Journal of Nuclear Materials 634 (2026) 157116

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Review

Magnesium potassium phosphate cement for low- and intermediate-level radioactive waste conditioning: advances, limitations and future trends

C. Fernández-García [a,*], P. Padilla-Encinas [b], R. Fernández [b], M. Criado [a], I. García-Lodeiro [a], E. Torres [c], M.C. Alonso [a]

[a] Institute of Construction Science "Eduardo Torroja" (IETcc), CSIC, Serrano Galvache 4, Madrid, 28033, Spain
[b] Department of Geology and Geochemistry, Faculty of Science, Universidad Autónoma de Madrid, Madrid, 28049, Spain
[c] Environmental HydroGeoSciences Unit, CIEMAT, Av. Complutense 40, Madrid, 28040, Spain

ARTICLE INFO

Keywords:
LILRW immobilisation
Cementitious wasteforms
Magnesium potassium phosphate cement
Reactive metals
Ion-exchange resins
Durability

ABSTRACT

Low- and intermediate-level radioactive waste (LILRW) comprises a highly heterogeneous range of materials that require immobilisation matrices capable of ensuring mechanical stability, chemical compatibility, and limited radionuclide mobility over extended time scales. Conventional cementitious binders, such as Portland cement (PC) and alkali-activated systems, are widely used for waste conditioning but may present limitations when applied to waste streams incompatible with highly alkaline environments, including certain reactive metals and ion-exchange resins. Magnesium potassium phosphate cement (MKPC) has emerged as a promising alternative binder due to its near-neutral pore solution pH, low water demand, rapid setting behaviour, and the formation of stable crystalline phases such as K-struvite. This review synthesises current knowledge on MKPC as a conditioning matrix for LILRW, with particular attention to the formulation parameters that control its reaction kinetics, phase assemblage, and the microstructural development. Key aspects examined include MgO reactivity, MgO/KH_2PO_4 molar ratio, water content, chemical retarders, mineral additions, and curing conditions. The implications of these parameters for key material properties relevant to waste immobilisation, such as mechanical strengths, pore solution chemistry, porosity, durability under leaching, corrosion and irradiation, are critically assessed. Overall, the available evidence highlights the potential of MKPC as a promising binder for challenging LILRW streams, while also identifying key knowledge gaps related to long-term performance under repository-relevant conditions, radionuclide retention mechanisms, broader radionuclide coverage, and formulation optimisation before large-scale implementation can be fully realised.

1. Introduction

Radioactive waste comprises materials containing radionuclides at activity concentrations above regulatory thresholds for which no further use is foreseen [1]. Although classification systems vary across countries, most follow international guidance and distinguish very low-level, low- and intermediate-level, and high-level waste according to activity and half-life.

Low- and intermediate-level radioactive waste (LILRW) represents the largest and most heterogeneous category by volume, posing significant challenges for management and conditioning [2]. Unlike high-level waste, largely associated with spent fuel, LILRW includes a wide range of materials such as metallic residues (e.g. aluminium, beryllium or uranium), organic wastes including spent ion-exchange resins (SIERs), sludges, evaporator concentrates, and various medical, industrial and research by-products. These waste streams commonly contain radionuclides such as ^{137}Cs, ^{90}Sr, ^{60}Co and actinides at levels requiring long-term isolation [2]. This compositional diversity complicates both short- and long-term stabilisation and requires conditioning approaches tailored to the specific characteristics of each waste type.

Near-surface disposal facilities (NSDF) are widely adopted for LILRW management. In these systems, waste is immobilised in cementitious matrices (wasteforms) and encapsulated in metallic drums, which are placed within engineered barrier systems (EBS) composed of reinforced-concrete cells and vaults. The drums are surrounded by a cementitious backfill, while granular materials such as gravel are used at the facility

* Corresponding author.
E-mail address: carla.fernandez@ietcc.csic.es (C. Fernández-García).

https://doi.org/10.1016/j.jnucmat.2026.157116
Received 26 March 2026; Received in revised form 30 July 2026; Accepted 29 September 2026
Available online 30 September 2026
0022-3115/© 2026 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

scale to minimise voids and enhance structural integrity. Together with multilayer cover systems, these barriers are designed to ensure environmental isolation over the approximately 300-year period required for LILRW management [3].

To guarantee performance under these conditions, waste acceptance criteria (WAC) for the wasteform define quantitative limits on key properties, including mechanical strength, leachability and thermal stability. In addition, cementitious wasteforms must satisfy operational requirements related to safe handling and durability throughout their service life [4,5]. These include adequate workability for encapsulating heterogeneous materials, setting times compatible with industrial processes, and controlled heat release to minimise thermal damage. The wasteform must also exhibit low porosity and no bleed water, together with sufficient dimensional, chemical and radiolytic stability to prevent degradation processes such as cracking, corrosion or gas generation, depending on the waste stream. Among these criteria, leachability is particularly critical, as it governs radionuclide release. It is commonly evaluated using standardised methods such as ANSI/ANS 16.1 [6], where performance is expressed through the leachability index (LI), with values above 6 generally indicating satisfactory retention.

Within this framework, the cementitious binder plays a central role in determining wasteform performance. Portland cement (PC) and related calcium silicate systems have long been the reference materials for LILRW immobilisation [5]. They are widely available, compatible with many aqueous wastes and capable of developing adequate strength and dimensional stability. Their high alkalinity also favours radionuclide retention through solubility control and incorporation into hydration products. However, this same alkaline environment (pH > 12.5) falls outside the passivation range of several reactive metals, promoting corrosion and sustained hydrogen generation during storage [7]. In addition, SIERs can induce swelling and microcracking in PC matrices, compromising integrity and facilitating radionuclide migration [8]. The relatively high-water content of PC systems further enhances radiolysis and gas accumulation. These limitations highlight the need for alternative binders with improved chemical compatibility for specific waste streams.

Considerable research is being devoted to alternative cementitious systems. Alkali-activated materials (AAMs), particularly those formulated with low-calcium precursors, have shown promising radionuclide retention through sorption and incorporation into their sodium–alumino–silicate–hydrate (N–A–S–H) phases [9,10]. Nevertheless, their highly alkaline pore solution reproduces many of the limitations observed in PC when applied to reactive metals or organic-rich wastes.

Magnesium potassium phosphate cement (MKPC) has emerged as a promising alternative for LILRW immobilisation [11], combining a near-neutral pore solution, low water demand, rapid setting and the formation of a stable K-struvite phase, which enhance chemical compatibility and processing behaviour [12]. These features position MKPC favourably within the design space of LILRW immobilisation matrices, particularly for waste streams that are difficult to stabilise with conventional binders, such as reactive metals (e.g., aluminium) and organic ion-exchange resins, where highly alkaline environments promote degradation processes including corrosion, gas generation and matrix deterioration [13–15]. However, its applicability remains waste-dependent, and for waste streams already compatible with PC or AAMs, its use must be justified against additional cost and process-related constraints. Further work is therefore required to optimise formulation design and to clarify key aspects related to phase stability, degradation mechanisms, and long-term behaviour under repository conditions, all of which remain insufficiently understood.

This review provides a critical synthesis of current knowledge on MKPC as a wasteform binder for LILRW immobilisation. Unlike previous reviews [12,16–18], which have focused mainly on the fundamental chemistry of MKPC and its engineering and construction-related applications, this work specifically addresses its use for radioactive waste management. It critically examines how MKPC formulation parameters influence wasteform performance for LILRW immobilisation. The review demonstrates that careful control of mix composition governs the physical, chemical, and mechanical properties critical to wasteform stability, providing a basis for the design and optimisation of matrices adapted to different waste streams. Building on this framework, it evaluates the suitability of MKPC for challenging waste streams, its long-term durability under repository-relevant conditions, including leaching, corrosion, and radiation effects, and its potential for large-scale implementation through life-cycle and scalability considerations. By integrating these aspects into a single framework, the review distinguishes between applications where MKPC offers clear advantages and those where its use remains less favourable or only potentially competitive. It also consolidates the available evidence, identifies key knowledge gaps, and clarifies the role of MKPC as a viable alternative to conventional binders for LILRW immobilisation.

2. Insights into MKPC as a matrix for LILRW immobilisation

2.1. Fundamentals of MKPC and design considerations

Magnesium potassium phosphate cement (MKPC) is a chemically bonded phosphate binder whose hydration is governed by an acid–base reaction between magnesium oxide (MgO) and monopotassium dihydrogen phosphate (KH_2PO_4, KDP). The reaction proceeds through a dissolution–precipitation mechanism, producing K-struvite ($MgKPO_4{\cdot}6H_2O$) as the principal binding phase (Eq. (1)) [19–23]. Compared with ammonium-based magnesium phosphate cements, which use ammonium dihydrogen phosphate ($NH_4H_2PO_4$, ADP) as the phosphate precursor, the use of KDP avoids ammonia release during setting, making MKPC more suitable for waste conditioning [24]. Although KDP moderates the reaction relative to ADP, MKPC remains characterised by rapid setting and significant heat evolution [24,25]:

$$MgO + KH_2PO_4 + 5H_2O \rightarrow MgKPO_4{\cdot}6H_2O \quad (1)$$

These characteristics make formulation design a key aspect of MKPC for LILRW immobilisation. Since waste streams differ markedly in chemical composition, physical characteristics and waste loading requirements, no single formulation is universally applicable. Instead, the binder must be tailored by controlling a series of interrelated variables, including MgO characteristics, the magnesium-to-phosphate molar ratio (M/P), water content, typically expressed as either the water-to-binder (w/b) or water-to-phosphate (w/P) ratio, the type and dosage of retarders, supplementary mineral additions and curing conditions [26]. Together, these variables govern reaction kinetics, phase assemblage and microstructural evolution, ultimately determining the processing behaviour and long-term performance of the wasteform.

Despite extensive experimental research, the level of understanding differs considerably among these formulation variables. A bibliometric

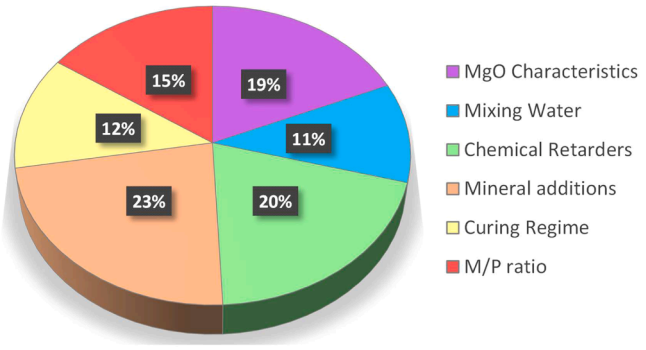


Fig. 1. Distribution of research on key MKPC formulation parameters from 1988 to 2026, based on sixty-five publications indexed in Scopus.

survey of sixty-five publications published between 1988 and 2026 (Fig. 1) shows that approximately 60% of the studies focus on MgO characteristics, retarders and supplementary mineral additions, whereas considerably less attention has been devoted to water content and curing conditions. Around two-thirds of the reviewed studies specifically address radioactive waste immobilisation, underscoring the importance of formulation optimisation for LILRW while highlighting variables that remain comparatively underexplored.

The principal formulation variables are discussed in detail below, focusing on their respective roles, their selection for current LILRW immobilisation practice, and recent approaches to formulation optimisation.

MgO is the principal reactive precursor in MKPC, making its reactivity a key parameter in formulation design. Calcination temperature primarily determines MgO reactivity, whereas particle size and grinding history further influence its dissolution behaviour in acidic phosphate solutions [27]. In order of increasing calcination temperature, MgO is classified as soft-burnt (SB), hard-burnt (HB) or dead-burnt (DB), exhibiting high, moderate and negligible reactivity, respectively, under MKPC conditions [28,29]. HB-MgO has traditionally been the preferred precursor for LILRW immobilisation because its moderate reactivity provides a practical balance between workability and hardening. However, increasing attention is being devoted to lower-calcination, more reactive SB-MgO, whose rapid dissolution can be effectively controlled by adjusting the type and dosage of the retarder admixture together with the M/P molar ratio, enabling controlled setting while maintaining comparable phase assemblages and matrix development [30,31]. Its lower calcination temperature also reduces energy consumption and material costs, making it an attractive option for large-scale applications.

To control the rapid acid–base reaction between MgO and KH_2PO_4, chemical retarders are incorporated in MKPC formulations to extend workability and moderate early heat evolution. Boron-based compounds, particularly boric acid (H_3BO_3) and borax ($Na_2[B_4O_5(OH)_4]\cdot 8H_2O$), have traditionally been the preferred retarders for LILRW immobilisation because they temporarily inhibit MgO dissolution in formulations based on HB- and DB-MgO [32,33]. However, their effectiveness decreases markedly with highly reactive SB-MgO, while their use is increasingly constrained by regulatory concerns arising from the classification of boron compounds as potential carcinogenic, mutagenic or reprotoxic (CMR) substances [34]. These limitations have stimulated the use of alternative retarders, including sodium thiosulfate ($Na_2S_2O_3$) [35], sodium triphosphate ($Na_5P_3O_{10}$) [36], aluminium nitrate [$Al(NO_3)_3\cdot 9H_2O$] [37], and sodium gluconate [38], among others, to achieve effective reaction control in highly reactive formulations while reducing reliance on boron-based systems.

