waste package.

Cement Durability: The cemented LL-ILW should have a low rate of dissolution when in contact with water to minimize the release of radioactive and chemical constituents. Knowledge of these rates is critical to ensure that waste acceptance criteria are met.

Radiation stability: Knowledge of the tolerance of the cemented LL-ILW to radiation is critical information for implementing geological disposal. A high tolerance to radiation effects is necessary to preserve the physical integrity of the waste.

Natural Analogues: As it is not possible to capture the behaviour of the waste packages in the laboratory over the necessary timescales (10^3 – 10^6 years), the existence of natural analogues can provide important supporting evidence for the long-term behaviour of cemented waste.

Environmental Compatibility: The cemented LL-ILW waste must be compatible with the near-field environment of the geological disposal repository. As it provides the physical and chemical conditions responsible for maintaining wasteform integrity over extended periods, knowledge of how it will affect the cementitious materials is integral.

Waste acceptance criteria specifications are on the authority of national regulators. Although several international organizations, like IAEA have issued recommendations, the differences are still significance. In Finland, for instance, waste acceptance criteria for waste and waste packages have to be derived from the safety analysis report and from the safety case. However, the Final Safety Analysis Report shall shall include a description of each waste package category to be disposed of; such descriptions shall include at least:

- waste type and conditioning specifications
- surface dose rate
- upper bounds for the activities of the most significant radionuclides
- average values of other properties relevant to safety, such as:
    - mechanical strength,
    - chemical durability,
    - radionuclide release characteristics (leaching or diffusion rate),
    - free liquid content,
    - flammability,
    - swelling capacity,
    - gas generation potential,
    - concentrations of substances which may degenerate the waste package or decrease sorption in surrounding media.

4.1 Integrated information, data or knowledge (from other domains) that impacts understanding of Cemented LL-ILW

Waste package performance (see Domain 3.2.2 LL-ILW containers). Selecting the container material is a key part of developing an appropriate waste package design, and many different factors, including the interactions between the container and the wasteform, need to be considered.

Improved mix formulations (see Domain 2.3.2 Optimisation). Ongoing research into cement-based material performance will lead to the development of higher performance materials that will improve the costs and environmental impact of the engineered barrier system.

Development and testing of cemented wasteforms (see Domain 5.1.4 Design qualification) will aid the demonstration that components of the EBS will perform their allocated safety functions.

Geochemical modelling of the behaviour of the cemented LL-ILW provides insight into the evolution of the wasteform (see Domain 7.3.1 Performance assessment and system models).

5. Maturity of knowledge and technology

This section provides an indication of the relative maturity of information, data, and knowledge for disposal of Cemented LL-ILW. It includes the latest developments for the most promising advances, including innovations at lower levels of technical maturity where ongoing RD&D and industrialization activities continue.

5.1 Advancement of safety case

Given that modern Portland cements have been in use for 150 years, the understanding of cement behaviour is a well-established discipline with a good consensus regarding the chemical processes that occur within cementitious materials. Accordingly, a considerable body of information is available on cemented LL-ILW, and the field is considered mature, although novel approaches continue to be devised (Faucon et al., 1998).

5.2 Optimisation challenges and innovations

Cement-waste interactions. Experience with the cementation of wastes has shown that some waste constituents can interact with the conventionally used ordinary Portland cement, retarding hydration reactions, and altering the properties of the solid. For example, complexing agents such as EDTA, can interfere with Ca availability, organic ion exchangers can take up water under high pH conditions and expand in the wasteform, and zinc salts and borates can inhibit hydration (Ochs et al. 2022, Young et al. 1976, Navarro-Blasco et al. 2013, Bensted et al. 1991). To combat these limitations, alternative formulations have been developed to improve the matrix binding capacity for selected radionuclides and to reduce the reactions between waste constituents and the cement hydrates. The four alternative cementitious systems of most interest are calcium aluminate cements, calcium sulphoaluminate cements, magnesium phosphate cements, and geopolymers (Gatner 2004).

