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Review

Cement-based solidification of nuclear waste: Mechanisms, formulations and regulatory considerations

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ABSTRACT

This review paper provides a comprehensive analysis of cement-based solidification and immobilisation of nuclear waste. It covers various aspects including mechanisms, formulations, testing and regulatory considerations. The paper begins by emphasizing the importance of nuclear waste management and the associated challenges. It explores the mechanisms and principles in cement-based solidification, with a particular focus on the interaction between cement and nuclear waste components. Different formulation considerations are discussed, encompassing factors such as cement types, the role of additives and modifiers. The review paper also examines testing and characterisation methods used to assess the physical, chemical and mechanical properties of solidified waste forms. Then the paper addresses the regulatory considerations and compliance requirements for cement-based solidification. The paper concludes by critically elaborating on the current challenges, emerging trends and future research needs in the field. Overall, this review paper offers a comprehensive overview of cement-based solidification, providing valuable insights for researchers, practitioners and regulatory bodies involved in nuclear waste management.

1. Introduction

Nuclear waste is a by-product of various nuclear activities, such as nuclear power generation, medical treatment and nuclear weapons production (Reed et al., 2018). It consists of materials that have become radioactive during nuclear reactions, posing potential risks to human health and the environment (Apostolidis et al., 2017). Therefore, the safe management of nuclear waste is essential to mitigate these risks and ensure long-term protection. The categorization of nuclear waste is based on its level of radioactivity and associated hazard. High-level waste (HLW) contains highly radioactive isotopes and demands rigorous isolation and management practices to prevent exposure. Intermediate-level waste (ILW) possesses lower levels of radioactivity but still requires proper containment and disposal measures. Low-level waste (LLW) has minimal radioactivity and can be managed with less stringent controls (Chouhan, 2018). Safe management of nuclear waste is crucial to mitigate risks, with categorization based on radioactivity levels determining necessary containment measures.

Managing nuclear waste entails several crucial considerations. Waste characterisation involves analysing the physical, chemical and radiological properties of the waste to determine appropriate handling and treatment strategies. Packaging and containment systems are designed to prevent the release of radioactive materials and ensure safe storage (Apostolidis et al., 2017). Storage facilities, such as interim storage facilities and spent fuel pools, are constructed to provide long-term safety and security (European Commission, 2016). Disposal methods, such as deep geological repositories, aim to isolate the waste from the biosphere for extended periods, utilizing multiple barriers to prevent the release of radioactive materials (USNRC, 2020).

The need for solidification of nuclear waste arises from its inherent characteristics and potential hazards. Fig. 1 depicts direct positive impact and advantage of nuclear waste solidification, stabilisation and immobilisation into solid matrix. Nuclear waste is a by-product of various nuclear activities, such as power generation and weapons production and it contains radioactive materials that pose significant risks to human health and the environment. Solidification serves as a crucial

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step in the management of nuclear waste by transforming it into a stable and immobilised form. This process involves incorporating the waste into a solid matrix, such as cement, ceramics, or glass, to prevent the release of radioactive materials and ensure long-term containment. There are several reasons why solidification is necessary for nuclear waste. Firstly, it reduces the volume of waste, making it more manageable for storage and disposal. By immobilizing the waste in a solid form, the risk of leakage or dispersion of radioactive materials is minimised. This helps protect both present and future generations from potential exposure. Furthermore, solidification enhances the physical and chemical stability of the waste, reducing the likelihood of corrosion, degradation, or alteration over time. It provides a barrier that can withstand environmental conditions and prevent the migration of radioactive substances into the surrounding environment. Solidification also facilitates the handling, transportation and storage of nuclear waste. By converting it into a solid form, the waste can be packaged more effectively, reducing the risks associated with its movement and storage. This is particularly important for high-level radioactive waste, which requires stringent containment measures due to its high level of radioactivity.

The need for solidification of nuclear waste has been extensively discussed in the scientific literature, as evidenced by several notable references. Barth (1990) provides a comprehensive overview of the history, present status and future direction of solidification/stabilisation technologies for hazardous waste treatment. This work emphasises the significance of effective waste stabilisation and immobilisation, particularly in the context of radioactive waste management. Trussell and Spence (1994) conduct a thorough review of solidification/stabilisation interferences, shedding light on the challenges and factors that can impact the success of these processes. Furthermore, Conner and Hoeffner (1998) critically evaluate stabilisation/solidification technology, analysing its advantages, limitations and application considerations. They also delve into the intriguing history of this technology, tracing its evolution and development over time. Overall, those literature highlights the need for solidification of nuclear waste, emphasizing the significance of effective waste stabilisation and immobilisation in the context of radioactive waste management.

In the realm of nuclear waste, researchers have explored ceramics, cement and glass-based solutions for solidification, highlighting their suitability, advancements and potential to ensure long-term safety and successful management. Wang and Liang (2012) focused their attention on ceramics as a viable solution for high-level radioactive waste solidification. Their research underscores the suitability of ceramic matrices, highlighting their robust chemical durability, thermal stability and structural integrity. Li and Wang (2006) contributed to the discourse by reviewing advancements in cement solidification technology specifically for waste radioactive ion exchange resins, underscoring the importance of cement-based approaches for addressing this specific waste stream. In addition to these studies, Tan (2022) delved into the glass-based stabilisation/solidification of radioactive waste, examining its potential as a method for effectively immobilizing and containing radioactive materials. Collectively, these references provide a compelling and comprehensive overview of the need for solidification in managing nuclear waste. They highlight the importance of reliable and advanced solidification/stabilisation methods for ensuring the long-term safety, environmental protection and successful management of nuclear waste.

The objectives of this review paper are to provide a comprehensive overview of solidification/stabilisation technologies for hazardous waste treatment, specifically focusing on nuclear waste. It aims to highlight the need for effective solidification methods in managing nuclear waste, explore advancements and challenges in various approaches, discuss their advantages and limitations and analyse the role of solidification in ensuring long-term safety and environmental protection. Additionally, the paper aims to review interferences and factors impacting solidification processes and identify future research directions. Overall, the objectives are to contribute to knowledge on the importance of solidification in nuclear waste management and guide further advancements in the field.

The paper has certain limitations that should be acknowledged. Firstly, the paper relies on a limited number of references, which may restrict the breadth and depth of the discussion on solidification/stabilisation technologies for nuclear waste. Additionally, the selected references span a wide time range and there may be newer research and developments not captured in the review. Furthermore, the paper may not address specific regional or site-specific considerations related to nuclear waste management. Lastly, while efforts have been made to provide a comprehensive overview, the review paper may not cover every aspect or emerging trends in the field.

2. Nuclear waste and its management

Nuclear waste, generated from the production and use of nuclear power, poses significant challenges due to its long-lasting and hazardous

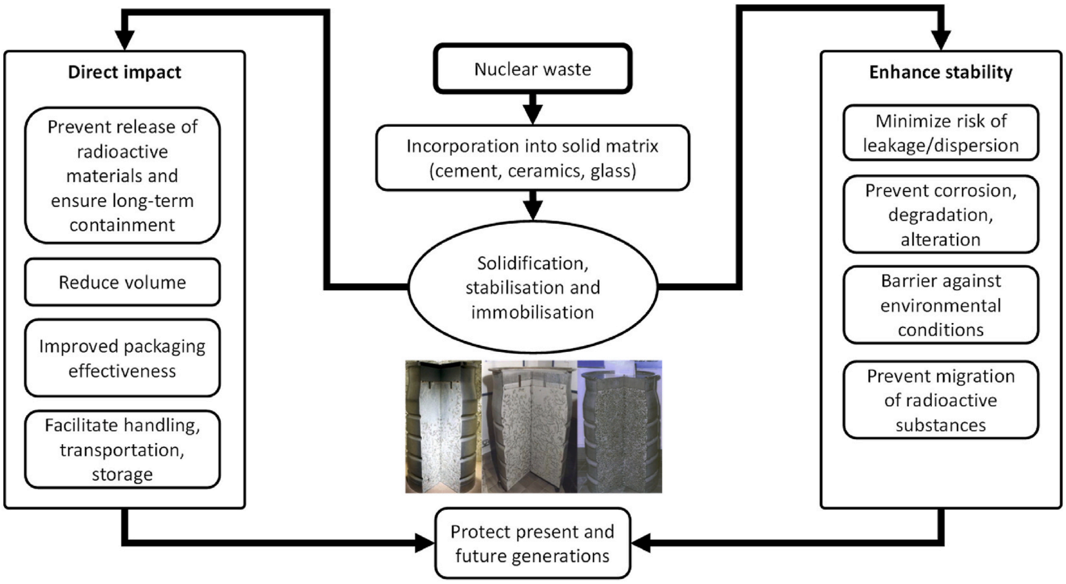

Fig. 1. Impact of nuclear waste solidification, stabilisation and immobilisation into solid matrix.

nature. Proper management of nuclear waste is crucial to ensure human and environmental safety. The management process involves multiple steps, including collection, transportation and disposal. High-level waste, consisting of spent nuclear fuel, requires careful handling and long-term storage in secure repositories, such as deep geological repositories. Low-level waste, with lower levels of radioactivity, can be treated and disposed of in specialized facilities. Strict regulatory frameworks, advanced technology and international cooperation are essential in implementing safe and sustainable nuclear waste management practices, minimising the risks and maximizing the benefits of nuclear energy.

2.1. *Types and characteristics of nuclear waste*

Different types of nuclear waste are categorised based on their radioactivity levels and composition. The distribution of various types of nuclear waste is shown in Fig. 2. High-level waste (HLW) is produced from spent nuclear fuel and contains highly radioactive isotopes. Due to its intense heat and long half-life, HLW requires long-term isolation to prevent potential environmental and human health hazards (Roxburgh, 1987). Intermediate-level waste (ILW) consists of materials with lower levels of radioactivity, such as reactor components and contaminated machinery. Although the radioactivity in ILW is lower than HLW, it still requires proper management and disposal to ensure safety (Ojovan et al., 2019). Low-level waste (LLW) includes items with minimal radioactivity, such as protective clothing and tools and can often be disposed of in specialized facilities (Fang, 2002). Transuranic waste (TRU) comprises isotopes with long half-lives, including plutonium and requires careful handling and isolation due to its potential long-term hazards (Fang, 2002).

The characteristics of nuclear waste are crucial in determining appropriate handling and disposal methods. Radioactivity, heat generation, chemical composition and volume are key factors to consider (Fig. 3). HLW, for example, poses challenges due to its high radioactivity and heat generation, necessitating advanced treatment and containment (Reed et al., 2018). LLW, with lower radioactivity, may be suitable for near-surface disposal with appropriate safeguards (European Commission, 2016). Understanding the types and characteristics of nuclear waste is fundamental for the development of effective waste management strategies. It allows for the implementation of appropriate waste immobilisation techniques, selection of suitable disposal methods and ensures the protection of human health and the environment (Fig. 3). By addressing the specific properties and challenges associated with different types of nuclear waste, comprehensive and safe waste management practices can be devised (Apostolidis et al., 2017; Chouhan, 2018).

2.2. *Challenges in nuclear waste management*

Fig. 4 presents multifaceted challenges and associated considering factors for in nuclear waste management field. One of the major challenges is the governance and policy aspect of nuclear waste management. Effective governance frameworks and international cooperation are crucial to address the technical, social and ethical aspects of nuclear waste disposal (Brunnengräber et al., 2018). It involves engaging stakeholders, ensuring transparency and establishing clear regulatory frameworks. Technical challenges also arise in managing nuclear waste. The selection of appropriate disposal methods, such as deep borehole disposal, requires engineering expertise and careful consideration of factors like geology, containment and long-term safety (Beswick et al., 2014). Innovative technologies and materials for waste immobilisation and storage are being developed to enhance waste management practices (Yim, 2021). Furthermore, the planning and integration of nuclear waste management systems present challenges. Drace et al. (2022) highlighted the need for comprehensive planning that considers various waste streams, disposal options and the overall lifecycle of nuclear waste. Coordination among different stakeholders, including waste producers, regulators and local communities, is essential for successful implementation.