Supplementary mineral additions are also incorporated into the mix design as inert or semi-reactive fillers to further tailor workability, reaction kinetics and microstructural development. Their partial replacement of MgO and/or KH_2PO_4 reduces the direct contact between reactants, slowing the dissolution–precipitation process and thereby extending setting time while lowering heat release [12]. At the same time, they reduce precursor consumption and material costs. Among the mineral additions investigated, fly ash (FA) and blast furnace slag (BFS) have traditionally been the most widely used for LILRW immobilisation because of their favourable particle characteristics and ability to enhance matrix cohesion while moderating heat evolution [39]. However, their role extends beyond a simple filler effect, as many additions contain reactive oxides (e.g., CaO, ZnO, Al_2O_3, Fe_2O_3 and residual MgO) capable of interacting with phosphate species and modifying hydration reactions depending on their composition and replacement level [40]. More recently, attention has expanded to alternative supplementary mineral additions, including metakaolin (MK) and silica fume (SF), among others [41–46], selected according to their physical and chemical characteristics to optimise fresh-state behaviour, phase development and dimensional stability while accommodating the diverse characteristics of LILRW streams.

Beyond the solid constituents, the amount of mixing water is equally important in MKPC, governing reactant dissolution, fresh-state workability and microstructural development. Water acts both as a reactant in K-struvite formation and as the medium enabling homogeneous mixing and ion transport, making adequate water contents essential for efficient reaction progression [47,48]. According to Eq. (1), water contents approaching the stoichiometric requirement (w/P mass ratio = 0.662; w/b ratio = 0.51) have traditionally been preferred for LILRW immobilisation, as they provide sufficient ionic mobility for hydration while limiting residual porosity after hardening [49,50]. However, both insufficient and excessive water contents compromise matrix development by restricting the acid–base reaction or increasing residual porosity, respectively [51]. Accordingly, recent studies have focused on adjusting the mixing water ratio to achieve an appropriate balance between workability and matrix densification, with current formulations typically employing w/b ratios between 0.14 and 0.25 [52–54].

In parallel, the chemical balance between the reactive precursors is another key aspect of MKPC design and is controlled by the magnesium-to-phosphate (M/P) molar ratio, which determines the extent of K-struvite formation, thereby governing the development of the hardened matrix [55,56]. M/P ratios slightly above the theoretical stoichiometric value (M/P = 1) have traditionally been preferred for LILRW immobilisation because only a fraction of the MgO particles dissolves during the acid–base reaction, requiring a moderate excess of MgO to sustain K-struvite precipitation [16]. However, excessively high M/P ratios increase the amount of residual MgO within the hardened matrix, which may subsequently hydrate to brucite [$Mg(OH)_2$] under favourable moisture conditions [57]. Although MKPC systems generally tolerate higher residual MgO contents than Portland cement (typically limited to <5 wt.% [58]), owing to the partial encapsulation of MgO particles by K-struvite, excessive MgO contents remain detrimental to matrix optimisation. Current optimisation efforts therefore seek to maximise K-struvite formation while limiting residual MgO, thereby promoting a denser and more chemically stable matrix for waste immobilisation.

After mixing, the curing regime ultimately governs MKPC by controlling reaction kinetics, K-struvite formation and microstructural development [59]. Ambient curing (22 ± 2°C) under moisture-controlled conditions has traditionally been adopted for LILRW immobilisation because it provides sufficient moisture for reactant dissolution, sustained K-struvite precipitation and matrix densification [60,61]. However, both insufficient and excessive moisture adversely affect hydration by limiting reaction progress or promoting partial K-struvite dissolution and the leaching of soluble species, respectively. Likewise, although moderate temperatures (<30°C) accelerate MgO dissolution, K-struvite precipitation and early strength development, prolonged exposure to higher temperatures (~50°C) can induce the beginning of K-struvite dehydration and microstructural degradation [62,63]. Current research is increasingly directed towards reproducing disposal-relevant curing conditions, particularly through isolated curing, while the influence of seasonal temperature fluctuations remains largely unexplored.

2.2. Design-derived variables governing MKPC performance

The formulation and curing variables discussed in Section 2.1 ultimately determine the performance of MKPC wasteforms for LILRW immobilisation by governing the chemical and microstructural evolution of the hardened matrix. Their combined influence is reflected in a series of complementary performance indicators describing its structural integrity, durability and chemical stability. Understanding the relationship between these indicators and the governing variables is therefore essential for the rational design of safe and durable wasteforms.

Among these indicators, mechanical strength provides the most direct assessment of the material's ability to withstand handling, storage

and disposal. Across the available literature, it is consistently governed by the M/P ratio, supplementary mineral additions, water availability and curing conditions, which together determine the extent of K-struvite formation and matrix densification. Increasing the M/P ratio generally enhances strengths by promoting a more complete reaction, although excessive MgO contents may become detrimental owing to the accumulation of residual MgO and its subsequent hydration to brucite [44,55–57,60]. Likewise, supplementary mineral additions generally improve mechanical performance through enhanced particle packing and matrix cohesion, with the magnitude of the improvement depending on the filler type [56,61,64]. Water availability also plays a decisive role, as lower water contents and curing strategies that minimise moisture exchange with the surrounding environment promote matrix densification by reducing residual porosity and preserving the integrity of the K-struvite network, whereas excess water or prolonged immersion have the opposite effect [31,59,60,64,65]. Collectively, the available evidence indicates that mechanical performance is maximised through the combined optimisation of reactant stoichiometry, filler selection and water management, providing mechanically robust MKPC wasteforms for the long-term immobilisation of LILRW.

Porosity governs the transport of water and dissolved species through the hardened matrix and is therefore a key performance indicator for MKPC wasteforms. Rather than being controlled by a single formulation variable, pore structure results from the combined effects of MgO reactivity, retarder selection, the M/P ratio and curing conditions [25,60,66]. Compared with HB-MgO, SB-MgO promotes a finer pore network owing to its higher reactivity, while sodium thiosulfate produces greater pore refinement than boric acid by increasing the proportion of pores smaller than 0.1 μm [66]. Increasing the M/P ratio generally results in higher porosity, whereas isolated curing consistently produces lower porosity than high-humidity curing by limiting moisture exchange and preserving a denser microstructure [25,60]. These observations demonstrate that minimising porosity requires the combined optimisation of MgO reactivity, retarder selection, reactant stoichiometry and curing conditions, thereby promoting a refined and less connected pore network that restricts fluid transport and enhances the long-term durability of MKPC wasteforms for LILRW immobilisation.

Long-term wasteform performance also depends on the chemical environment established within the hardened matrix. Pore solution pH provides a key indicator of this environment because it governs the compatibility of MKPC wasteforms with LILRW streams sensitive to pH variations. The available literature identifies the M/P ratio, filler type and curing conditions as the principal factors controlling pore solution pH, whereas MgO reactivity, retarder selection and the w/b ratio have little effect within the investigated ranges [66–68]. Increasing the M/P ratio consistently raises pore solution pH owing to the greater amount of unreacted MgO and the associated release of hydroxyl ions [44,60]. Likewise, Ca-bearing fillers such as wollastonite produce more alkaline pore solutions than aluminosilicate fillers, reflecting their different chemical compositions and interactions with the cement matrix [61]. High-humidity curing also results in slightly higher pore solution pH than isolated curing, probably because the greater availability of moisture promotes MgO hydration and dissolution [60]. Overall, pore solution pH can be tailored through the combined optimisation of reactant stoichiometry, filler type and curing conditions, thereby maintaining the mildly alkaline conditions required for the long-term chemical compatibility of MKPC wasteforms with some LILR waste streams.

Beyond pH, the ionic composition of the pore solution also defines the chemical environment experienced by the immobilised waste by determining the dissolved species available for interaction with the wasteform. In conventional MKPC formulations prepared with KDP, HB-MgO and boric acid, the pore solution is primarily composed of phosphate species ($H_2PO_4^-$ and HPO_4^{2-}) together with borate species ($B(OH)_4^-$ and $H_2BO_3^-$). Current evidence indicates that pore solution chemistry is mainly governed by the M/P ratio, curing conditions and the water-to-binder ratio. Increasing the M/P ratio reduces the concentration of dissolved phosphate species owing to the lower initial phosphate content and its greater incorporation into K-struvite [60]. Likewise, isolated curing maintains relatively stable ion concentrations, whereas high-humidity curing promotes the incorporation of phosphate species into hydration products. Increasing the w/b ratio decreases phosphate and borate concentrations because of pore solution dilution [67,68]. Collectively, these findings show that pore solution chemistry can be tailored through the combined optimisation of reactant stoichiometry, curing conditions and water content, providing a chemically stable environment for the long-term immobilisation of LILRW.

Table 1 summarises the influence of the principal formulation and curing variables on the performance indicators discussed in this section, providing a comparative overview of the experimental evidence reported after 28 days of ageing. Building on these relationships, Table 2

Table 1
Literature data compilation summarising the influence of the principal MKPC design variables on the key performance indicators relevant to LILRW immobilisation after 28 days of curing.

Variable *(reported formulation)*	Performance indicator (28 days)			
	Mechanical strength	Porosity	Pore solution pH	Ion content
MgO *(B, M/P =1)*	• HB vs SB: 10 MPa [31,60] • SB: 35 MPa [69]	SB: pore refinement (<0.1 μm) compared with HB [66]	HB vs SB: no changes (pH 7.5) [66]	-
Retarder *(M/P = 1)*	-	• B-T: 8%, no changes [66] • T: refinement (<0.1 μm)	B vs T: no changes (pH 7.5) [66]	-
Filler *(B, HB)* *(M/P = 1)*	• 10-60%: 40 to 75 MPa [56,64] • PM: 5 MPa; WO: 20 MPa [61] • FA & MK: 35 MPa [61]	-	• FA, MK, PM: 7.5 [61] • WO: 8.5 [61]	-
M/P ratio *(HB, B)*	• M/P = 1: ~10 MPa [55,60] (effl.) • M/P = 2-3: 10-30 MPa [44,55,56,60] • M/P = ≥4: 40-50 MPa [44,55–57] (brucite)	Under isolation: • M/P = 1-3: 10-12% [60] • M/P = 4-12: 8-14% [25]	Under isolation: • M/P = 1: 7.5 [44,60] • M/P = 2-4: 10.5 [44,60]	• M/P = 1 [60]: initial ↑P & ↑B • M/P 2-3 [60]: ↓P content
Curing *(HB, B)*	• Isolated: 15-40 MPa (M/P = 1-3) [59,60,65] • 50% RH: 13 MPa (M/P = 1) [65] • 100% RH: 10 MPa (M/P = 1) [31,60] • Water immersion: 20 MPa (M/P = 1) [65]	At M/P ratio = 1: • Isolated: 9 [60] • 100% RH: 10.5 [60]	At M/P ratio = 1: • Isolated: 7.5 [60] • 100% RH: 8 [60]	• Isolated: no changes [60] • 100% RH: ↓P & ↓B [60]
w/b; w/P *(HB, B)* *(M/P = 1)*	• w/b = 0.14: 70 MPa [64] • w/b = 0.20: 50 MPa [64]	-	w/b = 0.5-1: no changes (pH 7.8) [67,68]	w/b = 0.5-1: ↓P & ↓B [67,68]

Legend: B: boric acid; T: thiosulfate; SB: soft-burnt; HB: hard-burnt; w/b: water/binder ratio; w/P: water/phosphate ratio; FA: fly ash; MK: metakaolin; PM: pumice; WO: wollastonite; M/P: $[MgO]/[KH_2PO_4]$ ratio; effl: efflorescences.

Table 2
Design framework for MKPC wasteforms intended for LILRW immobilisation, summarising recommended formulation parameters, target performance indicators and their underlying rationale derived from the available literature.

Parameter	Typical range/ parameter	Recommended window	Justification for recommended range
MgO grade	HB MgO SB MgO + adapted retarder	HB MgO SB MgO + non-CMR retarder	HB provides controlled reactivity; SB is suitable when combined with effective retarders to ensure adequate workability and avoid flash setting.
M/P ratio *(molar)*	~2 – 4	2 – 3	Ratios of 2–3 maximise K-struvite formation while limiting excess MgO, providing high strength, mildly alkaline pH, and avoiding brucite-induced expansion and microcracking.
w/b ratio *(mass)*	~0.14 – 0.25	0.16 – 0.22	Balances workability and matrix densification; lower values hinder hydration, whereas higher values increase porosity and reduce strength.
w/P ratio *(mass)*	~0.6 – 0.7	0.60 – 0.68	Close to the stoichiometric water requirement for K-struvite, ensuring sufficient dissolution and hydration whilst limiting free water, porosity and leaching.
Retarder type	B-based: HB/DB-MgO Thiosulfate/other: SB-MgO	Non-CMR (thiosulfate): SB-MgO Boric acid/borax: HB/ DB-MgO	Balances reaction control and regulatory acceptance; non-CMR retarders are preferred for highly reactive matrices, whereas borates remain effective with less reactive MgO grades.
Retarder dosage *(% wt./b)*	~1 – 5% of MgO	2 – 4%	Sufficient to extend workability and moderate heat evolution without excessively delaying hardening; lower dosages risk flash setting, whereas higher dosages may impair early strength.
Filler type	FA, MK, PM, WO…	Aluminosilicates: FA, MK, PM…	Refines the pore network, improves packing and rheology, and maintains pore solution pH within the neutral-to-mildly alkaline range compatible with LILW and steel containers.
Filler content *(% wt./b)*	~10 – 30%	15 – 25%	Controls heat evolution and porosity while maintaining high strength and effective encapsulation of diverse LILW streams.
Waste loading *(% vol.)*	~20 – 40% (metallic LILW)	25 – 35%	Maximises repository efficiency while maintaining workable rheology, complete encapsulation and homogeneous wasteforms.
Mechanical strength	≥ national WAC	20 – 40 MPa	Exceeds typical regulatory requirements, providing a safety margin for handling, transport and disposal while remaining readily achievable with well-designed MKPC formulations.
Porosity	< 10–15%	< 10%	Low porosity limits water and ion transport, supporting long-term durability and reducing leaching under repository conditions.
Pore pH	~7 – 9.5	7.5 – 9.0	Sufficiently alkaline to stabilise the MKPC matrix while minimising corrosion of encapsulated metals.