New cement formulation challenges. While these alternative cementitious systems offer some benefits over OPC, there are still challenges associated with their use and research is ongoing. For example, alkali activated cements (AAC; which fall under the broad category of geopolymers) have been proposed as a more durable material than traditional OPC (Shi et al. 2015). However, there is still a need to understand the impacts of radioactive decay on their molecular-, and micro–, structure (Zhu et al., 2022). In addition, AACs experience considerably greater shrinkage than OPCs, resulting in cracking. Various methods have been used to control this, including the use of chemical admixtures and mineral additives (Zang et al. 2022).

Availability of materials. OPC has been the mainstay of the cement industry since the mid-1800s century while its use in the encapsulation of radioactive waste has taken place since the 1980s. OPC has evolved, and its production has been refined to become a highly developed and extremely energy efficient process. However, this progress means that modern cementitious materials are noticeably different from their counterparts of 40 years ago. As an example, OPC powders produced today are typically much finer (to increase reactivity) than those produced previously. This increased reactivity allows for a reduced setting time which is advantageous for the construction industry. However, a change in setting time is a challenge for the production of nuclear wasteforms, which requires a carefully controlled initial set to retain a sufficient fluidity to flow through the encapsulation systems. Accordingly, the need for the nuclear industry to retain a standard of thoroughly characterized cementitious material may be in tension with developments in a cement industry that is primarily driven by construction needs. Given this, security of cement powder supplies is currently a concern facing the nuclear industry (Kearney et al., 2022).

5.3 Past and ongoing (RD&D) EURAD projects

Past (RD&D) Projects:

- CEBAMA: Cement-based materials, properties, evolution, barrier functions
  - https://cordis.europa.eu/project/id/662147
- ECOCLAY Effects of cement on clay barrier performance
  - https://cordis.europa.eu/project/id/FIKW-CT-2000-00028

- MIND Development of the safety case knowledge base about the influence of microbial processes on geological disposal of radioactive wastes
    - https://cordis.europa.eu/project/id/661880
- ESDRED: Engineering Studies and Demonstrations of Repository Designs
    - https://cordis.europa.eu/project/id/508851

Ongoing (RD&D) Projects:

- *EURAD Work Package CORI: Cement-organic-radionuclide interactions*
- *EURAD Work Package ACED: Assessment of chemical evolution of ILW and HLW disposal cells*
- *EURAD Work Package MAGICS: Chemo-Mechanical AGIng of Cementitious materials*
- *PREDIS: Pre-disposal management of radioactive waste*

5.4 Lessons learnt

Extensive research work has been performed in recent decades on cement-based barriers for nuclear waste disposal. Different approaches to interrogate the performance of these materials have been conducted and the results generated have led to a considerable improvement in knowledge of the processes affecting the stability of cementitious materials under repository conditions.

In the framework of CEBAMA, experimental and modelling data were generated, helping to improve understanding of the evolution of cementitious materials in radioactive waste management applications (Duro et al. 2020). The evolution of the cement composition and the resulting changes in the chemical and physical properties were related to the alteration of radionuclide transport properties. The results obtained in this project have helped to reducing key uncertainties for Performance and Safety Assessment of radioactive waste management. Comparisons between the performance of traditional OPC mixes and newly developed “low-pH” cement blends showed the benefit of the latter materials in terms of lowering the pH and the extent of alteration of the contacting clays. One of the main outcomes of CEBAMA was the reduction of quantitative uncertainties, as specific data on the strength of the interaction of radionuclides onto different cementitious phases were generated. Further, some of the achievements of the CEBAMA project for future Performance Assessment exercises were the need to revise element analogies, reducing unnecessary conservativism in solute and radionuclide transport calculations, and understanding the extent of alteration of cement-related materials under different groundwater compositions.

In the case of Ecoclay II, the main aim of the project was to assess the effect of an alkaline plume on the chemical and mineralogical properties of clay and on the migration of the radionuclides released from a cementitious repository into clay (Ecoclay, 2005). To identify and assess the extent of the phenomena and processes which could influence the clay chemistry and the radionuclides migration, percolation experiments were performed on Boom Clay cores with two different types of synthetic cement water: young cement water and evolved cement water. Joint analysis of all aspects concerning the development and impact of an alkaline plume led to the conclusion that in case of clay rock (not fractured) the extent of the effects of the alkaline plume is limited. Since repository concepts in clay rocks normally rely on a rather thick clay layer (compared with the extent of the alkaline plume), the effects could be neglected in a Performance Assessment and strong arguments are now available to support this approach. In the case of fractured rock, the extent and dynamics of the alkaline plume is more uncertain, although the net effect is more likely to be beneficial than detrimental for the global safety of the system. The studies performed on the alkaline plume probed indicated that it did not jeopardize the integrity and functionality of the compacted bentonite barrier. The propagation of a high pH plume in the buffer seemed to be possible; however, the low diffusion coefficient and relatively high reactivity of the mineral system in the bentonite suggested that fast propagation is highly unlikely.