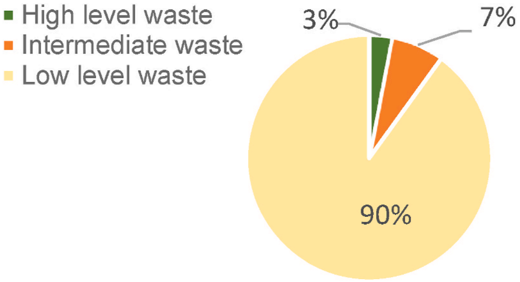

Fig. 2. The distribution various nuclear waste.

The societal dimension is also critical in nuclear waste management. Public perception, community acceptance and the communication of risks and benefits play a vital role (MacKerron, 2015). Stakeholder engagement and public participation are essential for building trust and ensuring that decision-making processes consider diverse perspectives. In summary, nuclear waste management faces multifaceted challenges, encompassing: governance, technical aspects, planning and societal considerations. Addressing these challenges requires international collaboration, innovative technologies, robust regulatory frameworks and effective stakeholder engagement. Overcoming these challenges is essential to ensure the safe and sustainable management of nuclear waste. Overall, addressing these multifaceted challenges in nuclear waste management requires international collaboration, innovative technologies, robust regulatory frameworks and effective stakeholder engagement.

2.3. *Role of solidification in nuclear waste management*

Solidification plays a crucial role in nuclear waste management by immobilizing and stabilizing radioactive waste, making it safer for long-term storage and disposal. The process involves transforming liquid or slurry forms of waste into a solid matrix, reducing the mobility of radioactive materials and preventing their release into the environment. The primary objective of solidification is to encapsulate radioactive waste within a stable and durable material, such as concrete, glass, or ceramics (Fig. 1). These materials provide physical and chemical barriers that isolate the waste and prevent its interaction with the surrounding environment. The selection of the solidification matrix depends on the characteristics of the waste, desired performance criteria and regulatory requirements.

Solidification offers several advantages in nuclear waste management (Fig. 1). It reduces the volume of waste, making it more manageable for storage and disposal. By immobilizing the radioactive materials, it minimises the potential for their migration and dispersion. Solidified waste forms can be safely stored in designated facilities or disposed of in engineered repositories, ensuring long-term containment and isolation. Furthermore, solidification enhances the handling and transportation of nuclear waste. Solidified waste is less prone to leakage, spillage, or accidental release during handling and transport operations, minimising the risks to workers and the environment. The solidification process requires careful formulation and testing to ensure the desired properties and performance of the waste form. Factors such as waste composition, waste loading, curing conditions and quality control measures need to be considered to achieve an effective and durable solidified waste product. Overall, solidification plays a vital role in nuclear waste management by immobilizing radioactive materials, reducing their mobility and providing a stable and safe form for long-term storage or disposal. It contributes to the protection of human health and the environment by minimising the risks associated with radioactive waste.

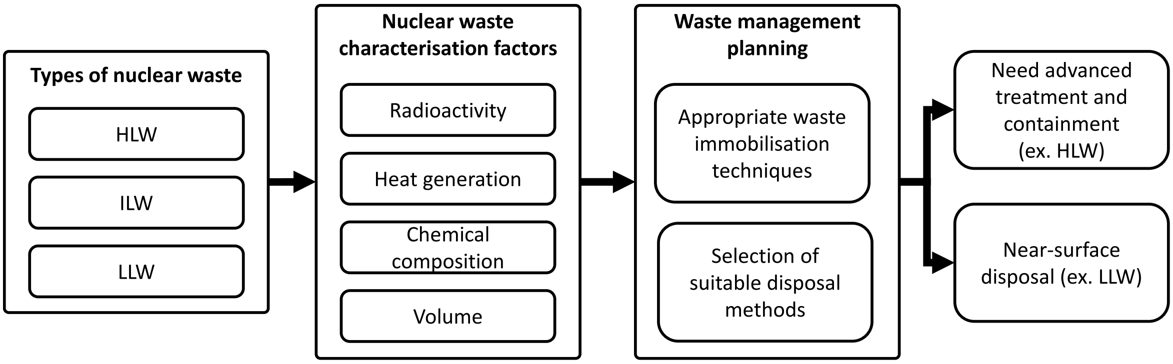

Fig. 3. Nuclear waste management process based on characterisation factors.

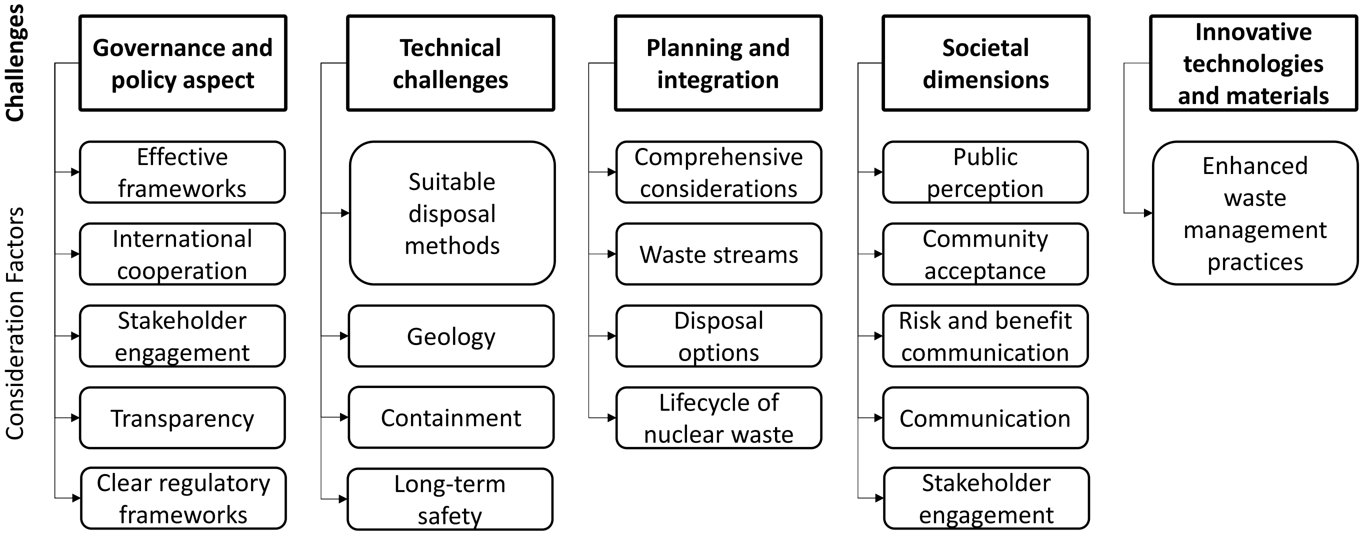

Fig. 4. Multifaceted challenges in nuclear waste management.

3. Cement-based solidification

Cement-based solidification is a widely used technique for the treatment and disposal of various types of hazardous waste. This process involves mixing hazardous waste materials with cementitious binders, such as Portland cement, to create a solid matrix. The binding properties of cement effectively immobilize and encapsulate the hazardous constituents, preventing their release into the environment. Cement-based solidification offers several advantages, including simplicity, cost-effectiveness and compatibility with a wide range of waste streams. The resulting solidified waste can be safely stored or disposed of in designated facilities. However, careful consideration should be given to the selection of cement types, waste compatibility and proper quality control to ensure the effectiveness and durability of the solidified waste forms.

3.1. Mechanisms and principles

Cement-based solidification of nuclear waste employs cementitious materials to create a durable, chemically resistant waste form. Governed by physical encapsulation, physical adsorption, and chemical fixation mechanisms as shown in Fig. 5 (Roy et al., 1992; Sun and Wang, 2010; Li et al., 2021), this process relies on cement-water hydration reactions. Hydration produces crucial products, including calcium silicate

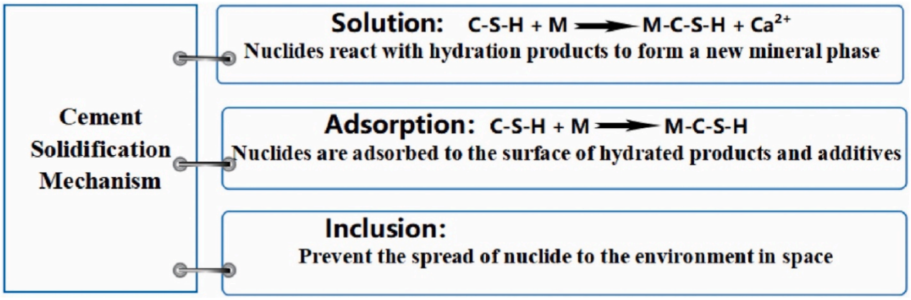

Fig. 5. The mechanisms of cement solidification of radionuclides (Roy et al., 1992; Sun and Wang, 2010; Li et al., 2021).

hydrates (C–S–H) and calcium hydroxide (CH), enhancing waste stability. The cementitious matrix physically binds waste particles, preventing the release of radioactive materials. The cementitious system's high pH aids chemical immobilisation through sorption and precipitation (Shi and Fernández-Jiménez, 2006). Cement-based solidification considers the chemistry and microstructure for stability and durability (Spence, 1992). Guided by principles, it optimizes waste loading, evaluating waste composition and compatibility with the cementitious mix, ensuring effective waste form design (Spence, 1992).

Fig. 6 illustrates the rigorous testing protocols crucial for evaluating the performance, durability, and regulatory compliance of cement-based solidification of nuclear waste. These protocols encompass common tests and long-term performance assessments under accelerated aging conditions, simulating extended storage or disposal periods. Results from these tests are pivotal in ensuring the safety, efficacy, and regulatory adherence of the waste immobilisation process. The incorporation of suitable admixtures, such as water reducers and set retarders, optimizes the cementitious mix's workability, setting time, and long-term performance. Additionally, alkali-activated cements present an alternative with higher early strength development and improved waste encapsulation efficiency, offering versatility in hazardous and radioactive waste stabilisation/solidification (Shi and Fernández-Jiménez, 2006). Comprehensive quality control and testing, evaluating compressive strength, leachability, durability, and resistance to environmental conditions, are imperative for the reliability of cement-based solidification.

3.2. *Interaction of cement with nuclear waste components*

Cement-based solidification crucially hinges on the interaction between cement and nuclear waste components, seeking to immobilize radioactive materials effectively. Cementitious materials, adept at encapsulating radionuclides, inorganic ions, and organic compounds, engage in various chemical and physical interactions illustrated in Fig. 7. Notably, radionuclides undergo sorption onto cement surfaces in the high pH environment. Inorganic ions like chloride and sulphate can influence cement hydration reactions, affecting long-term stability. Organic compounds, such as complexing agents, interact with cement, altering hydration processes and pore structure. These interactions, influenced by waste composition, cement type, curing conditions, and additives, underscore the importance of compatibility for secure waste immobilisation and stability.

Several studies have delved into the intricate realm of cement-waste interactions, elucidating chemical and physical phenomena. Ferrand et al. (2013) scrutinized nuclear waste glass and Portland cement interaction, emphasizing its influence on cement hydration and leaching behaviour. Milestone (2006) stressed the need for diverse cement types tailored to specific waste characteristics for effective immobilisation. William et al. (2013) explored radiation effects on concrete in nuclear power plants, emphasizing long-term considerations. Craeye et al. (2015) investigated gamma radiation's impact on self-compacting mortar, revealing changes in mechanical properties and microstructure. The results depicted in Fig. 8 indicate that low-dose gamma radiation leads to an increase in pore volume. Consequently, the decrease in strength observed can be attributed to the amplified presence of nano, micro and capillary porosity within the mortar matrix. Interestingly, the BET surface area remained largely unaffected by gamma radiation, as illustrated in Fig. 9. Nitrogen adsorption analysis demonstrated increased pore volume with low-dose gamma radiation, influencing mortar strength. Ichikawa and Koizumi (2002) and Lowinska-Kluge and Piszora (2008) probed gamma irradiation's effects on cement composites, unveiling insights into strength, microstructure, and mineralogy changes with implications for waste form performance and long-term stability.

