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Report on marketing and societal challenges of NORM in building materials

Final report

Work Package 6

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Executive Summary

This report is PhD thesis of Dr. Nazanin Love which includes the comprehensive research related to marketing and societal challenges of NORM in building materials.

In recent years, there has been increasing attention on sustainable construction materials, particularly in the cement industry, as countries aim to mitigate climate change and reduce carbon emissions. Cement production is a significant contributor to global greenhouse gas emissions, making the shift to sustainable alternatives critical for achieving sustainable development goals (SDGs). One promising approach is substituting clinker, the main component of cement, with secondary raw materials. This substitution not only has the potential to reduce carbon dioxide (CO_2) emissions, but it also preserves natural resources and supports the circular economy by repurposing industrial by-products. These by-products might otherwise end up in landfills, potentially posing both immediate environmental and health risks and long-term challenges for land use and future generations. Some of these by-products, such as those from the copper or aluminium industries, are classified as Naturally Occurring Radioactive Materials (NORM) due to increased radioactivity during production. Using these materials in cement production provides a beneficial use for substances that would, in most cases, end up as waste at various disposal sites, where they might potentially be hazardous and thus require special conditions.

While the technical aspects of using NORM-contained by-products in cement have been explored, non-technical aspects such as stakeholder perceptions have been largely overlooked. This thesis addresses this gap by investigating the perceptions of two key stakeholder groups: industry and end-users.

Due to the lack of prior research, the first step was to explore stakeholder perceptions through semi-structured interviews, which allowed for in-depth discussions. We began by interviewing representatives from the concrete industry in Belgium, uncovering six themes influencing their perceptions, with regulatory certainty being central to both barriers and facilitators. The exploratory phase continued with a comparative investigation across two additional countries with different contexts (Czechia and Slovenia) and expanded to include end-users (those who had recently built or renovated homes). This comparison revealed that economic and performance concerns were similar across both stakeholder groups and countries, while perceptions of health risks varied.

To further explore end-user perceptions, we tested the hypotheses generated during the exploratory phase through a survey-based questionnaire. This allowed us to generalise the findings and better understand the factors influencing end-users' attitudes. The survey, conducted across three European countries, was based on a framework developed from our qualitative findings and existing literature. We found significant cross-country differences in the factors that influenced end-users' attitudes towards alternative cement. Additionally, our analysis highlighted the important role of heuristics in shaping how risks and benefits are perceived by end-users.

This report provides recommendations for industry stakeholders, policymakers, regulatory authorities, and marketing and communication managers to support the adoption of sustainable cement alternatives.

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Chapter 1. Introduction

1. Background

Our planet faces an inflection point, as the continued degradation of natural resources, climate change, and unsustainable consumption patterns imperil the future of all ecosystems and societies. Thus, the need for radical action has never been more urgent. The effects of global warming—rising temperatures, increasing sea levels, and the intensification of extreme weather events—are not abstract challenges but immediate threats to the survival of societies and ecosystems, demanding immediate change (IPCC, 2021). It is within this critical context that the United Nations' (2015) Sustainable Development Goals (SDGs) call for urgent global collaboration to reshape the way we produce, consume, and interact with the environment. The global nature of climate change necessitates extensive international cooperation to accelerate the reduction of greenhouse gas emissions and address its adverse impacts.

In addressing these challenges, the SDGs provide a comprehensive roadmap that tackles the interconnected economic, social, and environmental dimensions of sustainability. These goals reflect the interconnectedness of global systems, where progress in one area often leads to synergies or trade-offs in others. For instance, advancements in industry and infrastructure (SDG 9) can promote economic growth and innovation, but may also generate environmental challenges, necessitating alignment with goals such as SDG 13 (Climate Action). Through integrated and indivisible goals, the SDGs aim to offer holistic solutions for sustainable development. This collective approach ensures that actions taken towards one goal contribute to broader sustainable development objectives, recognising the need for integrated strategies that balance economic development with environmental preservation and social inclusion (United Nations, 2015).

This thesis investigates the facilitators and barriers to sustainable pathways in cement production, including the use of alternative materials, with a focus on understanding stakeholders' acceptance of sustainable cement made from certain by-products. Among the Sustainable Development Goals (SDGs):

- Goal 9—building resilient infrastructure, promoting sustainable industrialisation, and fostering innovation
- Goal 12—ensuring sustainable consumption and production patterns
- Goal 13—calling for urgent climate action

are particularly relevant to the cement industry, a major contributor to global CO2 emissions. This research aligns with these goals by addressing one of the largest sources of industrial emissions (Gilfillan et al., 2020).