Legend: SB: soft-burnt; HB: hard-burnt; w/b: water/binder; w/P: water/phosphate; FA: fly ash; MK: metakaolin; PM: pumice; WO: wollastonite; M/P: [MgO]/[KH_2PO_4].

presents the recommended formulation parameters, target performance indicators and the corresponding design rationale for MKPC wasteforms intended for LILRW immobilisation. The proposed ranges provide practical guidance for formulation design based on the available experimental evidence but should be adapted to the characteristics of the waste stream and validated under representative curing conditions, waste loadings and scale-up scenarios.

3. Applicability of MKPC for LILRW immobilisation

The use of MKPC for LILRW immobilisation has gained increasing attention due to its chemical adaptability and versatile microstructural development. Compared with conventional PC and its blended variants (e.g., CEM I–SF [70], CEM I–BFS [71], CEM III [72]) as well as alternative binders such as AAMs [73], calcium sulfoaluminate cements (CSA) [74], calcium aluminate cements (CAC) [75], calcium aluminate phosphate cements (CAP) [76,77], magnesium silicate hydrate cements (M–S–H) [78], and brushite cements [79], MKPC offers a near-neutral pore pH, rapid setting, low water demand, and the formation of a dense K-struvite–based matrix.

These features indicate potential advantages for specific LILRW streams; however, the suitability of MKPC ultimately depends on the chemical and physical characteristics of the waste to be immobilised. Rather than a universal solution, MKPC performance must be evaluated with respect to each waste type's reactivity, interaction pathways, and degradation mechanisms. This section critically examines the applicability of MKPC to representative LILRW categories for which experimental evidence is available, focusing mainly on reactive metals and spent ion-exchange resins (SIERs). Emphasis is placed on chemical stability, matrix–waste interactions, gas-generation behaviour, and long-term durability under disposal-relevant conditions.

3.1. Distinctive advantages of MKPC in the immobilisation of reactive metals

The immobilisation of reactive metals in cementitious matrices depends critically on limiting corrosion processes that may compromise wasteform integrity. A key determinant is the pore solution pH, which dictates whether a metal remains passive or undergoes active corrosion accompanied by H_2 generation.

PC-based systems typically exhibit pore pH values well above the passivation range of metals such as aluminium, uranium, or beryllium, making them less suitable for these waste types. In contrast, the near-neutral pore chemistry of MKPC provides a more compatible environment, aligning more closely with the stability ranges of these metals [7].

A substantial body of evidence now shows that MKPC formulations can markedly reduce corrosion rates and suppress H_2 release during encapsulation. The following subsections examine specific cases, detailing matrix–metal interactions for representative reactive metals. Complementing this discussion, Table 3 summarises key corrosion-related parameters: passivation pH ranges, electrochemical corrosion rates and associated H_2 generation for each metal investigated, offering a direct comparison between PC and MKPC after 100 days of exposure.

3.1.1. Immobilisation of radioactive beryllium

Beryllium poses particular challenges for cementitious encapsulation due to its toxicity, high chemical reactivity and tendency to generate H_2 during corrosion. Under ambient conditions, the metal is protected by a thin BeO/$Be(OH)_2$ passive film, whose stability is strongly governed by the pH of the pore solution when encapsulated in a cementitious matrix. In highly alkaline environments, this film becomes destabilised, triggering active corrosion and associated H_2 evolution, as shown in Eq. (2):

$$Be + 2H_2O \rightarrow Be(OH)_2 + H_2 \quad (2)$$

Experimental studies confirm that beryllium behaviour is largely dictated by pore chemistry: strongly alkaline matrices accelerate degradation, whereas near-neutral to mildly alkaline conditions

markedly improve stability [84,85]. Although the available literature remains limited, comparative investigations of PC, PC–SF, MKPC, CSA and CAC binders consistently indicate that long-term compatibility depends on preserving the passive film and avoiding conditions that promote its breakdown [86–89].

In highly alkaline systems, beryllium may exhibit short-term resistance but typically undergoes progressive corrosion and sustained H_2 release with prolonged exposure [86,90]. In contrast, MKPC matrices, characterised by a near-neutral pore solution (pH 7–10) [60], fall within the reported passivation window for beryllium (pH 5.3–13.5 [84]). Available studies suggest that these conditions promote the formation of a protective beryllium phosphate layer at the metal–matrix interface, progressively limiting corrosion and suppressing H_2 evolution.

Taken together, these findings identify MKPC as a promising candidate for the immobilisation of beryllium-containing waste. Nevertheless, the limited number of available studies precludes definitive conclusions regarding its long-term durability and chemical compatibility, highlighting the need for further evaluation under representative disposal conditions.

3.1.2. Immobilisation of radioactive steel wastes

Although steel is primarily encountered in LILRW management as a container material (most commonly carbon-steel drums), certain legacy wastes, such as those stored in the UK, also contain steel as part of the waste stream itself and may include toxic elements requiring reliable immobilisation [91,92]. In such cases, the binder must be chemically compatible with the metal. Steel stability in cementitious matrices is governed largely by pore-solution chemistry, particularly pH and the presence of species that promote or inhibit passivation.

In PC-based systems, the highly alkaline pore environment promotes the formation of a stable passive oxide film. MKPC matrices, by contrast, develop near-neutral to mildly alkaline pore pH values [60], close to or below the threshold typically associated with steel passivation ($\geq$ 9.8) [7,93]. This raises concerns regarding possible depassivation when steel is directly encapsulated in MKPC. Nonetheless, several studies show that MKPC can still provide effective protection through the formation of phosphate-rich surface layers that act as chemical and physical barriers to corrosion [94].

The stability of these protective layers depends strongly on formulation variables, including the phosphate source, MgO reactivity and retarder type. HB-MgO generally favours more stable interfacial conditions, whereas soft-burnt grades tend to increase corrosion susceptibility [94,95]. Certain retarders, such as boric acid and sodium thiosulfate, can influence steel corrosion behaviour. While effective for controlling setting time, they may impair passivation, with boric acid often associated with less robust protective layers [95,96].

Relative to PC, MKPC may exhibit higher initial corrosion activity, but this typically decreases more rapidly as phosphate-based films mature. Under unfavourable conditions, such as incompatible admixtures or aggressive ions, enhanced gas evolution has been reported, highlighting the need for formulation optimisation when steel is present in the waste stream [95].

Although MKPC does not rely on high alkalinity for steel protection, its phosphate-mediated passivation mechanisms can provide adequate long-term stability when properly designed. Further research remains necessary to confirm performance under repository-relevant conditions.

3.1.3. Immobilisation of radioactive aluminium

Aluminium is particularly challenging to immobilise due to its amphoteric behaviour and strong tendency to generate H_2 upon corrosion. Within a pH window of ~4–9 [7], a passive alumina layer (Al_2O_3) protects the metal; outside this range, especially under alkaline conditions, this film dissolves and corrosion proceeds via water reduction [97], as shown in Eq. (3):

$$2Al + 6H_2O \rightarrow Al_2O_3{\cdot}3H_2O + 3H_2 \quad (3)$$

In PC matrices (pH 12–13.7), aluminium remains highly reactive, producing continuous H_2 and threatening wasteform integrity. By contrast, MKPC systems (typically pH 7–10 depending on formulation) lie within or close to the passivation range and consistently show reduced corrosion and improved chemical compatibility [65,98,99]. Quantitative H_2-release data vary widely due to inconsistent measurement methods: direct gas chromatography usually reports lower values than indirect electrochemical techniques under comparable conditions [98,99], highlighting the need for standardised testing protocols.

Despite methodological differences, the literature consistently identifies a set of formulation and environmental variables that govern aluminium behaviour in MKPC (Fig. 2). The most significant are:

- **Binder composition.** PC and blended cements promote aggressive corrosion. MKPC matrices systematically outperform all PC-based systems, typically yielding H_2 release values 2–3 orders of magnitude lower when formulated at M/P = 1 [65,99,100].
- **M/P ratio.** Lower M/P ratios promote aluminium passivation by maintaining phosphate-rich, moderately alkaline pore solutions. The higher availability of phosphates favours their adsorption onto the metal surface, forming a multilayer in combination with the native passive film, which inhibits corrosion. In contrast, increasing M/P raises pH and reduces phosphate buffering capacity, leading to enhanced corrosion and doubling H_2 evolution across M/P ratios of 1–3 [60,101].
- **Curing moisture.** Under isolated curing, slower MKPC reaction kinetics limit pH rise and retain higher phosphate/borate concentrations, improving inhibition [101]. H_2 release is commonly 2–5 $L/m^2{\cdot}$year lower than under saturated curing, where greater moisture accelerates corrosion [60,100].
- **Alloy composition.** Aluminium–magnesium alloys with >3 wt.% Mg develop more stable surface films and show markedly lower H_2 evolution, while alloys with <3 wt.% Mg are more susceptible, especially at high M/P, where alkalinity increases [60,99,102].
- **MgO reactivity and retarders.** SB-MgO generally yields lower H_2 evolution than HB-MgO due to differences in dissolution behaviour.

Table 3
Comparative summary of passivation pH ranges, corrosion rates, and H_2 gas generation (derived from electrochemical measurements) for key LIL reactive metals in PC and MKPC paste systems.

Radioactive Metallic LILRW	Passivation pH range	PC-ref			MKPC[a]			[Ref]
		Corr. Rate ($\mu m/y$)		Vol. H_2 (L/m^2)	Corr. Rate ($\mu m/y$)		Vol. H_2 (L/m^2)	
		1d	100d		1d	100d		
Beryllium	5.3 – 13.5	0.9	1.9	0.7	0.9	0.1	0.4	[80,81]
Steel	$\geq$ 9.8	0.1	2.6	0.3	42	0.13	2.8	[82]
Aluminium	4 – 9	150	0.3	45	2	0.03	1.5	[82]
Uranium	~ Up to 12	-	-	0.1	-	-	0.01	[23,83]

[a] MKPC: M/P molar ratio = 1 (Hard-burnt MgO/KH_2PO_4) + FA

Retarder type also plays a significant role: thiosulfate-based systems typically reduce corrosion more effectively than borate-based ones, likely through adsorption onto the metal surface, which inhibits corrosion processes [66,95].

- **External alkalinisation.** In NSDFs, wasteforms are typically emplaced in steel drums, delaying direct interaction between MKPC and the surrounding PC-based EBS. However, infiltrating groundwater becomes progressively alkaline as it percolates through the EBS, generating high-pH plumes that may eventually reach the wasteform once container integrity is lost, exposing the matrix to prolonged alkaline conditions. This external alkalinisation represents a plausible long-term degradation scenario for repository safety assessments because it increases pore solution pH, thereby accelerating the corrosion of encapsulated aluminium, with H_2 generation increasing by up to two orders of magnitude and corrosion rates approaching those of PC [95,100,103]. Although generally considered inert, the FA filler may also partially dissolve under sustained alkaline exposure, promoting hydration reactions that further modify the MKPC matrix. By contrast, PC containing a high silica-fume content (~50%) exhibits greater resistance under these conditions. However, the extent and kinetics of this process remain poorly characterised, representing a critical knowledge gap.

Overall, MKPC provides substantially better compatibility with aluminium than PC, largely due to its near-neutral pore chemistry and phosphate-mediated passivation. Nevertheless, careful optimisation of formulation parameters is essential to ensure long-term chemical stability, particularly under conditions where external alkalinisation or suboptimal admixtures could offset its advantages.

3.1.4. *Immobilisation of radioactive uranium wastes*

Uranium presents substantial encapsulation challenges due to its radiological hazards, toxicity, and reactive corrosion behaviour. Metallic U oxidises to UO_2 in the presence of water, generating H_2 and, under certain conditions, forming pyrophoric UH_3 [104]. Because corrosion products are expansive and H_2 accumulation can pose pressurisation and flammability risks, it is essential to control the kinetics of the U to UO_2 transformation. Across available studies, free-water availability consistently emerges as the dominant factor, outweighing the influence of pore-solution pH alone [105].

In PC-based binders, appreciable amounts of unbound water remain after hydration, sustaining long-term oxidation. Numerous campaigns have reported significant H_2 evolution from metallic uranium encapsulated in PC and PC–slag systems, indicating that high alkalinity does not mitigate corrosion when free water is present [11,105]. These results underline the limitations of PC for immobilising metallic U, despite thermodynamic predictions suggesting otherwise.

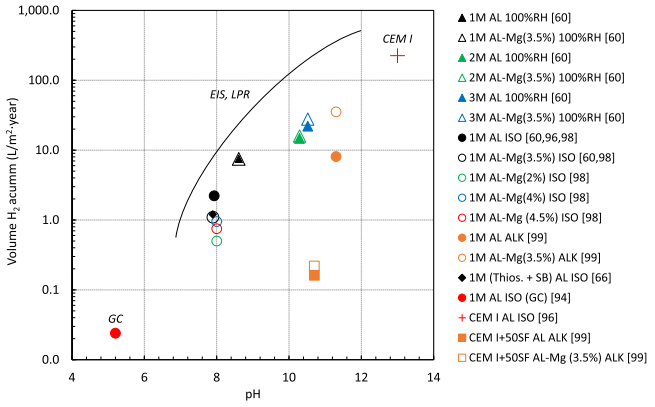


Fig. 2. Cumulative H_2 release (L/m^2·year) from aluminium and Al–Mg alloys immobilised in MKPC and PC-based matrices under different curing conditions (RH, relative humidity; ISO, isolation; ALK, alkaline medium), determined by gas chromatography (GC) and electrochemical methods (EIS, electrochemical impedance spectroscopy; LPR, linear polarisation resistance). Modified from [99].