Potts et al.'s (2021) study on gamma irradiation's long-term impact on concrete structures unveils significant microstructural changes, including microcrack formation and damage to the cement paste matrix. Fig. 10's EDS results illustrate these alterations, emphasizing deconvoluted Au points. Gamma radiation induces concrete mechanical property reduction and accelerates deterioration processes like alkali-silica reaction and sulphate attack. This research underscores the necessity of considering gamma irradiation effects in designing and evaluating concrete structures for nuclear waste containment. The study contributes to developing radiation-resistant concrete materials, vital for enduring nuclear waste management. In essence, the cement-waste interaction involves intricate chemical reactions, sorption, and radiation-induced changes, as emphasized by referenced studies. Tailored approaches are crucial, considering waste and cementitious system specifics, ensuring effective waste immobilisation and long-term stability in nuclear waste management.

3.3. *Factors affecting cement-based solidification*

The solidification of nuclear waste using cement-based materials is a

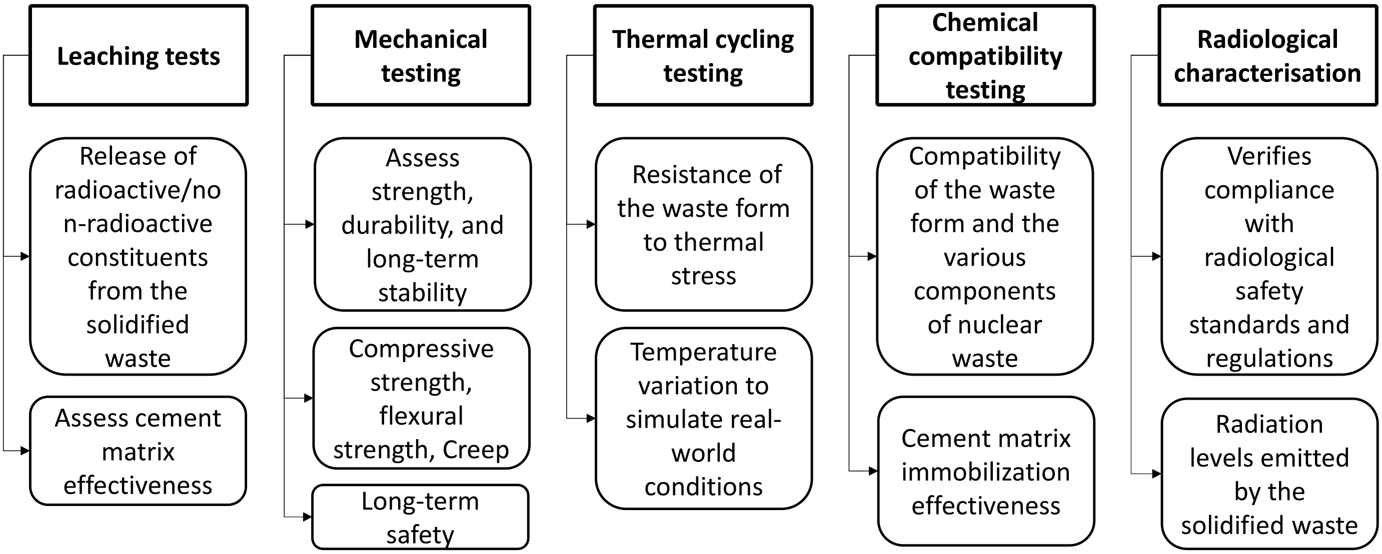

Fig. 6. Rigorous testing protocols to access the performance of cement-based solidification of nuclear waste.

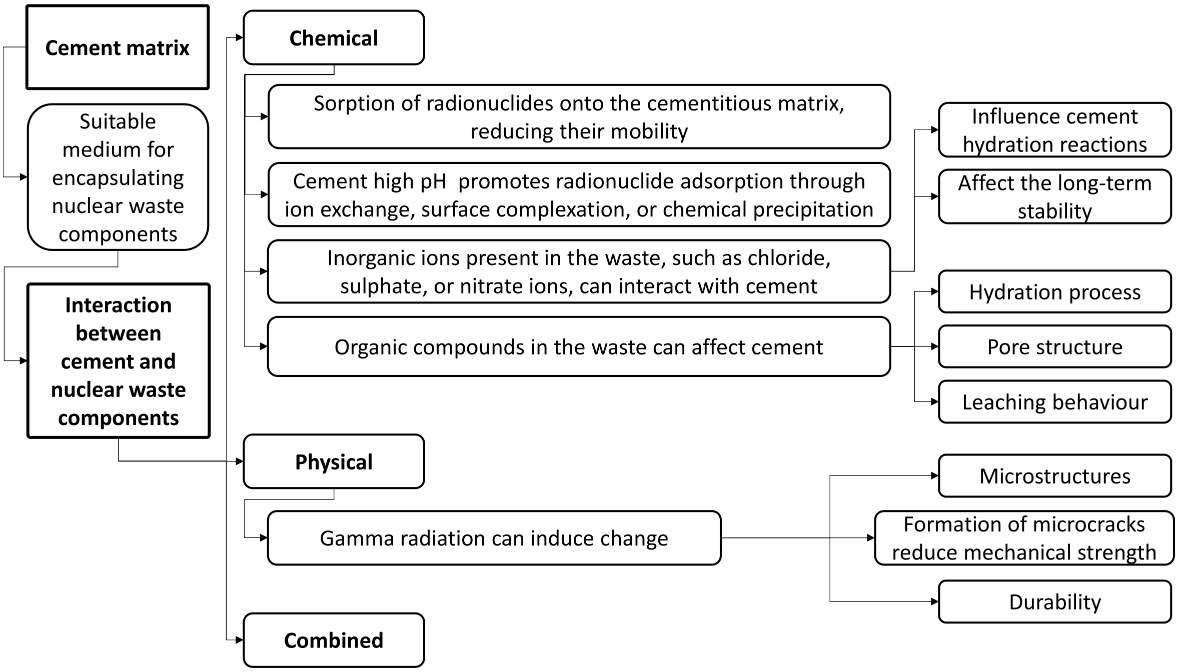

Fig. 7. Cementitious materials interaction with nuclear waste.

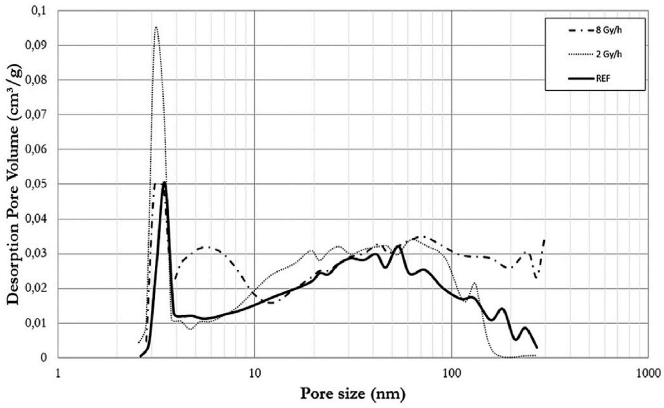

Fig. 8. Comparison of the pore volume distribution of radiated and non-radiated samples (Craeye et al., 2015).

complex process influenced by various factors. These factors play a crucial role in determining the effectiveness and long-term stability of the waste immobilisation system. Several key factors have been identified and studied in the field of cement-based solidification of nuclear waste.

1. Cement composition: The type and composition of cement used significantly affect the solidification process. Different types of cement, such as ordinary Portland cement (OPC) and alternative binders, exhibit varying performance in terms of waste encapsulation, mechanical strength and chemical resistance. The selection of an appropriate cement composition is important to ensure effective waste immobilisation.
2. Waste characteristics: The characteristics of the nuclear waste, including its chemical composition, radioactivity level and physical properties, influence the solidification process. The waste composition determines its compatibility with the cementitious matrix and the potential for chemical reactions. Understanding the waste characteristics is crucial for designing a suitable cement formulation.

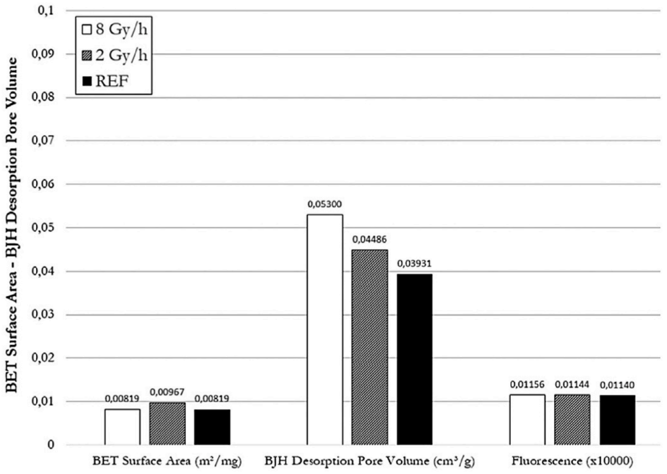

Fig. 9. BET surface area, BJH desorption pore volume and fluorescence of radiated and non-radiated samples (Craeye et al., 2015).

3. Water-to-cement ratio: The water-to-cement ratio affects the workability of the cementitious mix and the hydration process. It influences the development of strength, porosity and durability of the solidified waste form. Optimizing the water-to-cement ratio is essential to achieve the desired properties of the immobilised waste.
4. Additives and admixtures: Various additives and admixtures can be incorporated into the cementitious system to enhance its performance. These may include pozzolanic materials, such as fly ash or silica fume, which can improve the mechanical strength and reduce porosity. Chemical admixtures, such as superplasticisers, can be used to enhance workability and reduce water content. The selection and dosage of additives are critical for achieving the desired waste immobilisation characteristics.
5. Curing conditions: Curing conditions, including temperature, humidity and curing duration, influence the hydration process and the development of strength and durability of the cementitious waste

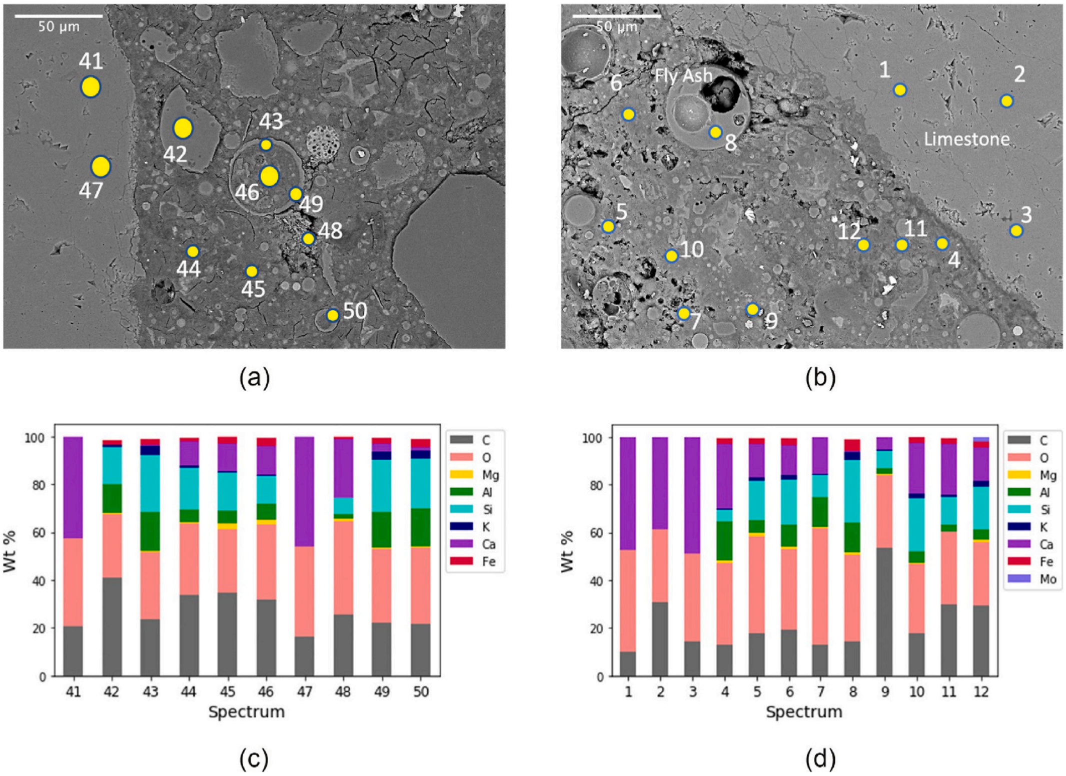

Fig. 10. (a) BSE Image of in-service sample (b) BSE Image of DCF sample (c) EDS data of in-service sample (d) EDS data of DCF sample (Potts et al., 2021).

form. Optimal curing conditions are required to achieve sufficient hydration and ensure long-term stability of the solidified waste.