The MIND project was one of the first projects to investigate the impact of microbial processes on organic materials in cementitious wasteforms and their behaviour on the technical feasibility and long-term performance of repository components including clay and canister materials (MIND, 2019). The findings of the MIND project contributed to increased knowledge of microbial processes in repository environments and pointed out the necessity of considering these processes when setting requirements for engineered barriers such as buffer and backfill. This has resulted in significant refinements of safety case models.

The overall objective of the Integrated Project ESDRED was to demonstrate the technical feasibility, at an industrial scale, of activities carried out to construct, operate, and close a deep geological repository, while complying with requirements for long-term safely, irretrievability, and monitoring (ESDRED, 2009). One of the focusses of this project was buffer construction, specifically the manufacturing and construction of an engineering barrier system for horizontal disposal drifts. For the construction of the buffer/backfill around emplaced high level waste (HLW) canisters, ESDRED developed a number of off-the-shelf solutions that can be applied when the need arises.

An example of incompatibility of a cementitious conditioning matrix with a wasteform has been learned in Belgium. The wasteform consisted of liquid effluents of a nuclear power plant. To reduce the volume of this waste, it was treated in evaporators. The waste was further stabilized at a pH >11 due to the addition of NaOH. After the treatment the resulting concentrates were cemented using a CEM I and siliceous aggregates (sand and gravel). The cemented concentrates were poured in a 400 liter metallic drum. During routine inspections (in 2013) a gel-like material was observed on several waste packages that had been produced in the paste. This was later attributed to the alkali-silica reaction (ASR) and an alternative treatment method had to be developed for the waste. To be able to dispose of the already produced waste packages, a R&D-programme has been launched (and is still running) since the observation in order to investigate the root cause, follow-up other waste packages that had been produced with the same production method, and define mitigation measures to be able to dispose the affected waste packages. This shows the need for preliminary studies regarding the compatibility of the wasteform and the cementitious matrix.

6. Uncertainties

Given its history of use in radioactive waste management, the properties and behaviour of cement-based materials are well known. Nonetheless uncertainties and knowledge gaps remain, including (IAEA, 2013):

Cement-waste interactions. Better understanding is needed of the physical and chemical effects of waste ions on the cementitious structure during solidification, the formation of exotic hydration products, the speciation of waste ions and the resistance of the constituent solid phases to degradation. These interactions must be understood due to the sensitivity of immobilization capacity to changes in the waste matrix chemistry.

Leach test standardization. Leach tests are necessary to verify the durability of the wasteforms. Several leaching methods have been developed but none have been subject to sufficient critical scrutiny to be considered as standard. One challenge is selecting the appropriate variables to base the tests on which can be problematic if no disposal site has been defined and thus hydrogeological conditions are not known.

Timescales. The requirements for the long-term isolation of radioactive waste present a unique problem. Testing and the extrapolation of short-term test data to centuries (or longer) is very complex and reliable data on the kinetics of all but the simplest processes are missing.

7. Guidance, Training, Communities of Practice and Capabilities

This section provides links to resources, organisations and networks that can help connect people with people, focussed on the domain of Cemented LL-ILW.

Guidance
https://www.rilem.net/publications-500175
Training
https://thecementinstitute.com/ https://www.rilem.net/events-610354 https://www.iccc-online.org/start/
Active communities of practice and networks
https://www.rilem.net/
Capabilities (Competences and infrastructure)
https://www.empa.ch/web/s308/cement-chemistry-and-thermodynamics https://www.ietcc.csic.es/en/group/cement-chemistry/ https://www.psi.ch/en/les/groups https://www.ine.kit.edu/english/344.php

8. Further reading, external Links and references

8.1 Further Reading

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8.2 External Links

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https://nagra.ch/downloads/

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