MKPC matrices create a markedly different environment. Their acid–base reaction binds most of the mixing water into K-struvite, producing a dense matrix with very low free-water content and pore solutions stabilising at near-neutral to mildly alkaline values (~7–9) [106]. Under these conditions, uranium oxidation and associated H_2 release are greatly reduced; long-duration studies show MKPC generating less than half the gas observed in PC under identical conditions [11]. In addition, phosphate-rich pore solutions can promote precipitation of sparingly soluble uranyl phosphate phases, providing an immobilisation pathway absent in Portland-based binders. Independent MPC/MKPC studies consistently report lower corrosion-driven gas release and more stable microstructures than PC [107].

Many uranium-containing wastes also include oxide phases, primarily UO_2, U_3O_8 and UO_3, which differ markedly in solubility and stability. UO_2 is the most stable under reducing conditions, U_3O_8 exhibits intermediate behaviour, and UO_3 is significantly more soluble, requiring stricter immobilisation control [108]. UK regulatory guidance (NDA WPS/230/01–GD) therefore emphasises accurate identification of uranium oxidation states and demonstration of subcriticality.

Comparative leaching studies of cementitious systems (PC–BFS, PC–FA, MPC/MKPC) and borosilicate glasses show that lead borosilicate glass and PC-based matrices provide the highest retention of uranium oxides, with fractional releases several orders of magnitude lower than less favourable binders [109]. Under these conditions, MKPC typically exhibits higher releases for pre-oxidised uranium than PC and borosilicate glass, despite its clear advantages for suppressing corrosion of metallic U.

Overall, immobilisation performance depends strongly on the chemical state of uranium. MKPC provides distinct advantages for metallic uranium due to its low free-water content and phosphate-mediated stabilisation mechanisms, which suppress oxidation and minimise H_2 generation. Conversely, for uranium oxides (particularly UO_2), PC-based matrices and lead borosilicate glasses exhibit superior retention in standard leaching assessments. These contrasting behaviours underscore the need to match binder selection to the specific uranium form present in the waste stream to ensure both effective corrosion control and long-term containment.

3.2. *Distinctive advantages of MKPC in the immobilisation of SIERs*

Spent ion-exchange resins (SIERs), often doped with elements such as B, Li, Zn, Cs, Ni, Cu and Co from plant operation [110], present encapsulation challenges comparable to those of reactive metals due to their organic nature, strong water affinity and the presence of readily leachable radionuclides. In PC-based matrices, these features frequently lead to swelling, cracking or gas evolution, especially under fluctuating humidity, immersion or thermal cycling [111]. This behaviour is further promoted by the highly alkaline pore environment, which can alter the functional groups and polymeric structure of the resins, as well as by the heat released during cement hydration, which may accelerate thermal damage. The severity of these effects increases with resin loading and depends strongly on resin type and binder chemistry.

To overcome these limitations, several alternative binders have been explored, including AAMs [112], CAP cements [76,77] and MPCs [113]. Among them, MKPC offers distinct advantages: its low water demand, near-neutral pore pH, and rapid setting collectively mitigate resin-induced deterioration, although resin-derived species may influence MKPC setting and reaction kinetics. In addition, the main binding phase, K-struvite, can contribute to the retention of various cations through partial substitution of K^+ in its crystal lattice [114,115]. This mechanism has been reported for several monovalent and multivalent cations and may enhance the immobilisation of species such as ^{137}Cs, with reported retention efficiencies approaching 99.89% [14,116].

Within the limited published data, García-Lodeiro et al. [117] studied MKPC formulations containing up to 20 wt.% of a Cs-doped Purolite cationic resin. Resin addition delayed reaction kinetics and increased porosity; nevertheless, all formulations exceeded the 10 MPa WAC requirement after 28 days. K-struvite crystallisation remained unaffected, demonstrating the robustness of the binding mechanism even at relatively high resin loadings. Subsequent leaching tests on MKPC (M/P = 3) containing 15 wt.% resin [13] showed only moderate reductions in compressive strength and minor increases in porosity after 28 days of water immersion. In contrast, anionic ion-exchange resins exhibit limited compatibility with MKPC systems. Their incorporation has been reported to induce expansion and gas evolution during setting, attributed to reactions between ammonium species and phosphate phases leading to ADP formation and ammonia evolution, thereby compromising matrix integrity [118]. Although the removal of ammonium introduced during resin doping partially mitigates these effects, the quaternary ammonium functional groups inherent to the resin remain a major source of instability. Consequently, the incorporation of suitable mineral fillers has been proposed to improve matrix stability and enhance the long-term immobilisation performance.

Overall, MKPC shows clear advantages for cationic SIERs, ensuring adequate mechanical performance and radionuclide retention at moderate loadings. However, incompatibility with anionic resins defines an important formulation constraint. Further research is required to clarify reaction mechanisms, optimise formulations for multi-radionuclide retention, and assess long-term stability under repository conditions.

4. Durability and long-term stability of MKPC wasteforms

The long-term durability of MKPC is a key factor governing its suitability as a conditioning matrix for LILRW. Following disposal in engineered repositories, wasteforms may be exposed to groundwater ingress, alkaline environments generated by adjacent cementitious materials in the EBS, irradiation fields, and variable thermal regimes. These conditions can modify the phase assemblage and microstructure of MKPC, influencing both wasteform integrity and radionuclide confinement. The following sections critically examine the available evidence on leaching resistance, radionuclide retention, irradiation stability and thermal resistance to assess the long-term performance of MKPC relative to conventional PC-based systems.

4.1. Leaching resistance

Leaching is one of the principal degradation processes affecting cementitious wasteforms, as prolonged groundwater contact can dissolve reaction products, alter porosity and compromise matrix durability. Standardised leaching tests are commonly used to quantify the release of soluble species, whereas complementary immersion studies provide insight into the associated microstructural evolution and degradation mechanisms under prolonged aqueous exposure and repository-relevant conditions [119].

Available immersion studies indicate that MKPC exhibits moderate susceptibility to water-induced alteration. Extended exposure causes partial dissolution of K-struvite, its transformation into amorphous phases and the release of soluble ions, particularly K^+ [64,120]. These changes are accompanied by early strength losses of ~10–20% [120]. Detailed investigations further indicate a diffusion-controlled degradation mechanism, characterised by leaching fronts with depleted outer layers and partially transformed intermediate zones [121,122]. Although reactive-transport models have been proposed, their applicability under repository conditions remains to be demonstrated, largely owing to the limited experimental data available for MKPC.

Leaching resistance can be substantially improved through formulation optimisation. Mineral additions such as FA and BFS enhance performance under neutral conditions, with major elements (K, Mg, P and B) typically exhibiting leachability indices above 9, often exceeding those reported for PC matrices (LI < 6) [122]. However, this favourable behaviour deteriorates under highly alkaline conditions representative of cementitious repositories, where groundwater ingress into the cementitious EBS generates alkaline plumes that promote partial dissolution of K-struvite, K^+/Na^+ exchange, increased porosity and the precipitation of secondary phases, including hydroxyapatite and brucite, progressively reducing matrix stability [95,103,123].

Overall, evidence from standardised leaching tests and complementary immersion studies indicates that MKPC exhibits good resistance to aqueous degradation under neutral conditions, particularly when appropriately formulated. Nevertheless, its susceptibility to alkaline alteration remains an important limitation for long-term repository performance and must be considered when assessing wasteform durability.

4.2. Radionuclide retention capacity

Beyond matrix durability, the long-term performance of a wasteform ultimately depends on its ability to retain radionuclides. Radionuclide retention therefore represents a complementary aspect of MKPC performance, although the available evidence remains limited and fragmented [124].

Experimental studies nevertheless demonstrate the potential of MKPC for radionuclide immobilisation. Early work showed effective confinement of hazardous metals, including Pb, Cr, Cd, Zn, Cu and Ni, with leachate concentrations often below detection limits after curing, even under aggressive leaching conditions (Fig. 3a) [80,124,125]. Likewise, the progressive reduction in matrix-component leaching with curing time (Fig. 3b) reflects continued matrix stabilisation, indicating that microstructural densification enhances contaminant retention. Low differential leaching rates (10^{-7}–10^{-9} g cm^{-2} day^{-1}) have also been reported for mobile radionuclides such as Cs and Sr, together with actinides including Pu and Am, in zeolite-modified MKPC formulations developed for high-level waste [126]. For conventional MKPC systems, direct evidence is largely limited to Cs and Eu. Satisfactory Cs retention (LI > 6) has been reported [13], while Fattori et al. [15] demonstrated stable immobilisation of several radionuclides, including Eu, after irradiation doses of 200–1000 kGy. The higher mobility of Cs than Eu further illustrates the strong influence of radionuclide chemistry on immobilisation behaviour.

These observations indicate that radionuclide immobilisation is governed by two complementary mechanisms: physical entrapment and chemical immobilisation. Physical entrapment results from the formation of a dense K-struvite matrix, which reduces pore connectivity and limits diffusive transport during hydration [16,25]. Chemical immobilisation, in contrast, depends on radionuclide chemistry through interactions with phosphate reaction products. For Cs, early studies proposed partial substitution of K within the K-struvite lattice, whereas more recent crystallographic evidence indicates that immobilisation occurs predominantly through precipitation of discrete Cs-phosphate (Cs-struvite) phases, with only limited incorporation into the K-struvite structure [81,115,116]. Although these findings provide valuable mechanistic insight, the relative contribution of each mechanism remains unresolved.

Despite these encouraging results, the available evidence is confined to a relatively small number of radionuclides and specific MKPC formulations. Information for radionuclides of particular relevance to LILRW disposal, including Co, remains scarce, while systematic comparisons across radionuclide chemistries and waste compositions are largely absent. Consequently, the proposed retention mechanisms cannot yet be generalised to the broad range of radionuclides expected in radioactive waste streams.

Taken together, the available evidence supports the potential of MKPC for radionuclide immobilisation under standardised conditions, with reported leachability indices generally exceeding the ANSI/ANS 16.1 criterion (LI > 6) [6]. However, the current evidence base remains

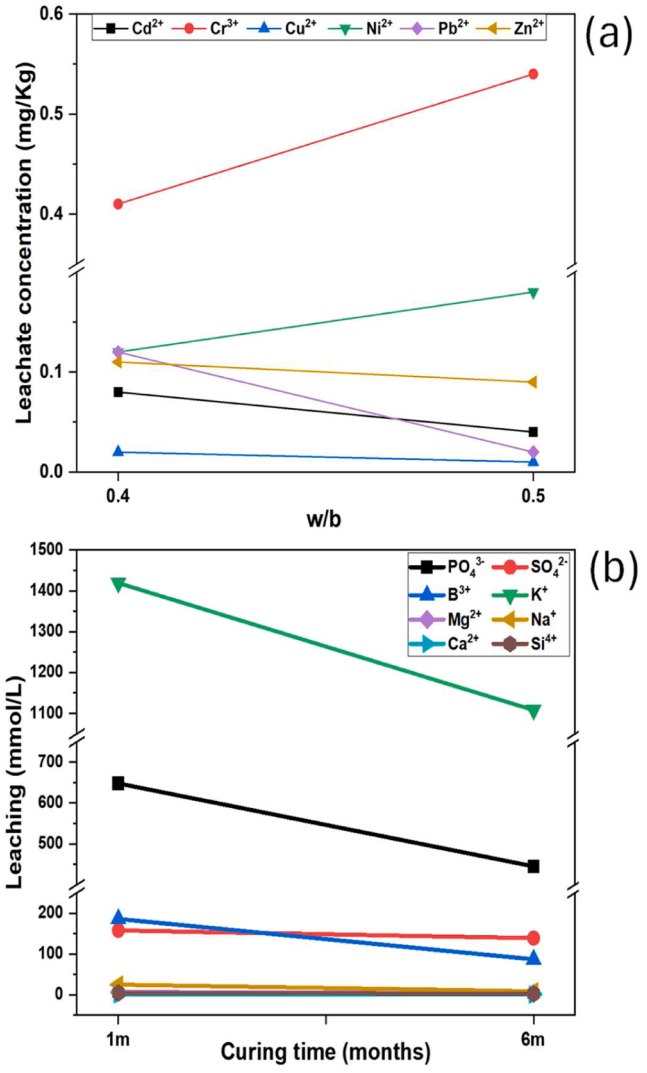


Fig. 3. Leaching behaviour of (a) heavy metals as a function of water-to-binder ratio, based on data from [124], and (b) leaching of matrix components as a function of curing time, based on data from [15].

insufficient to establish radionuclide-specific retention models or reliably predict long-term performance under representative repository conditions. Future studies should therefore investigate a broader range of radionuclides while quantifying the relative contributions of physical entrapment and chemical immobilisation.

4.3. Performance under irradiation

The long-term behaviour of cementitious wasteforms under irradiation is a key aspect of radioactive waste management. During storage, ionising radiation emitted by radionuclide decay induces water radiolysis within the cementitious matrix, generating mainly H_2 and, to a lesser extent, O_2. The accumulation of these gases may increase internal pressure, promote cracking and ultimately compromise waste package integrity over extended storage periods [2,127,128].

Radiolytic gas generation is primarily governed by the amount and state of water within the binder. Hydrogen production mainly originates from evaporable (free or capillary) water, whereas chemically bound water is far less susceptible to radiolysis, with only ~2–3% decomposing after 200 MGy of γ-irradiation [129,130]. Consequently, H_2 yields in PC may vary by more than one order of magnitude depending on moisture content and curing conditions. By contrast, MKPC generally exhibits lower and more stable H_2 generation ($\sim 2.5 \times 10^{-7}$ mol/J), as a substantial fraction of the mixing water becomes structurally bound within K-struvite ($MgKPO_4{\cdot}6H_2O$), thereby reducing the residual free-water content [15,127]. Nevertheless, radiolytic susceptibility in MKPC remains influenced by formulation variables, including the MgO/KH_2PO_4 ratio, water-to-solid ratio and curing regime.