6. Mechanical durability: The mechanical properties of the cement-based waste form, including compressive strength, resistance to cracking and resistance to leaching, are important for long-term stability. Factors such as the type and size distribution of aggregates, curing conditions and the incorporation of reinforcing fibres or particles, can affect the mechanical durability of the waste form.
7. Long-term performance: Consideration of the long-term performance of the cement-based waste form is crucial for assessing its suitability for nuclear waste immobilisation. Factors such as the resistance to leaching, chemical stability and radiation effects on the cementitious matrix need to be evaluated to ensure the long-term containment of radioactive isotopes.

In-depth research into cement-based nuclear waste solidification underscores critical considerations. Kearney et al. (2022) stressed the necessity of comprehending and refining the performance of cement-based materials in stabilizing and solidifying radioactive waste, emphasizing factors like cement composition, waste characteristics, water-to-cement ratio, and curing conditions. Bart et al. (2012) highlighted the pivotal role of factors such as cementitious binders, additives, and the long-term behaviour of the cementitious system in the selection and design of materials for nuclear waste storage. Exploratory studies delve into innovations, with Eskander et al. (2022) investigating a novel cement-ground granite scraps composite. Cau-dit-Coumes (2012) explored alternative binders beyond ordinary Portland cement, revealing their potential for enhancing the immobilisation process. Luhar et al. (2023) scrutinized cement-based technology for radioactive waste, emphasizing factors related to waste characteristics, cement formulation, curing conditions, and long-term performance. These references collectively stress multifaceted factors, urging a nuanced understanding and optimization for effective and sustainable methods in the secure containment and disposal of radioactive waste, prompting further research for technological advancements.

4. Formulations of cement-based solidification

Formulations of cement-based solidification involve the careful selection and proportioning of various components to achieve effective waste immobilisation. Fig. 11 presents the key factors considered for the formulation of cement-based solidification of nuclear waste. The key components typically include cementitious binders, water and waste materials. Different types of cement, such as Portland cement or blended cements, can be used based on the specific requirements and waste characteristics. Supplementary materials like fly ash, silica fume, or slag may be incorporated to enhance the properties of the solidified waste. Admixtures such as plasticizers or accelerators can be added to improve workability and setting time. The waste material itself may require pretreatment or stabilisation before mixing with cement. Overall, formulating cement-based solidification involves a balance between waste compatibility, mechanical strength and long-term stability to ensure the effective encapsulation and immobilisation of hazardous constituents.

4.1. Cement types and selection

The effect of cement types and selection on formulations of cement-based solidification for nuclear waste immobilisation has been widely studied. McDaniel et al. (1988) highlighted the importance of selecting appropriate cement-based waste forms based on factors such as waste composition and desired immobilisation properties. Glasser (1997) discussed the fundamental aspects of cement solidification and stabilisation, emphasizing the need for understanding cement chemistry to optimise waste encapsulation. Olmo et al. (2001) investigated the influence of specific oxides on cement setting time and strength development, providing insights into the effects of different elements on waste immobilisation. Coumes and Courtois (2003) explored the combined action of various chemicals on cement hydration, which is crucial for designing effective formulations. Shi and Spence (2004) conducted a comprehensive review, emphasizing the design of cement-based formulas for hazardous and radioactive wastes. Milestone (2006) argued

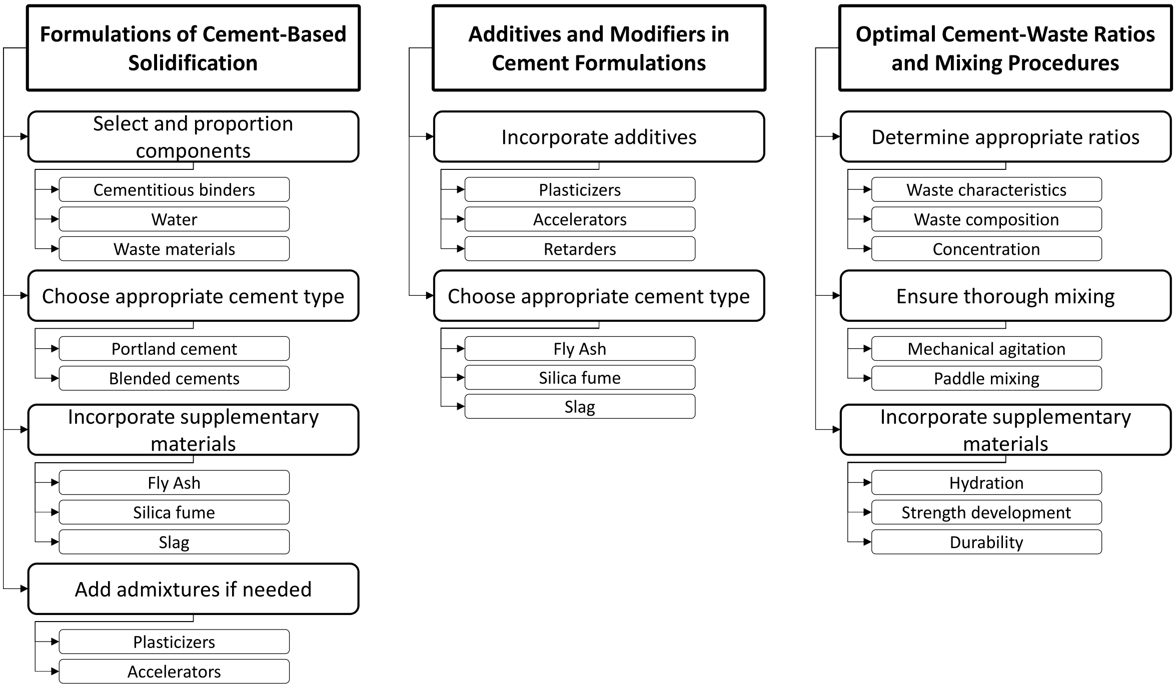

Fig. 11. Formulation and factors affecting the cement-based solidification of nuclear waste.

for the use of different cement types to address specific waste characteristics, emphasizing the need for a toolbox of cement options. Chen et al. (2009) provided a review of immobilizing heavy metals in cement-based solidification, highlighting the importance of cement selection for effective stabilisation. Voglar and Leštan (2011) developed an efficiency model for solidification/stabilisation of multi-metal contaminated soil, incorporating cement and additives. Finally, Li et al. (2021) discussed the solidification of radioactive wastes using cement-based materials, focusing on advancements and challenges. Overall, these studies collectively demonstrate the significance of cement type and selection in formulating effective cement-based solidification for nuclear waste immobilisation, emphasizing the need for tailored approaches based on waste characteristics and desired outcomes.

The cited studies provide valuable insights into the effect of cement types and selection on cement-based solidification for nuclear waste immobilisation. They emphasise the importance of considering waste composition, setting time, strength development and long-term stability. However, further research is needed to address gaps, including the long-term durability of cement-based waste forms and comprehensive frameworks that consider multiple factors. While the studies contribute valuable knowledge, additional studies are necessary to refine our understanding and develop sustainable waste management practices.

4.2. *Additives and modifiers in cement formulations*

Additives and modifiers play a crucial role in cement formulations for cement-based solidification of nuclear waste. These substances are introduced to enhance specific properties and address challenges associated with waste immobilisation. Additives such as plasticizers, accelerators, or retarders are utilized to improve workability, setting time and strength development of the cementitious matrix. Modifiers, on the other hand, are incorporated to address specific waste characteristics, such as heavy metal contamination or chemical reactivity. These modifiers can include substances like fly ash, silica fume, or slag, which contribute to increased durability, reduced permeability and enhanced waste encapsulation. The careful selection and incorporation of additives and modifiers optimise the performance of cement-based formulations in effectively immobilizing nuclear waste.

Multiple studies scrutinize the use of additives in cement-based solidification of nuclear waste. Saleh et al. (2019) showcased a composite material's efficacy, incorporating cement, slag, and titanate nanofibers, enhancing waste immobilisation during adverse conditions. However, long-term stability and leaching behaviour warrant further investigation. Swift et al. (2013) explored phosphate modification of calcium aluminate cement, exhibiting potential for improved waste encapsulation, yet lacking a comprehensive assessment of long-term performance. Zhu et al. (2022) discussed alkali-activated cement for radionuclide waste immobilisation, emphasizing alternative systems without an exhaustive evaluation of environmental impact. Eskander et al. (2011) demonstrated cement's versatility in immobilizing organic radioactive waste but overlook potential drawbacks. Cerbo et al. (2017) studied fly ash and heavy metal sludge solidification with additives, proving efficacy but lacking thorough assessment of long-term performance. Malviya and Chaudhary (2006) reviewed factors affecting hazardous waste solidification, though not focusing on nuclear waste's unique challenges.

while these studies contribute valuable insights into the use of additives and modifiers in cement-based solidification of nuclear waste, there is a need for more comprehensive research to evaluate the long-term performance, leaching behaviour and environmental impact of these modified cement formulations. Further studies should address the specific challenges associated with nuclear waste immobilisation and provide a holistic assessment of the effectiveness and safety of these approaches in long-term waste management.

4.3. *Optimal cement-waste ratios and mixing procedures*

Achieving optimal cement-waste ratios and employing precise mixing procedures is pivotal in the cement-based solidification of nuclear waste. Striking the right balance is crucial to ensure effective waste immobilisation while maintaining the desired mechanical strength and durability of the solidified waste form. The selection of an appropriate cement-waste ratio depends on the waste's characteristics, ensuring a balance between maximizing waste incorporation and preventing excessive cement consumption. Thorough and uniform blending of cement and waste is vital, utilizing proper mixing techniques such as mechanical agitation or paddle mixing to ensure homogeneity. Attention to the curing process is essential for adequate hydration and strength development. Optimizing these factors is paramount for producing cement-based waste forms with optimal performance, stability, and long-term nuclear waste immobilisation.

Several studies have explored this topic and provided valuable insights. Rahman and Zaki (2020) conducted a comparative analysis of performance models for spent ion exchanger-cement based waste forms, highlighting the importance of finding the optimal ratios to achieve effective waste immobilisation (Fig. 12). Saleh et al. 2020a, 2020b focused on the qualification of Phyto remediated radioactive wastes and emphasized the need for suitable mixing procedures to ensure waste containment under various weathering conditions.