Accordingly, hydrogen generation in MKPC under γ-irradiation is approximately three to four times lower than in comparable PC systems and tends to stabilise at high irradiation doses [82]. Oxygen evolution is also limited because oxidising radiolysis products are retained within the matrix, probably through the formation of peroxide species such as MgO_2 [131], thereby reducing the likelihood of explosive H_2/O_2 mixtures during long-term storage.

Beyond its favourable radiolytic behaviour, MKPC also exhibits excellent mechanical stability under irradiation. No noticeable swelling, cracking or significant loss of compressive strength has been reported following irradiation up to 100 MGy [132]. These observations are supported by the work of Fattori et al. [15], who found that MKPC mortars exposed to Co-60 γ-radiation up to 1000 kGy retained at least 70% of their initial compressive strength after 90 days of water immersion (Fig. 4), without significant mineralogical or microstructural alterations compared with non-irradiated specimens. Conventional PC also exhibits high radiation resistance, retaining its mechanical strength and microstructure over a wide irradiation range despite generating higher amounts of radiolytic hydrogen [133,134]. These findings suggest that the principal advantage of MKPC under irradiation lies not in superior mechanical stability, but in its substantially lower radiolytic gas generation.

Overall, current evidence indicates that MKPC combines excellent resistance to irradiation-induced degradation with substantially lower radiolytic hydrogen generation than conventional PC, primarily owing to its lower residual free-water content. However, the available evidence remains limited and strongly dependent on formulation and testing conditions. In particular, the influence of the MgO/KH_2PO_4 ratio, curing conditions and waste loading on long-term irradiation behaviour remains insufficiently understood. Further standardised studies under repository-relevant conditions are therefore required to improve confidence in the long-term performance of MKPC matrices [127].

4.4. Thermal stability

Thermal stability is a key requirement for wasteform materials, as packages may experience elevated temperatures from radioactive decay, accidental fires during transport or storage, and cyclic freezing–thawing in near-surface facilities [135]. Under such conditions, maintaining structural cohesion is essential to ensure containment performance. MKPCs have long been recognised for their low thermal expansion and strong mechanical performance, attributes that also underpin their use in fire-retardant applications.

There is broad consensus that MKPCs retain good structural integrity at high temperatures, particularly when blended with additives such as FA, BFS, wollastonite, CAC or CSA [136–139]. These additions refine the microstructure, reduce heat release during hydration and promote the formation of thermally stable phases (e.g., $MgAl_2O_4$ spinel), enabling strength retention up to ~800–1000°C [135]. However, performance remains formulation-dependent: FA-rich systems can be prone to cracking, while sand additions may induce volumetric deformation under thermal stress. Li et al. [139] demonstrated that MKPC pastes with an M/P ratio of 4M exhibit a progressive strength reduction with increasing temperature regardless of FA content (Fig. 5).

Beyond high-temperature exposure, MKPCs also show strong resistance to thermal cycling [83,140]. Freeze–thaw tests indicate strength retention of 60–75% after hundreds of cycles, even in saline or sulphate-rich solutions representative of repository environments [140]. By comparison, PC mortars often undergo severe degradation under similar conditions due to sulphate-induced expansive reactions. Enhanced frost resistance is reported for composites with ≤30% FA,

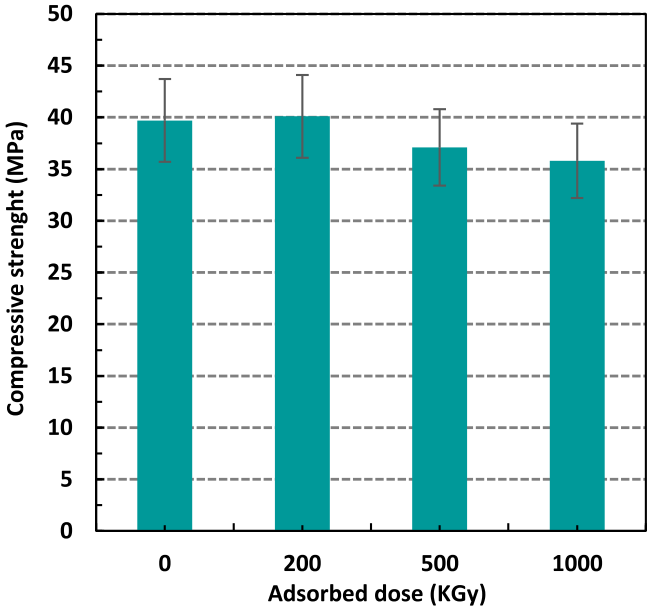


Fig. 4. Effect of γ-radiation dose (kGy) on the compressive strength (mean ± standard deviation) of MKPC mortars, based on data from [15].

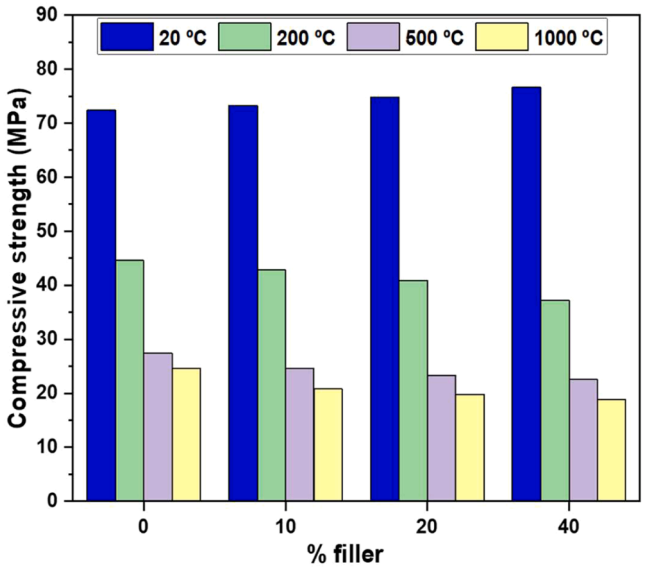


Fig. 5. Effect of temperature variation on the compressive strength (no standard deviation reported) of MKPC-based mortars, based on data from [139].

where microstructural refinement limits damage accumulation [83]. MKPCs also appear less vulnerable than PC to sulphate attack under combined chemical–thermal stress [141].

Overall, the available evidence positions MKPC as a thermally robust binder, capable of withstanding both extreme heat and cyclic environmental stresses. Nevertheless, performance varies noticeably with mix design, particularly FA content, and discrepancies across published results highlight the need for systematic, long-term studies under combined thermal, chemical and mechanical loading to strengthen predictive confidence.

In summary, the durability evidence reviewed in this section, including immersion, accelerated leaching, thermal cycling and irradiation tests, indicates that MKPC matrices can maintain mechanical integrity and low leach rates over the investigated timescales, typically on the order of months. However, long-term behaviour under the coupled conditions relevant to near-surface disposal, such as wetting–-drying cycles, carbonation and interactions with backfill and container materials, remains insufficiently characterised. Accordingly, statements regarding long-term repository performance should be regarded as well-founded hypotheses based on current evidence rather than validated predictions.

5. Life cycle considerations of MKPC wasteforms

The environmental sustainability and economic viability of MKPC, commonly evaluated through life-cycle assessment (LCA) and life-cycle cost (LCC), respectively, are key considerations for its large-scale application in LILRW conditioning, alongside its technical performance. These aspects are primarily governed by the sourcing, availability and embodied environmental impacts of the principal precursors, MgO and KH_2PO_4, together with formulation and processing efficiency. Recent LCA studies indicate that these two precursors account for approximately 47–67% of the total environmental impact associated with MKPC production [142], highlighting precursor optimisation as an effective strategy for improving sustainability.

Among these precursors, MgO is the main contributor to both the environmental impacts and the economic cost of MKPC. Conventional MgO production requires approximately 5.9 GJ t^{-1} and generates around 1.7 t CO_2 t^{-1} through combined process and fuel emissions [143]. This burden is further influenced by calcination temperature: HB-MgO requires higher energy input, whereas SB-MgO provides a lower-energy alternative when its reactivity is appropriately controlled. In addition, the limited and geographically uneven distribution of magnesite, identified by the European Union as a critical raw material [144], reinforces the need to optimise MgO grade and sourcing strategy [31,145]. Alternative production routes, including seawater- or brine-derived magnesia, Mg-silicate processing and recovery from industrial by-products, could reduce both environmental impacts and production costs, provided that their compositional variability is accommodated through formulation design.

Phosphate availability presents a comparable resource constraint. Although KH_2PO_4 is commercially available, phosphate rock is also classified as a critical raw material [144]. Consequently, reducing phosphate demand through optimisation of the M/P ratio is desirable from both environmental and economic perspectives, provided that wasteform performance is maintained. Supplementary mineral additions can further improve sustainability by partially replacing MgO or phosphate with low-cost, locally available materials. In particular, FA and BFS can reduce the carbon footprint of MKPC formulations by up to 45%, depending on replacement level and mix composition [146]. However, the future availability of these conventional additions is expected to decline with industrial decarbonisation, highlighting the need to identify alternative secondary resources that ensure long-term supply security without compromising wasteform standardisation or quality assurance (QA) and quality control (QC) requirements.

From a practical perspective, these material and formulation choices directly influence the LCC of LILRW immobilisation. Formulations incorporating lower-impact MgO, optimised M/P ratios and appropriate secondary fillers reduce both raw-material costs and CO_2 emissions per cubic metre of conditioned waste, while appropriate control of heat release, setting time and curing moisture improves processing efficiency by minimising rejected batches, wasteform non-conformance and the associated consumption of materials and energy during conditioning.

Overall, the successful implementation of MKPC requires balancing precursor selection, material consumption, and processing conditions to minimise environmental impacts and LCC without compromising the mechanical performance, microstructural stability, and pore solution characteristics required for repository acceptance.

Table 4
Comparative summary of PC and MKPC systems for LILRW immobilisation, highlighting the current state of knowledge, main limitations and key research needs associated with MKPC-based wasteforms.

Topic			PC	MKPC		
				Knowledge	Limitations	Research needs
Formulation			Established, well-known formulations.	Performance governed by M/P, MgO, retarders…	No standard LILRW formulations; high energy.	Waste-specific and lower-LCC/LCA formulations[a]
LILRW immobilisation	Metals	Al	High reactivity; high corrosion and H_2.	Less corrosion by neutral pH + phosphates + retarders.	Formulation-sensitive; risk of external alkalinisation.	Standardised H_2 testing; EBS-wasteform studies.
		Be	$BeO/Be(OH)_2$-layer degradation over time.	Less corrosion at neutral pH + phosphate layers effect.	Limited laboratory-scale evidence.	Long-term studies under repository conditions.
		Steel	Stable passive oxide films; less corrosion.	Depassivation. Phosphate-rich layers reduce corrosion.	Formulation sensitivity & film instability.	Optimised formulations; realistic-condition studies.
		U	U-metal corrosion. Retention of U oxides.	Reduced corrosion via low free water and phosphates.	Variable U-oxide retention.	Waste-specific binder selection & retention tests.
	SIERs		Curing-dependent swelling/degradation.	Cationic resin retention in K-struvite (K^+ substitution).	Setting/strength changes; anionic resins = NH_4-gas.	Long-term studies under repository conditions
Durability	Leaching		Well-known matrix stability in water.	Fillers in MKPC formulation improve resistance in water.	No fillers + alkaline media: K-struvite dissolution.	Long-term studies under repository conditions.
	Radionuclide retention		Radionuclide retention reported as LI < 6.	Acceptable radionuclide retention (LI > 6 for Cs, Eu).	Limited database; unclear retention mechanisms.	Mechanisms; expanded radionuclide dataset.
	Irradiation		Free-water favours radiolytic gas.	Less H_2; limited O_2 (MgO_2); no matrix degradation.	Limited and variable irradiation data.	Standardised & long-term irradiation studies.
	Thermal stability		Degradation at >800 °C & freeze–thaw test	Strength retention at >800 °C by thermally stable phases.	Limited long-term and cyclic thermal data.	Repository-relevant thermal ageing studies.

[a] Tentative design strategy for MKPC formulations intended for LILRW immobilisation is provided in Table 2.

6. Key insights and future directions

The literature reviewed indicates that MKPC is a promising alternative to conventional alkaline binders, particularly for LILRW streams incompatible with highly alkaline matrices. Its near-neutral pore chemistry, low water demand and dense K-struvite-based microstructure improve compatibility with reactive wastes such as aluminium and selected ion-exchange resins, helping to limit corrosion, hydrogen generation and swelling phenomena.

In contrast, the advantages of MKPC are less evident for more conventional LILRW streams, including aqueous concentrates and non-reactive solids already effectively conditioned with Portland cement-based matrices. Although MKPC generally exhibits lower radiolytic gas generation and promising short-term durability, it does not consistently outperform PC in terms of radionuclide retention or repository performance. MKPC should therefore be regarded as a targeted solution for challenging waste streams rather than a universal replacement for conventional cementitious systems.

More broadly, the behaviour of MKPC wasteforms remains strongly formulation-dependent, as binder composition and curing conditions govern reaction pathways, microstructural development and long-term stability. Despite significant progress, important uncertainties remain regarding long-term performance under repository-relevant conditions, matrix–waste interactions and radionuclide retention mechanisms. Table 4 summarises the current state of knowledge through a comparative assessment of MKPC and PC systems, highlighting the principal limitations and research priorities for MKPC-based wasteforms in LILRW immobilisation.

Addressing these uncertainties will require integrated studies linking formulation design, matrix–waste interactions and long-term behaviour under repository-relevant conditions, with particular emphasis on predictive degradation models, a mechanistic understanding of radionuclide retention, systematic studies involving a broader range of radionuclides relevant to LILRW disposal, and standardised methodologies for designing waste-specific MKPC formulations. Progress in these areas will strengthen confidence in long-term performance predictions and support the reliable implementation of MKPC systems for radioactive waste management.