Fabian et al. (2022) investigated a new type of cement mix for simulated liquid radioactive waste, emphasizing the importance of understanding the cement-waste interactions. Shon et al. (2022) evaluated the disposal stability of cement solidification of lime waste, shedding light on the significance of proper mixing procedures for waste immobilisation. Kearney et al. (2022) discussed the cement-based stabilisation/solidification of radioactive waste, highlighting the need for comprehensive approaches to optimise cement-waste ratios and mixing procedures. Overall, these studies emphasise the critical role of optimal ratios and mixing procedures in achieving effective solidification of nuclear waste and provide valuable insights for future research and practical applications.

5. Testing and characterisation of cement-based solidification

Testing and characterisation of cement-based solidification of nuclear waste play a crucial role in ensuring the effectiveness and safety of waste immobilisation. Fig. 13 presents testing and characterisation best practice on the cement-based solidification of nuclear waste. Various techniques are employed to evaluate the performance of cementitious matrices, including mechanical testing, leaching tests and microstructural analysis. These tests assess parameters such as compressive strength, durability, leachability and microstructure of the solidified waste form. Additionally, advanced analytical techniques like X-ray diffraction, scanning electron microscopy and spectroscopy are used to investigate the mineralogical and chemical composition of the waste form. The comprehensive testing and characterisation provide valuable insights into the long-term stability, containment and environmental impact of cement-based solidification of nuclear waste (see Fig. 14).

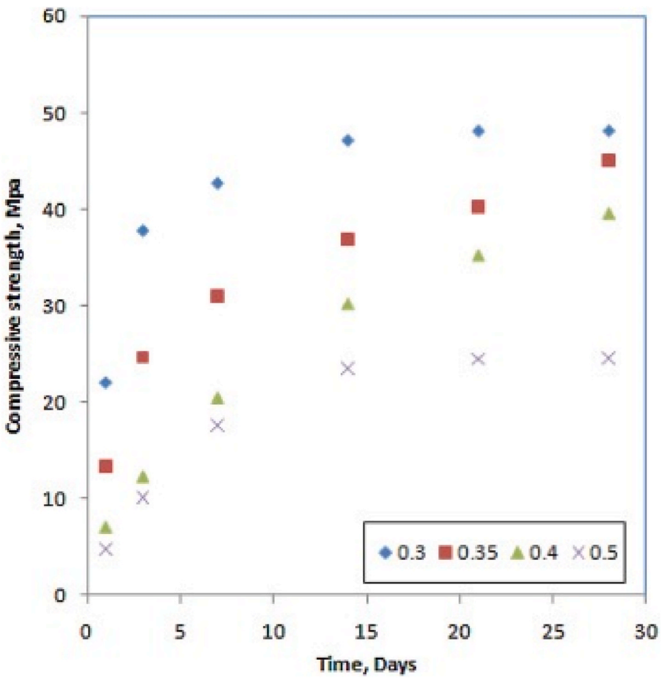

Fig. 12. Development of the solidification performance for samples containing different water to cement ratio (Rahman and Zaki, 2020).

5.1. Physical testing of solidified waste forms

Physical testing is crucial for evaluating the structural integrity and performance of cement-based solidification in nuclear waste management. Key parameters, including compressive strength, density, porosity, and dimensional stability, are assessed through various tests. Compressive strength gauges the waste form's ability to withstand pressure, while density and porosity tests unveil material characteristics. Dimensional stability tests measure potential volume changes over time. Singh and Pant (2006) explored arsenic-containing waste solidification with Portland cement, fly ash, and polymeric materials. Li and Wang (2006) reviewed cement solidification for radioactive ion exchange resins. Hills and Pollard (1997) investigated the influence of interference effects on the mechanical and microstructural characteristics of cement-solidified hazardous waste forms. Bayoumi et al. (2013) studied the solidification of hot real radioactive liquid scintillator waste using a cement-clay composite. Jang et al. (2016) explored the physical barrier effect of geopolymeric waste forms on the diffusivity of cesium and strontium. These studies contribute valuable insights into optimizing waste form formulations, emphasizing the need for standardized testing protocols in ensuring the reliability and safety of cement-based waste immobilisation techniques.

5.2. Chemical and mineralogical analysis

Chemical and mineralogical analyses are pivotal for evaluating the effectiveness and long-term stability of cement-based solidification in nuclear waste management. Examining the chemical composition allows researchers to assess interactions between waste and cementitious materials, identifying potential reactions or leaching risks. Mineralogical analysis helps determine the formation of new mineral phases, contributing to the strength and durability of the solidified waste form. These analyses aid in understanding structural integrity and potential release mechanisms of hazardous elements, crucial for optimizing cement-based waste solidification processes. Brough et al. (2001) investigated alkali-activated cement-based waste forms, revealing insights into reaction mechanisms and phase transformations during curing. Bayoumi et al. (2013) explored the solidification of real radioactive liquid scintillator waste using a cement-clay composite, providing critical information on long-term behaviour and durability. Saleh et al. (2019) reinforced cement with iron slag and titanate nanofibers, evaluating waste incorporation and mineral phases. Chartier et al. (2020) studied magnesium phosphate cement-based materials under irradiation, offering insights into structural changes. Wang et al. (2020) explored low-carbon cement-based approaches for green remediation, assessing composition and microstructural development. These analyses have proven critical for developing effective immobilisation strategies, ensuring safety, and promoting environmental sustainability in radioactive waste disposal.

5.3. Mechanical strength and durability testing

Mechanical strength and durability testing are pivotal in assessing the effectiveness of cement-based solidification for nuclear waste containment. These tests, including compressive and flexural strength measurements, evaluate the load-bearing capacity and resistance to deformation, ensuring the waste can endure long-term stress. Durability testing examines resistance to environmental factors such as chemical attacks, freeze-thaw cycles, and thermal stress. Robust mechanical strength and durability testing are essential for verifying the suitability of cement-based waste forms for extended storage, ensuring the

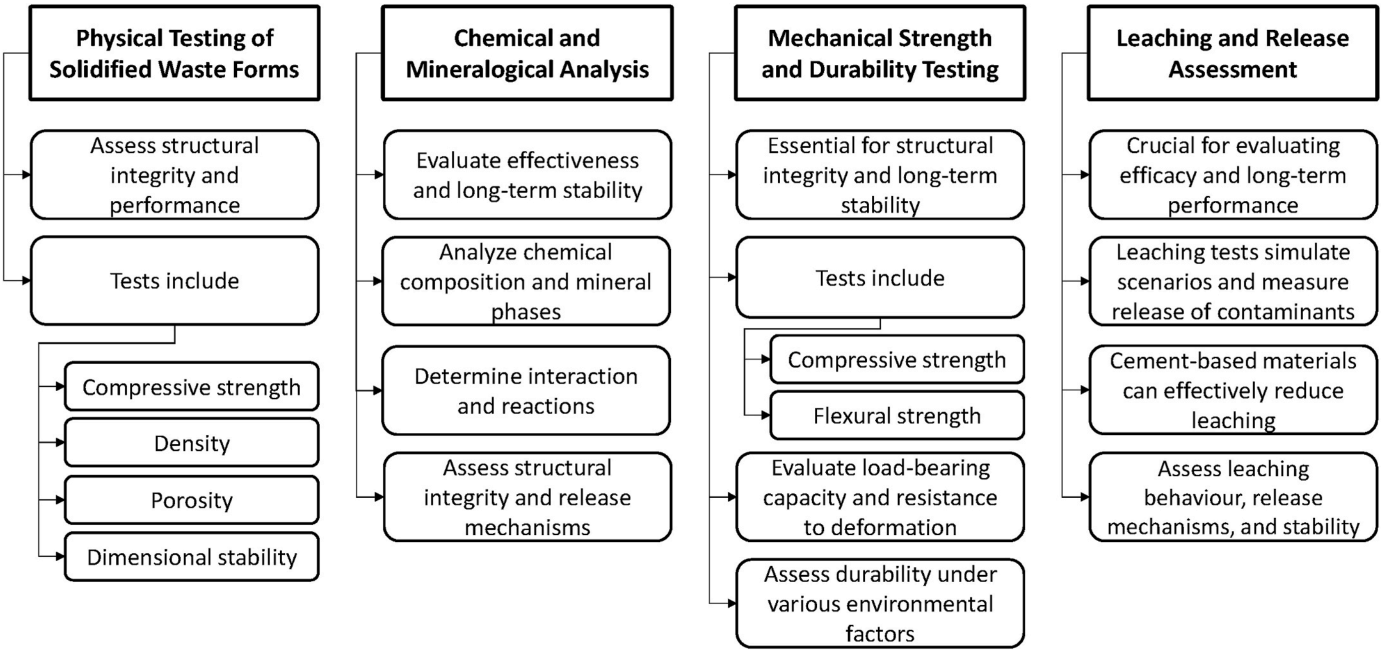

Fig. 13. Testing and characterisation of cement-based solidification of nuclear waste.

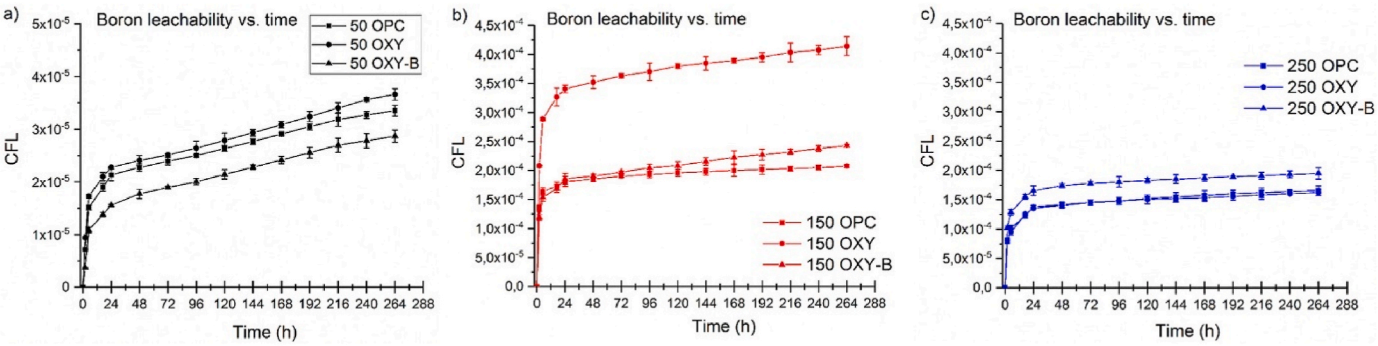

Fig. 14. Cumulative leach fraction of B from the different cementitious waste form in different simulated liquid waste concentrations (Fabian et al., 2022).

containment system's integrity. Studies, such as (Handler, 1989), advanced our understanding of low-level waste solidification but must be considered in light of subsequent technological advancements. Asavapisit et al. (2001) explored the influence of silica fume, revealing improved properties but within specific conditions. Koťátková et al. (2017) emphasized suitable cementitious materials for radioactive waste but faced limitations in evaluating long-term performance. Investigations into recycled cement powder (Kim et al., 2021), composite materials (Saleh et al., 2019), and innovative solidification methods (Ma et al., 2022) expanded possibilities, though comprehensive, long-term assessments under diverse scenarios are crucial. While these studies provide valuable insights, ongoing research is essential to ensure the effective and enduring immobilisation of radioactive waste in diverse contexts.

5.4. *Leaching and release assessment*

Assessing leaching and release mechanisms is integral to evaluating the effectiveness of cement-based solidification for nuclear waste immobilisation. Various studies, including Fabian et al. (2022), have extensively examined the leaching behaviour of cement-based solidified waste through experimental methods such as batch and column leaching tests. These tests simulate leaching scenarios and measure the release of radionuclides and contaminants. Cement-based materials, due to their alkaline nature and stable mineral phase formation, effectively reduce the leaching of radioactive and hazardous elements. Fabian et al.'s (2022) study (Fog. 14) focused on leaching and release assessment, characterizing simulated liquid radioactive waste in a novel cement mix. The study analysed cumulative leached fractions of boron (B) over time for different concentrations, revealing dynamic leaching activity within the first 24 h, followed by a gradual increase. The findings underscored the efficacy of the cement mix in immobilizing radioactive waste, demonstrating low leaching rates and minimal radionuclide release.