CRediT authorship contribution statement

C. Fernández-García: Writing – review & editing, Writing – original draft. **P. Padilla-Encinas:** Writing – review & editing, Writing – original draft. **R. Fernández:** Writing – review & editing, Validation, Supervision. **M. Criado:** Writing – review & editing, Validation, Supervision. **I. García-Lodeiro:** Writing – review & editing, Validation, Supervision. **E. Torres:** Writing – review & editing, Validation, Supervision. **M.C. Alonso:** Writing – review & editing, Visualization, Validation.

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.

Acknowledgements

The authors acknowledge funding from the European Union's Horizon 2020 Research and Innovation Programme for Nuclear Fission and Radiation Protection Research (NFRP-2019-2020 call) under Grant Agreements No. 945098 (PREDIS) and 10116671 (EURAD-2). C. Fernández-García and M. C. Alonso also acknowledge support from the CSIC PIE projects No. 202260E009 and No. 202560E173.

Data availability

Data will be made available on request.

References

[1] D. Deng, L. Zhang, M. Dong, R.E. Samuel, A. Ofori-Boadu, M. Lamssali, Radioactive waste: a review, Water Env. Res. 92 (2020) 1818–1825, https://doi.org/10.1002/wer.1442.
[2] International Atomic Energy Agency (IAEA), Long Term Behaviour of Low and Intermediate Level Waste Packages Under Repository Conditions : Results of a Co-Ordinated Research Project 1997-2002, International Atomic Energy Agency, 2004.
[3] M.-S. Yim, Management of low and intermediate level waste, in: M.-S. Yim (Ed.), Nuclear Waste Management: Science, Technology, and Policy, Springer Netherlands, Dordrecht, 2022, pp. 635–685, https://doi.org/10.1007/978-94-024-2106-4_13.

[4] J. Scott, The development of cement formulations for radioactive waste encapsulation, stabilization and solidification of hazardous, radioactive, and mixed wastes: 2nd Volume (1997) 348.
[5] M. Atkins, F.P. Glasser, Application of portland cement-based materials to radioactive waste immobilization, Waste Manag. 12 (1992) 105–131, https://doi.org/10.1016/0956-053X(92)90044-J.
[6] Standard, ANSI/ANS-16.1-2019: measurement of the leachability of solidified low-level radioactive wastes by a short-term test procedure, 2019.
[7] M. Pourbaix, J. Burbank, Atlas D-equilibres electrochimiques, J. Electrochem. Soc. 111 (1964) 14C, https://doi.org/10.1149/1.2426051.
[8] Brookhaven National Lab., Solidification of ion exchange resin wastes, United States, 1982. https://doi.org/10.2172/6794443.
[9] X. Niu, Y. Elakneswaran, C.R. Islam, J.L. Provis, T. Sato, Adsorption behaviour of simulant radionuclide cations and anions in metakaolin-based geopolymer, J. Hazard. Mater. 429 (2022) 128373, https://doi.org/10.1016/j.jhazmat.2022.128373.
[10] W. Ashraf, M. Khan, S. Yusan, M. Qasim, N. Jie, Geopolymers as emerging materials for immobilization of toxic radionuclides, Nucl. Technol. 212 (2026) 383–394, https://doi.org/10.1080/00295450.2025.2464426.
[11] L.J. Gardner, Assessment of magnesium potassium phosphate cements for radioactive waste encapsulation. Doctoral Thesis, Dissertation University of Sheffield, England, 2016.
[12] M.A. Haque, B. Chen, Research progresses on magnesium phosphate cement: a review, Constr. Build. Mater. 211 (2019) 885–898, https://doi.org/10.1016/j.conbuildmat.2019.03.304.
[13] S. Martínez Sánchez, Inmovilización de resinas de intercambio iónico en cementos de fosfato de magnesio, Master Final Dissertation Universidad Carlos III (UC3M), Spain, 2024.
[14] A.S. Wagh, S.Y. Sayenko, V.A. Shkuropatenko, R.V Tarasov, M.P. Dykiy, Y. O. Svitlychniy, V.D. Virych, E.A. Ulybkina, Experimental study on cesium immobilization in struvite structures, J. Hazard. Mater. 302 (2016) 241–249, https://doi.org/10.1016/j.jhazmat.2015.09.049.
[15] F. Fattori, G. Magugliani, A. Santi, E. Mossini, I. Moschetti, F. Galluccio, E. Macerata, X. de la Bernardie, A. Abdelouas, D. Cori, D. Comboni, G.D. Gatta, M. Mariani, Radiation stability and durability of magnesium phosphate cement for radioactive reactive metals encapsulation, Prog. Nucl. Energy 177 (2024) 105463, https://doi.org/10.1016/j.pnucene.2024.105463.
[16] A. Dabarera, R. Fernández, J.L. Provis, A systematic review of engineering properties of magnesium potassium phosphate cement as a repair material, Front. Mater. 11 (2024) 1451079.
[17] B. Fang, Z. Hu, T. Shi, Y. Liu, X. Wang, D. Yang, K. Zhu, X. Zhao, Z. Zhao, Research progress on the properties and applications of magnesium phosphate cement, Ceram. Int. 49 (2023) 4001–4016, https://doi.org/10.1016/j.ceramint.2022.11.078.
[18] C. Xu, J. Han, Y. Yang, A review on magnesium potassium phosphate cement: characterization methods, J. Build. Eng. 82 (2024) 108284, https://doi.org/10.1016/j.jobe.2023.108284.
[19] B.E.I. Abdelrazig, J.H. Sharp, B. El-Jazairi, The chemical composition of mortars made from magnesia-phosphate cement, Cem. Concr. Res. 18 (1988) 415–425, https://doi.org/10.1016/0008-8846(88)90075-0.
[20] E. Soudée, J. Péra, Mechanism of setting reaction in magnesia-phosphate cements, Cem. Concr. Res. 30 (2000) 315–321, https://doi.org/10.1016/S0008-8846(99)00254-9.
[21] M. Le Rouzic, T. Chaussadent, G. Platret, L. Stefan, Mechanisms of k-struvite formation in magnesium phosphate cements, Cem. Concr. Res. 91 (2017) 117–122, https://doi.org/10.1016/j.cemconres.2016.11.008.
[22] S.A. Walling, J.L. Provis, Magnesia-based cements: a journey of 150 years, and cements for the future? Chem. Rev. 116 (2016) 4170–4204, https://doi.org/10.1021/acs.chemrev.5b00463.
[23] T. Zhang, H. Chen, X. Li, Z. Zhu, Hydration behavior of magnesium potassium phosphate cement and stability analysis of its hydration products through thermodynamic modeling, Cem. Concr. Res. 98 (2017) 101–110, https://doi.org/10.1016/j.cemconres.2017.03.015.
[24] F. Qiao, C.K. Chau, Z. Li, Property evaluation of magnesium phosphate cement mortar as patch repair material, Constr. Build. Mater. 24 (2010) 695–700, https://doi.org/10.1016/j.conbuildmat.2009.10.039.
[25] H. Ma, B. Xu, Z. Li, Magnesium potassium phosphate cement paste: Degree of reaction, porosity and pore structure, Cem. Concr. Res. 65 (2014) 96–104, https://doi.org/10.1016/j.cemconres.2014.07.012.
[26] R. Fernández, Deliverable 4.8 Characterization of magnesium phosphate cement and low-cost magnesium phosphate cement, (2024).
[27] T.L. Drnek, M.N. Moraes, P.B. Neto, Overview of magnesite, J. Refract. Innov. RHIM Bull 1 (2018) 14–22.
[28] J. Nobre, H. Ahmed, M. Bravo, L. Evangelista, J. De Brito, Magnesia (MgO) production and characterization, and its influence on the performance of cementitious materials: a review, Materials 13 (2020) 4752, https://doi.org/10.3390/ma13214752.
[29] M.A. Shand, The Chemistry and Technology of Magnesia, John Wiley & Sons, 2006. https://books.google.es/books.
[30] X. Zhang, Z.-Y. Zhang, Y. Liu, L. Yang, Y. Zheng, S. Kang, J. Zhou, Preparation of magnesium potassium phosphate cement from magnesite tailings under lower calcination temperature, Constr. Build. Mater. 451 (2024) 138869, https://doi.org/10.1016/j.conbuildmat.2024.138869.
[31] I. Garcia-Lodeiro, S. Chhaiba, N. Husillos-Rodriguez, Á. Palomo, H. Kinoshita, Development of magnesium phosphate cement based on low-grade MgO, Materials 18 (2025), https://doi.org/10.3390/ma18061198.
[32] S. Adu-Amankwah, P. Hou, A comparative study on retarders for magnesium phosphate cements. Advances in Applied Ceramics, Taylor and Francis, 2022.
[33] F.R. Stierli, J.M. Gaidis, C.T. Clayton, Control of setting time in magnesia-phosphate cement, UK Patent 1 (1978).
[34] I. Jagadeeswaran, H. Sriram, EU 1907/2006 – registration, evaluation, authorisation and restriction of chemicals, in: P.S. Timiri Shanmugam, P. Thangaraju, N. Palani, T. Sampath (Eds.), Medical Device Guidelines and Regulations Handbook, Springer International Publishing, Cham, 2022, pp. 237–260, https://doi.org/10.1007/978-3-030-91855-2_13.
[35] L. Stefan, T. Chaussadent, H. Bessaies-bey, Thiosulfates for use as retarders for magnesium phosphate cement pastes, (2023).
[36] Z. Lai, X. Lai, J. Shi, Z. Lu, Effect of Zn2+ on the early hydration behavior of potassium phosphate based magnesium phosphate cement, Constr. Build. Mater. 129 (2016) 70–78, https://doi.org/10.1016/j.conbuildmat.2016.11.002.
[37] C. Cau Dit Coumes, A. Rousselet, B. Xu, C.A. Mercier, S. Gauffinet, Investigation of aluminum nitrate as a set retarder of magnesium potassium phosphate cement: mechanisms involved in diluted suspension, Cem. Concr. Res. 150 (2021) 106608, https://doi.org/10.1016/j.cemconres.2021.106608.
[38] Z. Luo, Y. Wang, X. Liu, C. Tian, Y. Wang, Y. Mu, M. Zhang, Y. Hao, Comparative investigation of effect of borax and sodium gluconate retarders on properties of magnesium phosphate cement, Arab, J. Sci. Eng. 47 (2022) 13187–13198, https://doi.org/10.1007/s13369-022-06762-0.
[39] L.J. Gardner, S.A. Bernal, S.A. Walling, C.L. Corkhill, J.L. Provis, N.C. Hyatt, Characterisation of magnesium potassium phosphate cements blended with fly ash and ground granulated blast furnace slag, Cem. Concr. Res. 74 (2015) 78–87, https://doi.org/10.1016/j.cemconres.2015.01.015.
[40] A.S. Wagh, Chapter 3 - raw materials, in: A.S. Wagh (Ed.), Chemically Bonded Phosphate Ceramics, Elsevier, Oxford, 2004, pp. 29–41, https://doi.org/10.1016/B978-008044505-2/50007-7.
[41] Z. Qin, C. Ma, Z. Zheng, G. Long, B. Chen, Effects of metakaolin on properties and microstructure of magnesium phosphate cement, Constr. Build. Mater. 234 (2020) 117353, https://doi.org/10.1016/j.conbuildmat.2019.117353.
[42] X. Xu, X. Lin, X. Pan, T. Ji, Y. Liang, H. Zhang, Influence of silica fume on the setting time and mechanical properties of a new magnesium phosphate cement, Constr. Build. Mater. 235 (2020) 117544, https://doi.org/10.1016/j.conbuildmat.2019.117544.
[43] B. Xu, B. Lothenbach, F. Winnefeld, Influence of wollastonite on hydration and properties of magnesium potassium phosphate cements, Cem. Concr. Res. 131 (2020) 106012, https://doi.org/10.1016/j.cemconres.2020.106012.
[44] P. Padilla-Encinas, M. Dieguez, J. Cuevas, A.I. Ruiz, R. Fernández, The influence of the magnesium-to-phosphate molar ratio on magnesium potassium phosphate cement properties using either wollastonite or volcanic ash as fillers, Minerals 14 (2024) 103, https://doi.org/10.3390/min14010103.
[45] J. Yang, J. Lu, Q. Wu, M.F. Xia, X. Li, Influence of steel slag powders on the properties of MKPC paste, Constr. Build. Mater. 159 (2018) 137–146, https://doi.org/10.1016/j.conbuildmat.2017.10.081.
[46] Y. Liu, Z. Qin, B. Chen, Experimental research on magnesium phosphate cements modified by red mud, Constr. Build. Mater. 231 (2020) 117131, https://doi.org/10.1016/j.conbuildmat.2019.117131.
[47] B. Xu, B. Lothenbach, A. Leemann, F. Winnefeld, Reaction mechanism of magnesium potassium phosphate cement with high magnesium-to-phosphate ratio, Cem. Concr. Res. 108 (2018) 140–151, https://doi.org/10.1016/j.cemconres.2018.03.013.
[48] J. Qin, J. Qian, X. Dai, C. You, H. Ma, Z. Li, Effect of water content on microstructure and properties of magnesium potassium phosphate cement pastes with different magnesia-to-phosphate ratios, J. Am. Ceram. Soc. 104 (2021) 2799–2819, https://doi.org/10.1111/jace.17695.
[49] D.A. Hall, R. Stevens, B. El Jazairi, Effect of water content on the structure and mechanical properties of magnesia-phosphate cement mortar, J. Am. Ceram. Soc. 81 (1998) 1550–1556.
[50] Y. Zheng, Y. Zhou, X. Huang, H. Luo, Effect of raw materials and proportion on mechanical properties of magnesium phosphate cement, J. Road Eng. 2 (2022) 243–251, https://doi.org/10.1016/j.jreng.2022.06.001.
[51] W. Xie, B. Chen, H. Rong, J. Li, Unveiling the impact of water-to-binder ratio on foaming behavior of foamed magnesium phosphate cement, Constr. Build. Mater. 474 (2025) 141072, https://doi.org/10.1016/j.conbuildmat.2025.141072.
[52] T. Li, Z. Wang, T. Zhou, Y. He, F. Huang, Preparation and properties of magnesium phosphate cement foam concrete with H2O2 as foaming agent, Constr. Build. Mater. 205 (2019) 566–573, https://doi.org/10.1016/j.conbuildmat.2019.02.022.
[53] G. Yi, C. Ma, G. Long, B. Zhao, Y. Xie, Effects of metakaolin on a novel aerated magnesium phosphate cement with high early strength, Constr. Build. Mater. 187 (2018) 1130–1133, https://doi.org/10.1016/j.conbuildmat.2018.08.037.
[54] C. Ma, B. Chen, Experimental study on the preparation and properties of a novel foamed concrete based on magnesium phosphate cement, Constr. Build. Mater. 137 (2017) 160–168, https://doi.org/10.1016/j.conbuildmat.2017.01.092.
[55] M. Le Rouzic, T. Chaussadent, L. Stefan, M. Saillio, On the influence of Mg/P ratio on the properties and durability of magnesium potassium phosphate cement pastes, Cem. Concr. Res. 96 (2017) 27–41, https://doi.org/10.1016/j.cemconres.2017.02.033.
[56] Y. Li, J. Sun, B. Chen, Experimental study of magnesia and M/P ratio influencing properties of magnesium phosphate cement, Constr. Build. Mater. 65 (2014) 177–183, https://doi.org/10.1016/j.conbuildmat.2014.04.136.
[57] M. Xue, H. Wang, X. Xiao, J. Cao, Influence of m (P)/m (M) mass ratio on properties of magnesium phosphate cement and its mechanism analysis, Funct. Mater. 46 (2015) 23090–23095.