In Szajerski's (2021) study, the leaching behaviour of radioactive waste solidified in lignite slag and bismuth oxide-filled elastomer matrices was thoroughly investigated. The research focused on understanding the release mechanism, immobilisation efficiency, long-term radiation stability, and aging of the solidified waste. Fig. 15 in the study provides a clear depiction of specific leaching timeframes when NR composites were in contact with the leaching agent, aiding in the comparison and analysis of variations among different composites and tracers. Results indicated high immobilisation efficiency, signifying effective containment of radioactive elements. Minimal radionuclide release during leaching tests demonstrated the excellent stability of the matrices under diverse conditions, offering valuable insights into cement-based solidification matrices for long-term radioactive waste

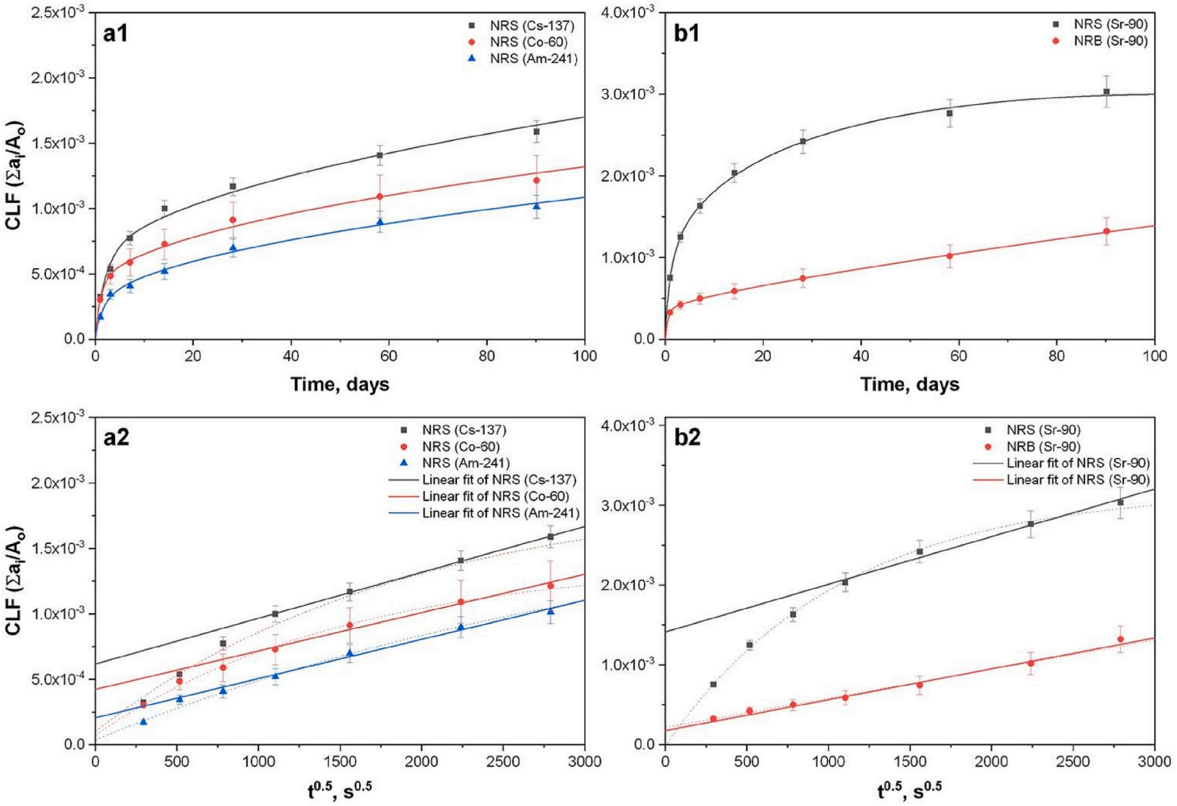

Fig. 15. Selected leaching kinetics for Cs-137, Co-60 and Am-241 tracers from lignite slag filled composite (a1-2) and Sr-90 from lignite slag (NRS) and Bi2O3 (NRB) filled composites (b1-2) (Szajerski, 2021).

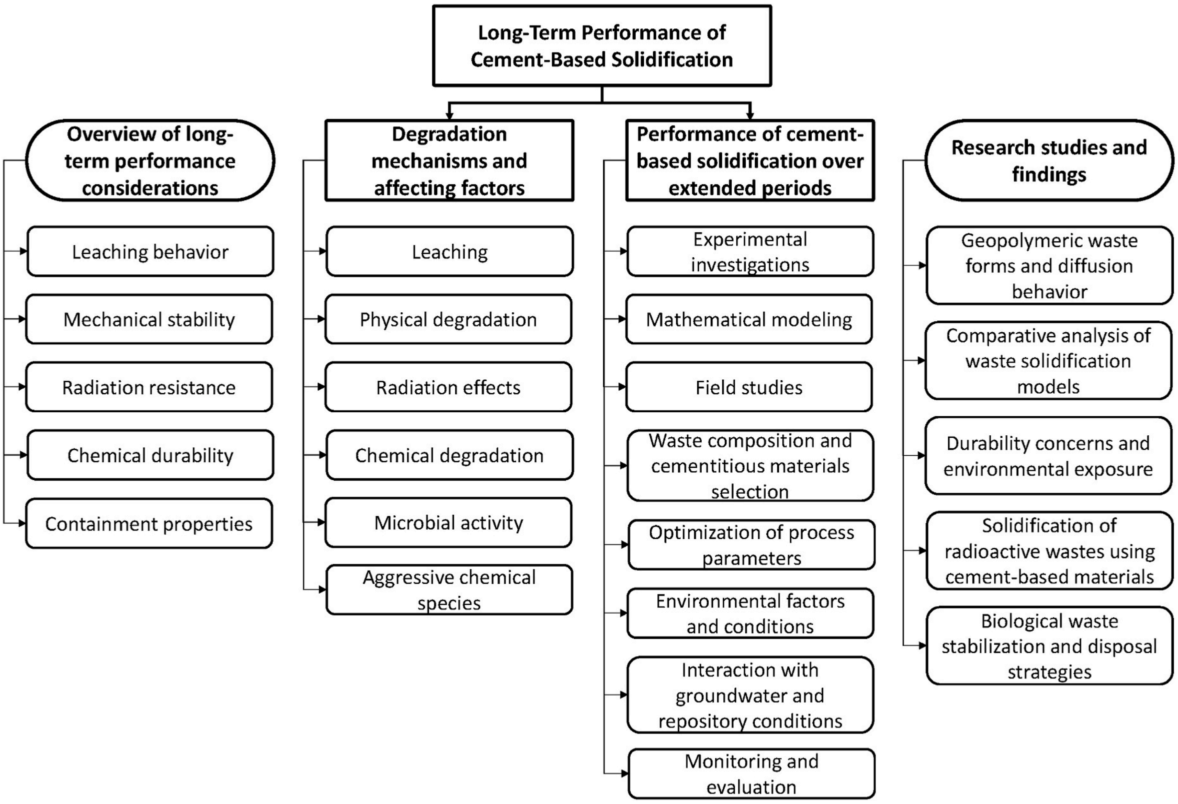

Fig. 16. Long-term performance evaluation consideration and research studies on cement-based solidification.

immobilisation.

Studies by Cote et al. (1987), Seveque et al. (1992), Rahman et al. (2007), and El-Kamash et al. (2006) delved into leaching behaviour, mathematical modelling, and kinetics of specific radionuclides in cement matrices. Their models became crucial tools for predicting releases, aiding in assessing the long-term performance and stability of cement-based waste forms. Torras et al. (2011) focused on nickel-containing wastes stabilized with magnesium potassium phosphate cements, demonstrating the effectiveness of the stabilisation/solidification process through semi-dynamic leaching tests. Saleh et al. (2020a,b) provided a comprehensive assessment of phytoremediated radioactive wastes, emphasizing the significance of considering environmental conditions for understanding leaching behaviour. These collective findings enhance our understanding of leaching and release assessment, contributing to the optimization and evaluation of waste immobilisation techniques for the safe and environmentally sustainable disposal of nuclear waste.

6. Long-term performance of cement-based solidification

The long-term performance of cement-based solidification in nuclear waste management is of paramount importance. Cement-based materials are commonly used to immobilize radioactive waste, preventing the release of hazardous substances into the environment. Fig. 16 show consideration overview of long-term performance evaluation and consideration on cement-based solidification of nuclear waste. The effectiveness of cement-based solidification is assessed through various parameters, including leaching behaviour, mechanical strength and stability over time. Extensive research and testing are conducted to ensure the long-term integrity and durability of the waste forms. The goal is to provide a reliable and robust solution that effectively immobilizes and contains radioactive materials, minimising the risk of environmental contamination and ensuring long-term safety in nuclear waste disposal.

6.1. Overview of long-term performance considerations

The long-term performance considerations in cement-based solidification of nuclear waste are essential for ensuring the safe and effective management of radioactive materials over extended periods. These considerations involve evaluating various factors that can influence the stability, durability and containment of the waste form.

Leaching behaviour is a critical aspect to assess as it determines the potential release of radioactive and hazardous substances into the surrounding environment over time. Leaching tests are conducted to monitor the leachability of the waste form and ensure that the release of contaminants remains within acceptable limits (Dermatas et al., 2004; Torras et al., 2011; Yin et al., 2020). Mechanical stability is another important consideration, as the waste form must maintain its structural integrity to prevent the release of radioactive materials (Chapman and Hooper, 2012; Katoh et al., 2012; Saleh and Eskander, 2020). Factors such as shrinkage, cracking and deformation need to be evaluated to ensure that the waste form can withstand long-term stress and environmental conditions without compromising its containment properties. Radiation resistance is also a key factor in assessing the long-term performance of cement-based waste forms (Petit, 1992; Badreddine et al., 2004; Ojovan et al., 2011). The material should be capable of withstanding radiation exposure without significant degradation, maintaining its structural and chemical stability over time. Chemical durability is an essential aspect that evaluates the waste form's resistance to chemical reactions, such as dissolution or alteration due to exposure to different environmental conditions (Day et al., 1998; Ewing, 1999; Meegoda et al., 2003; Bohre et al., 2017). The stability of the cementitious matrix and its ability to retain radioactive materials within the waste form are critical for long-term containment.

Considering these factors collectively, the long-term performance of cement-based solidification of nuclear waste aims to ensure the secure immobilisation and confinement of radioactive materials, minimising the potential for environmental contamination and human exposure. By thoroughly evaluating leaching behaviour, mechanical stability, radiation resistance and chemical durability, scientists and engineers can design effective waste forms that can safely isolate and contain nuclear waste over extended periods, contributing to the overall safety and sustainability of nuclear waste management.

6.2. Degradation mechanisms and affecting factors

The degradation of cement-based nuclear waste solidification involves multiple mechanisms impacted by various factors. Leaching, influenced by matrix composition, waste loading, and environmental exposure, releases radionuclides. Physical degradation, induced by freeze-thaw cycles and mechanical stress, forms cracks, enhancing leaching. Chemical degradation involves reactions altering waste form mineralogy and chemistry. Radiation effects, microbial activity, and aggressive chemical species also contribute to degradation. To ensure long-term performance, optimizing formulations, using additives, and selecting suitable repository conditions are crucial strategies. Recognizing these degradation mechanisms is vital for designing resilient cement-based waste forms in nuclear waste management, ensuring stability and minimising environmental impact.

Jang et al. (2016) investigated degradation mechanisms in cement-based solidification (CBS) of nuclear waste, emphasizing the physical barrier effect of geopolymeric waste forms on cesium and strontium diffusion. Experimental tests revealed geopolymeric waste forms provided a more effective barrier, limiting isotopic diffusion compared to conventional cement-based forms (Fig. 17). The study proposed that integrating geopolymers in CBS could enhance long-term stability and containment of radioactive waste. Identified factors influencing CBS degradation included waste form composition, properties, chemical interactions, and environmental conditions, impacting leaching behaviour and overall stability, subsequently affecting radioactive isotope release into the environment (see Fig. 18).