[58] AENOR, UNE EN 197-1 Cement - Part 1: Composition, Specifications and Conformity Criteria for Common Cements, AENOR, Madrid, Spain, 2011. www.aenor.es.

[59] L. Chong, J. Yang, C. Shi, Effect of curing regime on water resistance of magnesium–potassium phosphate cement, Constr. Build. Mater. 151 (2017) 43–51, https://doi.org/10.1016/j.conbuildmat.2017.06.056.

[60] C. Fernández-García, M.C. Alonso, J.M. Bastidas, I. García-Lodeiro, R. Fernández, MgO/KH2PO4 and curing moisture content in MKPC matrices to optimize the immobilization of pure Al and Al-Mg alloys, Materials 17 (2024) 1263, https://doi.org/10.3390/ma17061263.

[61] M. Dieguez, A.I. Ruiz, J. Cuevas, M.C. Alonso, I. García-Lodeiro, R. Fernández, Evaluation of fillers for magnesium potassium phosphate cement (MKPC) for the encapsulation of low and intermediate level metallic radioactive wastes, Materials 16 (2023) 679, https://doi.org/10.3390/ma16020679.

[62] T. Li, G. Chen, J. Yang, L. Chong, X. Hu, Influence of curing conditions on mechanical properties and microstructure of magnesium potassium phosphate cement, Case Stud. Constr. Mater. 17 (2022) e01264, https://doi.org/10.1016/j.cscm.2022.e01264.

[63] B. Xu, F. Winnefeld, B. Lothenbach, Effect of temperature curing on properties and hydration of wollastonite blended magnesium potassium phosphate cements, Cem. Concr. Res. 142 (2021), https://doi.org/10.1016/j.cemconres.2021.106370.

[64] Y. Li, B. Chen, Factors that affect the properties of magnesium phosphate cement, Constr. Build. Mater. 47 (2013) 977–983, https://doi.org/10.1016/j.conbuildmat.2013.05.103.

[65] R. Perona, C. Fernández-García, I. García-Lodeiro, M. Criado, J.M. Bastidas, M. C. Alonso, Corrosion behavior and immobilization of pure aluminum and Al−Mg alloy LLRW in magnesium potassium phosphate cements, J. Nucl. Mater. 582 (2023) 154501, https://doi.org/10.1016/j.jnucmat.2023.154501.

[66] C. Fernández-García, K.-K. Le, M.C. Alonso, C. Cannes, S. Delpech, Passivation of aluminium A1050 in MKPC matrices: effect of MgO type and chemical retarder composition, Electrochim. Acta 525 (2025) 146104, https://doi.org/10.1016/j.electacta.2025.146104.

[67] H. Lahalle, C. Cau Dit Coumes, C. Mercier, D. Lambertin, C. Cannes, S. Delpech, S. Gauffinet, Influence of the w/c ratio on the hydration process of a magnesium phosphate cement and on its retardation by boric acid, Cem. Concr. Res. 109 (2018) 159–174, https://doi.org/10.1016/j.cemconres.2018.04.010.

[68] H. Lahalle, C. Patapy, M. Glid, G. Renaudin, M. Cyr, Microstructural evolution/durability of magnesium phosphate cement paste over time in neutral and basic environments, Cem. Concr. Res. 122 (2019) 42–58, https://doi.org/10.1016/j.cemconres.2019.04.011.

[69] J. Formosa, J.M. Chimenos, A.M. Lacasta, M. Niubó, Interaction between low-grade magnesium oxide and boric acid in chemically bonded phosphate ceramics formulation, Ceram. Int. 38 (2012) 2483–2493, https://doi.org/10.1016/j.ceramint.2011.11.017.

[70] M. Liu, Y. Xia, Y. Zhao, Z. Cao, Immobilization of Cu (II), Ni (II) and Zn (II) in silica fume blended Portland cement: Role of silica fume, Constr. Build. Mater. 341 (2022) 127772, https://doi.org/10.1016/j.conbuildmat.2022.127772.

[71] D.P. Prentice, B. Walkley, S.A. Bernal, M. Bankhead, M. Hayes, J.L. Provis, Thermodynamic modelling of BFS-PC cements under temperature conditions relevant to the geological disposal of nuclear wastes, Cem. Concr. Res. 119 (2019) 21–35, https://doi.org/10.1016/j.cemconres.2019.02.005.

[72] M. Nicu, L. Ionascu, F. Dragolici, C. Turcanu, The investigation of low-pH modified CEM III and CEM V cementation systems for encapsulation of radioactive metallic aluminium waste, in: International Multidisciplinary Scientific GeoConference : SGEM 4, 2015, pp. 27–34.

[73] M.Y. Khalil, E. Merz, Immobilization of intermediate-level wastes in geopolymers, J. Nucl. Mater. 211 (1994) 141–148, https://doi.org/10.1016/0022-3115(94)90364-6.

[74] G. Cann, S. Cockburn, S. Farris, D. Geddes, M. Hayes, S. Morgan, S. Nelson, O. Tuck, Development of Calcium Sulfoaluminate Cements for the Encapsulation of Intermediate Level Waste, (n.d.).

[75] M.A. Chavda, H. Kinoshita, J.L. Provis, Modification of low-pH calcium aluminate cement to enhance stability for immobilisation of metallic wastes, (n.d.).

[76] I. Garcia-Lodeiro, K. Irisawa, F. Jin, Y. Meguro, H. Kinoshita, Reduction of water content in calcium aluminate cement with/out phosphate modification for alternative cementation technique, Cem. Concr. Res. 109 (2018) 243–253, https://doi.org/10.1016/j.cemconres.2018.04.019.

[77] P. Swift, H. Kinoshita, N C Collier, C A Utton, Phosphate modified calcium aluminate cement for radioactive waste encapsulation, Adv. Appl. Ceram. 112 (2013) 1–8, https://doi.org/10.1179/1743676112Y.0000000033.

[78] M.R. Marsiske, C. Debus, F. Di Lorenzo, E. Bernard, S.V Churakov, C. Ruiz-Agudo, Immobilization of (Aqueous) cations in Low pH M-S-H Cement, Appl. Sci. 11 (2021), https://doi.org/10.3390/app11072968.

[79] J. Jdaini, C.C. dit Coumes, Y. Barré, M.-N. de Noirfontaine, M. Courtial, E. Garcia-Caurel, F. Dunstetter, D. Gorse-Pomonti, Strontium release from wollastonite-based brushite cement paste under semi-dynamic leaching conditions, in: NUWCEM 2022–International Symposium on Cement-Based Materials for Nuclear Wastes, 2022.

[80] I. Buj, J. Torras, M. Rovira, J. de Pablo, Leaching behaviour of magnesium phosphate cements containing high quantities of heavy metals, J. Hazard. Mater. 175 (2010) 789–794, https://doi.org/10.1016/j.jhazmat.2009.10.077.

[81] D. Leng, Q. Fu, Y. Ge, C. He, Y. Lv, X. Li, Cs+ promoting the diffusion of K+ and inhibiting the generation of newberyite in struvite-K cements: experiments and molecular dynamics simulation calculations, Materials 17 (2024), https://doi.org/10.3390/ma17040814.

[82] G.L. Bykov, E.V Abkhalimov, V.A. Ershov, B.G. Ershov, Radiolysis of Portland cement and magnesium phosphate cement: effect of the content and state of water on the Physicochemical properties and the mechanism and kinetics of hydrogen formation, Radiat. Phys. Chem. 190 (2022) 109822, https://doi.org/10.1016/j.radphyschem.2021.109822.

[83] H. Feng, L. Wang, Z. Yu, A. Guo, J. Liang, Freeze-thaw resistance and service life prediction of fly ash incorporated ultra-high ductility magnesium phosphate cement-based composites, Constr. Build. Mater. 449 (2024) 138330, https://doi.org/10.1016/j.conbuildmat.2024.138330.

[84] P. Bouhier, C. Cannes, D. Lambertin, C. Grisolia, D. Rodrigues, S. Delpech, Evaluation of several conditioning matrices for the management of radioactive metal beryllium wastes, J. Nucl. Mater. 559 (2022), https://doi.org/10.1016/j.jnucmat.2021.153464.

[85] C. Cannes, P. Bouhier, D. Lambertin, C. Grisolia, D. Rodrigues, S. Delpech, Reactivity of beryllium in aqueous solution from acidic to basic pH, J. Electroanal. Chem. 950 (2023) 117879, https://doi.org/10.1016/j.jelechem.2023.117879.

[86] S. Caes, A. Bukaemskiy, C. Cannes, S. Delpech, V. De Souza, B. Kursten, Study of the corrosion behaviour of beryllium in solutions representative of Portland cement and magnesium phosphate cement, J. Nucl. Mater. 616 (2025) 156023, https://doi.org/10.1016/j.jnucmat.2025.156023.

[87] A. Bukaemskiy, S. Caes, G. Modolo, G. Deissmann, D. Bosbach, Investigation of kinetics and mechanisms of metallic beryllium corrosion for the management of radioactive wastes, MRS Adv 9 (2024) 391–396, https://doi.org/10.1557/s43580-024-00835-y.

[88] R. Laflotte, C. Cau Dit Coumes, J. Haas, D. Rodrigues, C. Cannes, S. Delpech, M. Rivenet, Stabilization and solidification of beryllium waste: influence of the cement composition on the corrosion of Be metal, Materials 17 (2024), https://doi.org/10.3390/ma17225401.

[89] N. Çevirim-Papaioannou, I. Androniuk, S. Han, N.A. Mouheb, S. Gaboreau, W. Um, X. Gaona, M. Altmaier, Sorption of beryllium in cementitious systems relevant for nuclear waste disposal: Quantitative description and mechanistic understanding, Chemosphere 282 (2021) 131094, https://doi.org/10.1016/j.chemosphere.2021.131094.

[90] S. Caes, A. Bukaemskiy, G. Deissmann, G. Modolo, V. de Souza, B. Kursten, Deliverable 4.12 Beryllium reactivity in magnesium phosphate cement, (2024).

[91] K.J. Rodgers, A. Hursthouse, S. Cuthbert, The Potential of Sequential Extraction in the Characterisation and Management of Wastes from Steel Processing: A Prospective Review, Int. J. Env. Res. Public Health 12 (2015) 11724–11755, https://doi.org/10.3390/ijerph120911724.

[92] A.L. Riley, J.M. MacDonald, I.T. Burke, P. Renforth, A.P. Jarvis, K.A. Hudson-Edwards, J. McKie, W.M. Mayes, Legacy iron and steel wastes in the UK: Extent, resource potential, and management futures, J. Geochem. Explor. 219 (2020) 106630, https://doi.org/10.1016/j.gexplo.2020.106630.

[93] H.H. Uhlig, R.W. Revie, Corrosion and corrosion control, Third edition, John Wiley and Sons, Inc., New York, NY, United States, 1984. https://www.osti.gov/biblio/7195167.

[94] S. Yin, H. Yang, Y. Dong, C. Qu, J. Liu, T. Guo, K. Duan, Environmentally favorable magnesium phosphate anti-corrosive coating on carbon steel and protective mechanisms, Sci. Rep. 11 (2021) 197, https://doi.org/10.1038/s41598-020-79613-3.

[95] C. Bucur, M.C. Alonso, Deliverable 4.11 Aluminium and steel reactivity in magnesium phosphate cement, (2024).

[96] F. Zhang, J. Qin, K. Cai, J.J. Myers, H. Ma, Anti-Corrosion Performance of Magnesium Potassium Phosphate Cement Coating on Steel Reinforcement: The Effect of Boric Acid, Materials 17 (2024), https://doi.org/10.3390/ma17215310.

[97] C. Vargel, Corrosion of aluminium, Elsevier, 2020.

[98] C. Cau Dit Coumes, D. Lambertin, H. Lahalle, P. Antonucci, C. Cannes, S. Delpech, Selection of a mineral binder with potentialities for the stabilization/solidification of aluminum metal, J. Nucl. Mater. 453 (2014) 31–40, https://doi.org/10.1016/j.jnucmat.2014.06.032.