Malviya and Chaudhary's (2006) review extensively explored factors influencing the solidification/stabilisation of hazardous waste using cement-based materials. Emphasizing material selection, process optimization, and environmental conditions, they underscored the role of waste composition, binder characteristics, curing conditions, and additives in determining stability and long-term performance. Saleh and Eskander (2012) characterized a composite material for solidifying radwastes, examining its degradation behaviour under immersion conditions. Analysing physical, chemical properties, and leaching behaviour, their study emphasized understanding degradation mechanisms and the immersion process's impact on cement-based solidification.

Phung et al. (2018) addressed concrete durability concerns in nuclear power plants and waste repositories, highlighting the importance of long-term performance assessment. Considering factors like temperature, moisture, radiation, and chemical exposure, they stressed specific environmental conditions and appropriate design and maintenance strategies for structural durability. Zheng et al. (2022) investigated the transformation and leaching behaviour in cement-based solidified matrices under water, heat, and chemistry. Analysing the effects on stability and leaching, their study provided insights into reaction mechanisms, product transformation, and leaching behaviour, contributing to understanding long-term performance and potential degradation pathways in cement-based solidification of nuclear waste. These studies collectively illuminate degradation mechanisms and factors influencing cement-based solidification's stability and performance in nuclear waste management, guiding robust strategies for safe immobilisation and long-term containment.

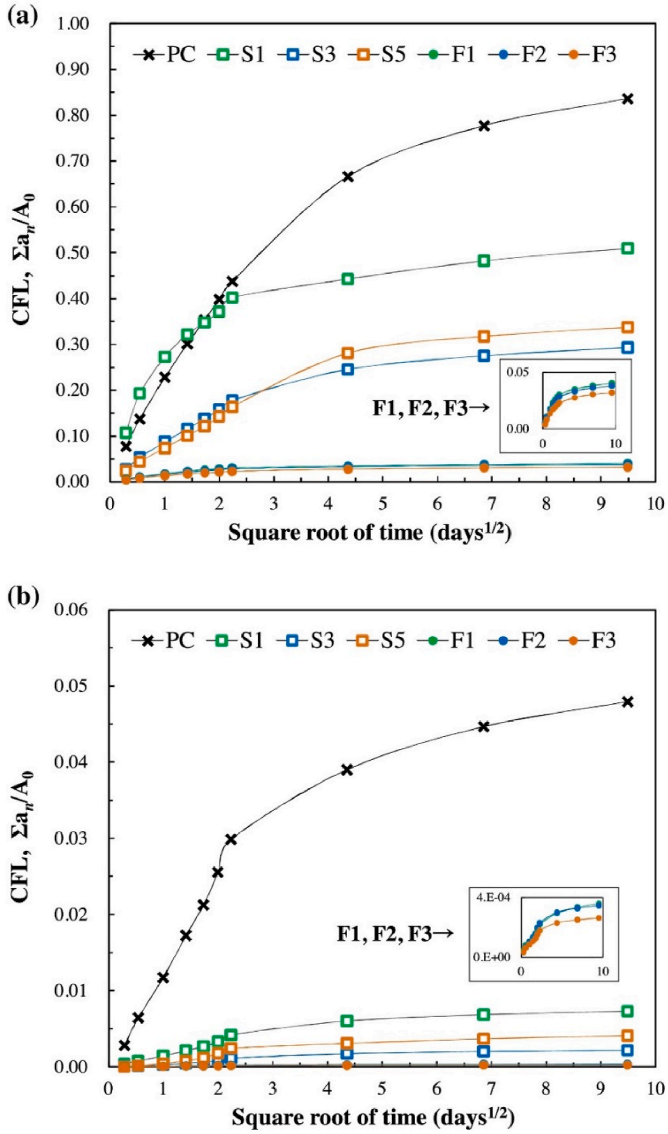

Fig. 17. The cumulative fraction leached (CFL) of (a) cesium and (b) strontium (Jang et al., 2016).

6.3. Performance of cement-based solidification over extended periods

The long-term performance of cement-based solidification in nuclear waste disposal is crucial for safety. While cement materials offer durability and strength, their prolonged use can lead to degradation influenced by factors like water exposure, temperature changes, radiation, and chemical interactions. Research, involving leaching behaviour, structural integrity, and chemical reactions, provides insights into stability and durability. Key factors impacting performance include cement selection, process optimization, waste composition, curing conditions, and environmental interactions. Ongoing monitoring, leachate analysis, and structural checks are essential for risk mitigation. Advanced techniques and modelling contribute to understanding degradation mechanisms, supporting predictions for sustained effectiveness.

The reviewed studies critically addressed the long-term performance of cement-based solidification in nuclear waste management. Saleh et al. (2019) explored a composite's resilience to extreme conditions, showing improved performance during frost and flooding. Rahman and Zaki (2020) conducted a comparative analysis of models for spent ion exchanger-cement wasteforms, evaluating their efficacy in predicting long-term performance. Li et al. (2021) emphasized material selection's role in achieving stability for radioactive waste solidification. Bayoumi et al. (2013) characterized cement-stabilized biological waste immersed in aqueous media, offering disposal insights. Saleh et al. (2020a,b) qualified phytoremediated radioactive waste, examining long-term behaviour under leaching and weathering. Rahman et al. (2007) developed models predicting radionuclide leaching from cement-clay matrices. These studies enhance our understanding of cement-based solidification's extended-term performance, emphasizing diverse factors and environmental conditions.

7. Regulatory considerations

The regulatory requirements for cement-based solidification of nuclear waste play a critical role in ensuring the safe and effective management of radioactive materials, protecting human health and the environment. Compliance with these regulations is essential for organisations involved in cement-based solidification, as it requires understanding and adherence to specific licensing and permit systems, waste classification and characterisation requirements, quality assurance and control programs and long-term monitoring and reporting obligations. Fig. 17 presents a SWOT Analysis for Regulatory Considerations in Cement-Based Solidification of Nuclear Waste. The strengths of this approach lie in the strict regulatory requirements that ensure safe practices, compliance with standards and protection of human health and the environment. However, weaknesses include challenges in international collaboration and the complexity of understanding and meeting compliance criteria. Opportunities for improvement arise from collaborative efforts, advancements in waste characterisation and knowledge sharing among countries. On the other hand, potential threats include the risks of inadequate compliance, the need for ongoing adaptation to evolving regulations and the impact of unclear or inconsistent requirements on the effectiveness of solidification practices.

7.1. Regulatory requirements for cement-based solidification

The regulatory requirements for cement-based solidification of nuclear waste vary among countries and are typically governed by national and international regulations. These regulations aim to ensure the safe and effective management of radioactive waste, including the use of cement-based solidification techniques. While specific requirements may differ, there are some common elements found in regulatory frameworks (Rahman et al., 2014; Abdel Rahman and Ojovan, 2016; Rahman and Zaki, 2020):

Licensing and Permits: Facilities engaged in cement-based solidification of nuclear waste are typically required to obtain appropriate licenses and permits from regulatory authorities. These licenses ensure compliance with specific safety, operational and environmental standards.

Waste Classification and Characterisation: Regulatory frameworks often outline requirements for waste characterisation, including the determination of waste types, properties and radioactivity levels. This information is essential for proper waste handling, selection of appropriate cementitious materials and determination of waste acceptance criteria.

Cementitious Material Selection: Regulatory guidelines may specify the acceptable types of cementitious materials that can be used in the solidification process. The performance, stability and compatibility of these materials with the waste are evaluated to ensure the long-term integrity of the cement matrix.

Waste Acceptance Criteria: Regulatory authorities typically establish waste acceptance criteria that must be met before waste can be processed using cement-based solidification. These criteria may include waste composition, radioactivity limits and physical properties to ensure the safety and effectiveness of the solidification process.

Quality Assurance and Quality Control: Regulatory requirements often mandate the implementation of quality assurance and quality

S

Regulatory requirements ensure safe and controlled cement-based solidification of nuclear waste, protecting human health and the environment.

Licensing and permit systems establish standards for safety, operational practices, and environmental protection, ensuring compliance.

Waste classification and characterization enable proper waste handling, selection of suitable materials, and establishment of acceptance criteria.

Quality assurance and control programs promote consistent and reliable solidification processes, ensuring waste form integrity.

Long-term monitoring and reporting contribute to transparency and accountability, assessing performance and stability.

W

Variations in regulatory requirements among countries create challenges for international collaboration and standardization.

Keeping up with evolving regulations and ensuring compliance can be resource-intensive and require continuous monitoring and updates.

Complexity of regulatory frameworks and technical requirements may pose challenges in understanding and meeting compliance criteria.

O

Collaborative efforts can lead to harmonized and standardized regulatory frameworks for cement-based solidification.

Advancements in waste characterization and understanding can inform more precise waste acceptance criteria.

Knowledge sharing can facilitate improvements in regulatory approaches, promoting efficient waste management strategies.

T

Inadequate compliance can result in safety breaches, environmental contamination, and legal consequences, damaging organizational reputation.

Evolving regulations may require significant resources to adapt processes and ensure ongoing compliance.

Lack of clarity or inconsistencies in requirements can lead to confusion and impact the effectiveness of solidification practices.

Fig. 18. SWOT analysis for regulatory consideration in cement-based solidification of nuclear waste.

control programs to ensure that solidification processes are performed correctly and consistently. This may involve documentation, record keeping, audits, inspections and testing protocols to verify compliance with regulatory standards.

Environmental and Safety Considerations: Regulatory frameworks emphasise the need for adequate measures to protect the environment and ensure worker and public safety. This includes proper handling, transportation, storage and disposal of solidified waste, as well as appropriate monitoring and control of potential environmental releases.

Long-Term Monitoring and Reporting: Regulatory authorities may require facilities to establish long-term monitoring programs to assess the performance and stability of the cementitious waste forms over time. Regular reporting to regulatory agencies is often mandated to ensure transparency and compliance.

It is important for organisations involved in cement-based solidification to understand and comply with the regulatory requirements specific to their jurisdiction. Collaboration with regulatory authorities and adherence to the established guidelines are crucial to ensure the safe and responsible management of nuclear waste through cement-based solidification techniques.

7.2. Approaches to compliance with regulations

Compliance with regulations regarding cement-based solidification of nuclear waste is crucial to ensure the safe and effective management of radioactive materials. Organisations involved in waste solidification must adopt various approaches to meet regulatory requirements. Here are some key approaches to compliance (Saul and McGeary, 1991; Stegemann and Cote, 1996; Meegodaet al. 2003; Courtois et al., 2022):

Understanding Regulatory Frameworks: Organisations need to have a thorough understanding of the applicable regulatory frameworks governing cement-based solidification. This includes familiarising themselves with national and international regulations, guidelines and standards specific to their jurisdiction. Regular updates and communication with regulatory authorities are essential to stay informed about any changes or new requirements.

Establishing Compliance Programs: Organisations should develop comprehensive compliance programs tailored to their operations. These programs should outline the specific regulatory requirements and establish procedures, protocols and documentation systems to ensure compliance. This includes incorporating regulatory requirements into operational processes, waste management plans and quality assurance programs.

Conducting Regulatory Assessments: Regular assessments should be conducted to evaluate the organization's compliance status. This involves reviewing operational practices, documentation and procedures against regulatory requirements. The assessments can identify any gaps or areas of non-compliance, allowing organisations to take corrective actions promptly.

Training and Education: Ensuring that staff members are adequately trained and educated on regulatory requirements is essential for compliance. Organisations should provide comprehensive training programs to employees involved in cement-based solidification, focusing on waste characterisation, handling procedures, safety protocols and regulatory compliance. Ongoing training sessions can help keep employees up to date with evolving regulations.

Engaging with Regulatory Authorities: Establishing open lines of communication with regulatory authorities is crucial for compliance. Organisations should actively engage with these authorities, seeking guidance and clarifications when needed. Proactive communication can help organisations understand and address any regulatory concerns and ensure a collaborative approach to compliance.

Continuous Improvement: Compliance is an ongoing process that requires organisations to continually assess and improve their practices. Regular internal audits, reviews and assessments can help identify areas for improvement and ensure that processes and procedures are in line with regulatory requirements. Incorporating lessons learned and best practices from the industry can further enhance compliance efforts.

Documentation and Record-Keeping: Maintaining accurate and detailed documentation is vital for demonstrating compliance. Organisations should establish robust record-keeping systems to document waste characterisation, operational procedures, quality control measures and regulatory interactions. These records serve as evidence of compliance and can be used for audits, inspections and regulatory reporting.

By adopting these approaches, organisations can enhance their compliance with regulations governing cement-based solidification of nuclear waste. Compliance not only ensures adherence to legal requirements but also contributes to safe waste management practices, protecting human health and the environment.

7.3. Comparison of regulations in different regions

Regulations regarding cement-based solidification of nuclear waste can vary across different regions due to varying legal frameworks, national priorities and technological capabilities. While it is challenging to provide an exhaustive comparison, here are some general points of differentiation in regulations across regions.

7.3.1. United States

Regulations in the United States regarding cement-based solidification of nuclear waste have evolved over time to ensure the safe and effective management of radioactive materials. Stegemann and Cote (1996) proposed a protocol for evaluating solidified wastes, which served as a foundation for assessing the performance and compliance of cement-based waste forms. This protocol included rigorous testing procedures to evaluate the structural integrity, leachability and long-term stability of the solidified waste. Additionally, regulatory agencies such as the Nuclear Regulatory Commission (NRC) and the Environmental Protection Agency (EPA) established guidelines and requirements for waste characterisation, disposal and monitoring. According to Bayoumi and Saleh, 2018, the dry fuel storage containment management should follow 10 elements: (1) scope of program (2) preventive actions (3) parameters monitored or inspected (4) detection of aging effects (5) monitoring and trending (6) acceptance criteria (7) corrective actions (8) confirmation process (9) administrative controls (10) operating experience (www.nrc.gov). These regulations aimed to protect public health and the environment by setting standards for waste immobilisation, storage and transportation. The research conducted by Hartmann et al. (1999) investigated the effect of supercritical carbon dioxide treatment on the leachability and structure of cemented radioactive waste-forms, contributing to the understanding of waste form improvement. The study by Shi and Spence (2004) emphasized the importance of designing cement-based formulations tailored to specific waste types to achieve effective solidification and stabilisation. Compliance with these regulations and guidelines ensured that cement-based solidification of nuclear waste met stringent criteria for safety and environmental protection in the past.

7.3.2. European union

The European Union has a comprehensive framework for the management of radioactive waste, with general requirements outlined in the EU Directive on the management of spent fuel and radioactive waste. While the directive provides a broad framework, individual member states have the authority to establish their own specific regulations and guidelines for waste management, including cement-based solidification. As a result, there may be variations in regulations across EU member states based on their national priorities, technological capabilities and waste management strategies.

Cowgill (1991) conducted a study comparing different solidification media for the stabilisation of low-level radioactive wastes. Although this specific study focuses on the comparison of solidification media rather than regulations, it provides valuable insights into the effectiveness of different stabilisation methods. Kearney et al. (2022) discussed cement-based stabilisation/solidification of radioactive waste in the context of low carbon stabilisation and solidification of hazardous wastes. While the specific regulations in the EU are not discussed in detail, the authors provide an overview of the challenges and considerations in using cement-based techniques for radioactive waste immobilisation.

7.3.3. Canada

In Canada, the management of nuclear waste is primarily regulated by the Canadian Nuclear Safety Commission (CNSC). The CNSC is responsible for ensuring the safe and secure use, storage and disposal of nuclear substances, including radioactive waste. The CNSC has established regulatory requirements and guidelines for the management of radioactive waste, including cement-based solidification. These regulations aim to protect human health, safety and the environment during the handling, storage and disposal of nuclear waste.

The specific requirements for cement-based solidification of nuclear waste may vary depending on the type and level of radioactive materials involved. The CNSC sets criteria for the selection and use of appropriate cement-based materials, as well as the design and construction of waste containers and disposal facilities. The regulations also address the long-term performance and stability of the cement-based waste forms. This includes considerations for the potential release of radionuclides over time and the prevention of any detrimental effects on the surrounding environment. To ensure compliance with the regulations, licensees and waste management organisations are required to develop and implement waste management plans that demonstrate the safe and effective use of cement-based solidification for nuclear waste. These plans undergo review and approval by the CNSC. In addition to the CNSC regulations, provincial and territorial authorities may also have their own regulations and requirements for the management of radioactive waste, including cement-based solidification. It is important for organisations involved in the cement-based solidification of nuclear waste in Canada to stay updated on the applicable regulations and ensure compliance to maintain the safety and security of radioactive waste management practices.

7.3.4. Japan

In Japan, the regulation and management of radioactive waste, including cement-based solidification, are overseen by the Nuclear Regulation Authority (NRA). The NRA is responsible for ensuring the safety and security of nuclear facilities and materials, as well as the proper management of radioactive waste. The regulatory framework in Japan for cement-based solidification of nuclear waste is guided by the Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors. This act sets out the requirements for the safe handling, storage and disposal of radioactive waste.

The NRA has developed regulations and guidelines that specify the technical requirements for cement-based solidification of nuclear waste. These regulations cover various aspects, including the selection and use of appropriate cementitious materials, the design and construction of waste containers and packages and the long-term performance and stability of the solidified waste forms. The regulations in Japan also address the management and disposal of cement-based solidified waste. This includes requirements for storage facilities, transportation procedures and monitoring and reporting obligations. In addition to the NRA, other government agencies, such as the Ministry of Economy, Trade and Industry (METI) and the Ministry of the Environment (MOE), may also play a role in the regulation and oversight of cement-based solidification of nuclear waste.

7.3.5. International atomic energy agency (IAEA)

The International Atomic Energy Agency (IAEA) is an international organisation that provides guidance and recommendations on nuclear safety, including waste management. The IAEA's publications, such as the Safety Standards Series and Technical Reports Series, offer guidance on cement-based solidification practices, emphasizing safety, effectiveness and international best practices. The IAEA's guidelines aim to promote harmonization and encourage the adoption of standardized approaches while allowing flexibility for each country's specific regulatory framework.

It is important to note that regulations and requirements in each region can evolve over time. National priorities, scientific understanding and technological advancements influence the development and updates of regulatory frameworks. Therefore, it is crucial to refer to the latest regulations and consult the relevant regulatory authorities in each specific region for accurate and up-to-date information on cement-based solidification of nuclear waste.

8. Areas for further research and development

Areas for further research and development in the field of cement-based solidification of nuclear waste include improving the long-term stability and performance of waste forms, optimizing the composition and design of cementitious materials, enhancing waste encapsulation techniques and studying the behaviour of solidified waste under various environmental conditions.

1. Alternative Cementitious Materials: Investigating the potential use of alternative cementitious materials, such as geopolymers or blended cements, could provide opportunities for enhancing the performance and long-term durability of cement-based solidification. Research should focus on understanding their chemical and physical properties, as well as their interactions with nuclear waste components.
2. Waste Stream Compatibility: Further studies are needed to assess the compatibility of different waste streams with cement-based solidification formulations. Research should aim to identify potential challenges, such as variations in waste composition and develop strategies to optimise the solidification process for diverse waste types.
3. Optimization of Formulations: Continued research is essential to optimise the composition and properties of cement-based solidification formulations. This includes investigating the influence of various additives, admixtures and supplementary cementitious materials on the performance, workability and long-term stability of the solidified waste form.
4. Long-Term Performance Assessment: Extending the understanding of long-term performance is crucial. Research should focus on evaluating the behaviour of cement-based solidified waste over extended periods, including factors such as leaching, chemical stability, mechanical strength and resistance to environmental conditions. Long-term monitoring and predictive modelling can provide insights into the overall performance and potential degradation mechanisms.
5. Sustainable and Low-Carbon Technologies: Exploring sustainable and low-carbon approaches in cement-based solidification is a pressing research area. Investigating the use of alternative materials, reducing carbon emissions during cement production and developing more energy-efficient curing processes can contribute to environmental sustainability and reduce the ecological footprint of solidification techniques.
6. Innovative Testing Methods: Developing advanced testing methods to assess the performance of cement-based solidified waste can improve accuracy and efficiency. This includes non-destructive evaluation techniques, advanced imaging methods and in-situ monitoring to study microstructural changes, identify potential degradation mechanisms and enhance quality control during solidification.
7. Repository Considerations: Studying the behaviour of cement-based solidified waste in repository conditions is crucial for long-term disposal. Research should focus on the interaction between the solidified waste and the repository environment, including factors such as temperature, moisture and chemical interactions, to ensure the safety and stability of the waste form over time.
8. Regulatory Frameworks and Standardisation: Further research is needed to develop standardised protocols, guidelines and best practices for cement-based solidification. This includes harmonizing regulatory requirements, addressing technical challenges and ensuring compliance with safety and environmental regulations.

In summary, further research and development in the areas mentioned above will contribute to enhancing the effectiveness, performance and sustainability of cement-based solidification for nuclear waste. Continued scientific investigations, technological advancements and collaboration between researchers, industry and regulatory bodies are essential to address the challenges and optimise the application of this solidification technique.

9. Concluding remarks

Cement-based solidification stands out as a widely embraced and efficient method for immobilizing nuclear waste, having been employed in the nuclear industry for decades. This process entails blending the waste with cementitious materials, predominantly Portland cement, to establish a solid matrix that effectively encapsulates and immobilizes radioactive elements. The method's proven effectiveness and practicality have contributed to its extensive use in the nuclear sector.

A notable advantage of cement-based solidification lies in its straightforwardness and ease of application. Cement, a widely available construction material, facilitates easy access for waste immobilisation. The procedure involves mixing the waste with cementitious materials and subsequent curing to solidify the mixture. This simplicity allows for efficient implementation and scalability, catering to both small-scale and large-scale waste management operations. Moreover, the versatility of cement-based solidification accommodates various types of nuclear waste, including liquids, sludges, and solids. The thorough mixing ensures uniform distribution and encapsulation within the solid matrix, offering multiple barriers to prevent the release of radionuclides.

Despite these benefits, challenges associated with cement-based solidification necessitate attention. A significant concern revolves around the long-term durability of the cement matrix. Factors such as chemical reactions, physical stresses, and environmental conditions can potentially compromise the structure over time, affecting its ability to contain the waste. Hence, careful selection of cementitious materials, additives, and facility design is imperative to ensure the sustained performance and integrity of the solidified waste forms. Additionally, specific radionuclides may require alternative treatment methods if not adequately immobilised by cement-based solidification alone. Long-lived radionuclides with high solubility or unique chemical characteristics may demand tailored approaches to meet their immobilisation requirements.

In summary, cement-based solidification remains a widely utilized and effective technique for nuclear waste immobilisation due to its simplicity, versatility, and cost-effectiveness. The resulting cementitious matrix provides robust barriers against radionuclide release. However, the challenge of ensuring the long-term durability of the cement matrix underscores the need for ongoing research and development efforts. Continuous improvements in solidification techniques are crucial for ensuring the safe management and disposal of nuclear waste, safeguarding both human health and the environment for current and future generations.

CRediT authorship contribution statement

Salim Barbhuiya: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Bibhuti Bhusan Das:** Writing – review & editing. **Tanvir Qureshi:** Writing – review & editing. **Dibyendu Adak:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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