[99] C. Fernández-García, P. Padilla-Encinas, R. Fernández, M.C. Alonso, Interaction of aluminum alloys with MKPC and Portland-based cements on the metal-matrix interface, Appl. Geochem. 172 (2024) 106105, https://doi.org/10.1016/j.apgeochem.2024.106105.

[100] S. Delpech, C. Cannes, N. Barré, Q.T. Tran, C. Sanchez, H. Lahalle, D. Lambertin, S. Gauffinet, C.C.D. Coumes, Kinetic Model of Aluminum Behavior in Cement-Based Matrices Analyzed by Impedance Spectroscopy, J. Electrochem. Soc. 164 (2017) C717–C727, https://doi.org/10.1149/2.0211713jes.

[101] C. Fernández-García, M.C. Alonso, Mechanistic role of phosphate and borate species in aluminium passivation in simulated MKPC pore solutions, Electrochim. Acta 546 (2026) 147824, https://doi.org/10.1016/j.electacta.2025.147824.

[102] G. Poras, C. Cau Dit Coumes, P. Antonucci, C. Cannes, S. Delpech, S. Perrin, Electrochemical Behavior of Al/Mg Alloys Immobilized in a Magnesium Potassium Phosphate Cement-Based Mortar, Materials 16 (2023), https://doi.org/10.3390/ma16155415.

[103] C. Fernández-García, M.C. Alonso, Aluminium corrosion reactivation in MKPC and Portland-based wasteforms under simulated alkaline repository conditions, J. Nucl. Mater. 616 (2025) 156064, https://doi.org/10.1016/j.jnucmat.2025.156064.

[104] W. Montague, The suitability of magnesium phosphate cement for uranium metal encapsulation. Doctoral Thesis, Dissertation Imperial College London, England, 2014.

[105] M. Hayes, I.H. Godfrey, Development of the use of alternative cements for the treatment of intermediate level waste, in: Proc. Conf. WM 7, 2007.

[106] M. Mathew, L.W. Schroeder, Crystal structure of a struvite analogue, MgKPO 4.6H 2O, Acta Crystallogr. B 35 (1979) 11–13, https://doi.org/10.1107/S0567740879002429.
[107] A. Covill, N.C. Hyatt, J. Hill, N.C. Collier, Development of magnesium phosphate cements for encapsulation of radioactive waste, Adv. Appl. Ceram. 110 (2011) 151–156, https://doi.org/10.1179/1743676110Y.0000000008.
[108] Radioactive Waste Management, WPSGD no. WPS/230/01 - Geological Disposal: Generic Specification for waste packages containing depleted, natural and low enriched uranium, United Kingdom, 2015.
[109] N. Collier, M. Harrison, M. Brogden, B. Hanson, Release of uranium from candidate wasteforms, Miner. Mag. 76 (2012) 2939–2948, https://doi.org/10.1180/minmag.2012.076.8.09.
[110] D. Scheithauer, W. Heschel, B. Meyer, S. Krzack, Pyrolysis of undoped and multi-element doped ion exchange resins with regard to storage properties, J. Anal. Appl. Pyrolysis 124 (2017) 276–284, https://doi.org/10.1016/j.jaap.2017.01.024.
[111] J. Li, J. Wang, Advances in cement solidification technology for waste radioactive ion exchange resins: a review, J. Hazard. Mater. 135 (2006) 443–448, https://doi.org/10.1016/j.jhazmat.2005.11.053.
[112] M.J. de Hita, E. Torres, D.A. Geddes, J.L. Provis, M. Criado, Immobilisation of simulant nuclear-grade spent ion-exchange resins in alkali-activated cement: fresh state properties of the cement matrix, J. Nucl. Mater. 617 (2025) 156169, https://doi.org/10.1016/j.jnucmat.2025.156169.
[113] Y. Yue, Q. Zhou, Y. Bai, L. Li, J. Song, C. You, J. Qian, C. McCague, F. Jin, A. Al-Tabbaa, Immobilisation of Caesium in Magnesium Phosphate-Based Blends, The Institute of Materials, Minerals and Mining, 2016.
[114] Y. Tao, L. Zhenyu, R. Chunrong, W. Yuanyuan, H. Zhichao, H. Xin, W. Jie, L. Mengliang, D. Qiubai, K. Khan, L. Zhongyuan, L. Shuzhen, Study on solidification properties of chemically bonded phosphate ceramics for cesium radionuclides, Ceram. Int. 46 (2020) 14964–14971, https://doi.org/10.1016/j.ceramint.2020.03.025.
[115] J.-Y. Pyo, B. Lee, G.-Y. Kim, H.W. Kang, J.-H. Choi, H.-S. Park, K.-R. Lee, Cesium immobilization in magnesium potassium phosphate cement: limited solid solution and polymorphism of Cs-struvite, Ceram. Int. 51 (2025) 52676–52687, https://doi.org/10.1016/j.ceramint.2025.09.026.
[116] D. Leng, X. Li, Y. Lv, H. Tan, N. Li, Z. Liu, W. Jiang, D. Jiang, Cesium immobilization by K-struvite crystal in aqueous solution: Ab initio calculations and experiments, J. Hazard. Mater. 387 (2020) 121872, https://doi.org/10.1016/j.jhazmat.2019.121872.
[117] I. García-Lodeiro, S. Chhaiba, N. Husillos-Rodriguez, Á. Palomo, Leaching behaviour of MKPC containing nuclear wastes, in: 1st International Conference on Mg-Based Cements (MgO2026), Murten, Switzerland, Empa, 2026, p. 89. www.empa.ch/web/MgO2026.
[118] C. Fernandez-Garcia, E. Torres, I. Garcia-Lodeiro, M. Criado, M.C. Alonso, Influence of ion-exchange resins on the physico-chemical performance of MKPCs formulated with high-grade MgO, in: 1st International Conference on Mg-Based Cements (MgO2026), Empa, Murten, Switzerland, 2026, p. 89. www.empa.ch/web/MgO2026.
[119] NRC Nuclear Regulatory Comission, Waste From Technical Position, Revision 1, United States, 1991. https://www.nrc.gov.
[120] Q. Yang, B. Zhu, X. Wu, Characteristics and durability test of magnesium phosphate cement-based material for rapid repair of concrete, Mater. Struct. 33 (2000) 229–234, https://doi.org/10.1007/BF02479332.
[121] L. Diaz Caselles, C. Cau Dit Coumes, P. Antonucci, A. Rousselet, A. Mesbah, V. Montouillout, Chemical degradation of magnesium potassium phosphate cement pastes during leaching by demineralized water: experimental investigation and modeling, Cem. Concr. Res. 178 (2024) 107456, https://doi.org/10.1016/J.CEMCONRES.2024.107456.
[122] V. Shkuropatenko, S. Sayenko, Y. Svitlycnyi, L.D. Caselles, C.C.D. Coumes, A. Rousselet, Deliverable 4.9 Leaching behavior of magnesium phosphate cement-based materials, (2024).
[123] L. Diaz Caselles, C. Cau Dit Coumes, P. Antonucci, A. Rousselet, A. Mesbah, V. Montouillout, Leaching of magnesium potassium phosphate cement pastes under alkaline conditions, Appl. Geochem. 170 (2024) 106067, https://doi.org/10.1016/j.apgeochem.2024.106067.
[124] I. Buj, J. Torras, M. Rovira, J. de Pablo, Leaching behaviour of magnesium phosphate cements containing high quantities of heavy metals, J. Hazard. Mater. 175 (2010) 789–794, https://doi.org/10.1016/j.jhazmat.2009.10.077.
[125] S.C. Zhen, Y. Xun, B.Q. Miao, Solidification/stabilization of heavy metals by magnesium potassium phosphate cement, Adv. Mat. Res. 664 (2013) 683–689, https://doi.org/10.4028/www.scientific.net/AMR.664.683.
[126] S.A. Kulikova, S.E. Vinokurov, The influence of zeolite (sokyrnytsya deposit) on the physical and chemical resistance of a magnesium potassium phosphate compound for the immobilization of high-level waste, Molecules 24 (2019), https://doi.org/10.3390/molecules24193421.
[127] D. Chartier, J. Sanchez-Canet, P. Antonucci, S. Esnouf, J.P. Renault, O. Farcy, D. Lambertin, S. Parraud, H. Lamotte, C.C.D. Coumes, Behaviour of magnesium phosphate cement-based materials under gamma and alpha irradiation, J. Nucl. Mater. 541 (2020), https://doi.org/10.1016/j.jnucmat.2020.152411.
[128] B. Biwer, D. Ma, Y. Xi, Y. Jing, M. Sircar, in: Review of Radiation-Induced Concrete Degradation and Potential Implications for Structures Exposed to High Long-Term Radiation Levels in Nuclear Power Plants, Washington, DC, USA, 2021. https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr7280/index.
[129] S. Ishikawa, I. Maruyama, M. Takizawa, J. Etoh, O. Kontani, S. Sawada, Hydrogen production and the stability of hardened cement paste under gamma irradiation, J. Adv. Concr. Technol. 17 (2019) 673–685, https://doi.org/10.3151/jact.17.673.
[130] K. Noshita, T. Nishi, M. Matsuda, Generation mechanism of hydrogen gas from hardened cement paste by γ-irradiation, MRS Proc. 353 (1994) 921, https://doi.org/10.1557/PROC-353-921.
[131] G.L. Bykov, V.A. Ershov, B.G. Ershov, Radiation stability of magnesium phosphate ceramic under γ-irradiation: formation of hydrogen and peroxides, Radiochemistry 62 (2020) 406–410, https://doi.org/10.1134/S1066362220030145.
[132] G.L. Bykov, V.A. Ershov, B.G. Ershov, Radiolysis of the magnesium phosphate cement on γ-irradiation, Constr. Build. Mater. 252 (2020) 119156, https://doi.org/10.1016/j.conbuildmat.2020.119156.
[133] I. Maruyama, S. Ishikawa, J. Yasukouchi, S. Sawada, R. Kurihara, M. Takizawa, O. Kontani, Impact of gamma-ray irradiation on hardened white Portland cement pastes exposed to atmosphere, Cem. Concr. Res. 108 (2018) 59–71, https://doi.org/10.1016/j.cemconres.2018.03.005.
[134] G.L. Bykov, E.V Abkhalimov, V.A. Ershov, B.G. Ershov, Effect of gamma irradiation on Portland cement: Hydrogen evolution and radiation resistance, Constr. Build. Mater. 295 (2021) 123644, https://doi.org/10.1016/j.conbuildmat.2021.123644.
[135] L.J. Gardner, S.A. Walling, C.L. Corkhill, S.A. Bernal, V. Lejeune, M.C. Stennett, J. L. Provis, N.C. Hyatt, Temperature transformation of blended magnesium potassium phosphate cement binders, Cem. Concr. Res. 141 (2021) 106332, https://doi.org/10.1016/j.cemconres.2020.106332.
[136] X. Gao, A. Zhang, S. Li, B. Sun, L. Zhang, The resistance to high temperature of magnesia phosphate cement paste containing wollastonite, Mater. Struct. 49 (2016) 3423–3434, https://doi.org/10.1617/s11527-015-0729-9.
[137] X. Zhang, G. Li, M. Niu, Z. Song, Effect of calcium aluminate cement on water resistance and high-temperature resistance of magnesium-potassium phosphate cement, Constr. Build. Mater. 175 (2018) 768–776, https://doi.org/10.1016/j.conbuildmat.2018.04.200.
[138] J. Yu, J. Qian, H. Chen, Y. Ji, D. Kuang, X. Jia, B. Guan, Behavior of magnesium phosphate cement with addition of sulphoaluminate cement at elevated temperatures, Constr. Build. Mater. 401 (2023) 132932, https://doi.org/10.1016/j.conbuildmat.2023.132932.
[139] Y. Li, T. Shi, B. Chen, Y. Li, Performance of magnesium phosphate cement at elevated temperatures, Constr. Build. Mater. 91 (2015) 126–132, https://doi.org/10.1016/j.conbuildmat.2015.05.055.
[140] L. Chong, J. Yang, Z.Z. Xu, X. Xu, Freezing and thawing resistance of MKPC paste under different corrosion solutions, Constr. Build. Mater. 212 (2019) 663–674, https://doi.org/10.1016/j.conbuildmat.2019.03.269.
[141] Y. Yang, J. Han, R. Liu, Understanding hydration properties of magnesium potassium phosphate cement with low magnesium-to-phosphate ratio, Constr. Build. Mater. 416 (2024) 135221, https://doi.org/10.1016/j.conbuildmat.2024.135221.
[142] X. Shen, X. Wang, K. Li, X. Hu, C. Shi, Life cycle assessment of magnesium phosphate cement production, J. Clean. Prod. 467 (2024) 142981, https://doi.org/10.1016/j.jclepro.2024.142981.
[143] S. Ruan, C. Unluer, Comparative life cycle assessment of reactive MgO and Portland cement production, J. Clean. Prod. 137 (2016) 258–273, https://doi.org/10.1016/j.jclepro.2016.07.071.
[144] I. European Commission: Directorate-General for Internal Market Entrepreneurship and SMEs, M. Grohol, C. Veeh, Study on the Critical Raw Materials for the EU 2023 – Final Report, Publications Office of the European Union, 2023, https://doi.org/10.2873/725585.
[145] S. Chhaiba, S. Martinez-Sanchez, N. Husillos-Rodriguez, Á. Palomo, H. Kinoshita, I. Garcia-Lodeiro, Durability of magnesium potassium phosphate cements (MKPCs) under chemical attack, Materials 17 (2024), https://doi.org/10.3390/ma17174252.
[146] Y. Tan, S. Liu, M. Achintha, R. Mi, Is it possible to make magnesia-based cement environmentally friendly? ACS Sustain. Chem. Eng. 12 (2024) 16869–16883, https://doi.org/10.1021/acssuschemeng.4c05985.