Following this, the chapter explores the impact of cement on global climate change, focusing on clinker substitution as a key strategy for reducing emissions, with particular emphasis on the utilisation of NORM-containing by-products. This is followed by an examination of the complex challenges surrounding the acceptance of sustainable novel technologies. Finally, the objectives and structure of the thesis are discussed. Throughout the thesis, the focus is on the perception and acceptance of key stakeholders, including industry representatives and end-users, whose views play a pivotal role in facilitating the transition towards sustainable cement alternatives.

2. Impact of Cement on Global Climate Change

Cement is a crucial binding material widely used in construction to create concrete, which consists of cement mixed with water, sand, and gravel. Concrete is one of the most versatile and durable materials in the world, forming the backbone of infrastructure such as buildings, bridges, and roads (CEMBUREAU, 2020). The history of cement dates back over 2,000 years, with its earliest forms being used by the Romans to construct iconic structures like the Pantheon and aqueducts, many of which still stand today (Smith and Doe, 2021). Cement production continues to play a pivotal role in modern society, supporting the infrastructure of buildings, bridges, and roads that underpin our urban environments. Cement is the second-most consumed substance globally after potable water (Czigler et al., 2020), with annual global production reaching approximately 4.4 billion metric tonnes (USGS, 2022). The cement industry is the third-largest emitter of CO_2 globally (Benhelal et al., 2021). Compared to other construction materials such as steel, cement has a low embodied emissions intensity by mass (Kua and Maghimai, 2017). However, the massive scale of cement production is responsible for around 8% of anthropogenic emissions and a quarter of industrial emissions globally (World Economic Forum, 2024).

Although cement constitutes only 7-20% of concrete, it is responsible for approximately 95% of concrete's CO_2 emissions (Ellen MacArthur Foundation, 2019). More than 10 billion tonnes of concrete are used annually in the construction industry, likely continuing as the preferred construction material due to its versatility, durability, workability, cost-effectiveness, aesthetics, and resistance to severe environmental conditions. Additionally, its high thermal mass and low air infiltration help reduce the energy required to heat and cool buildings (Antunes et al., 2022; Dave et al., 2018; Lehne and Preston, 2018; van Deventer et al., 2021). Cement is essential to socio-economic development, as it is used to build houses, schools, hospitals, dams, and infrastructure, all crucial for quality of life and social and economic well-being (Czigler et al., 2020, IEA, 2018, Pamenter and Myers, 2021).

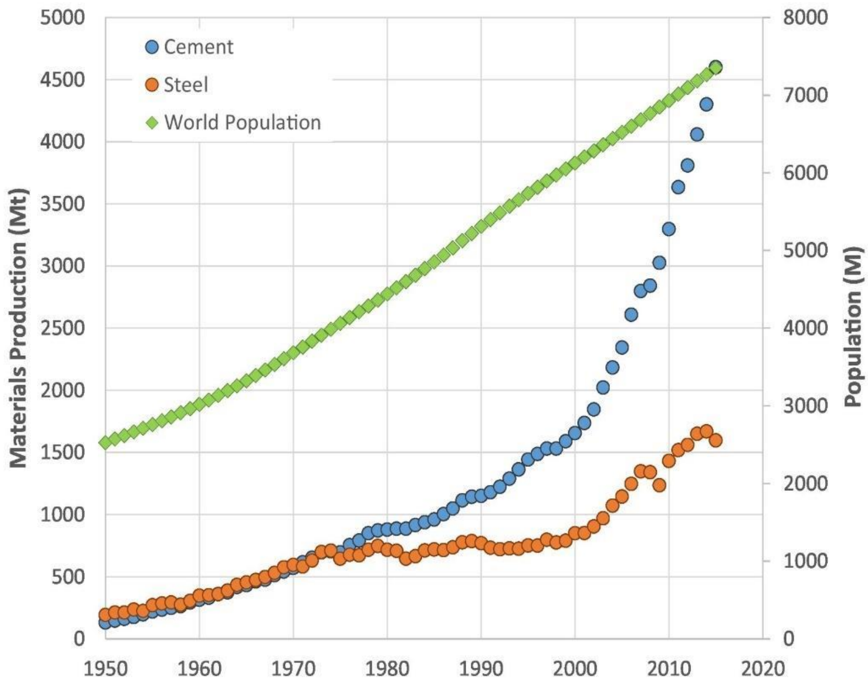
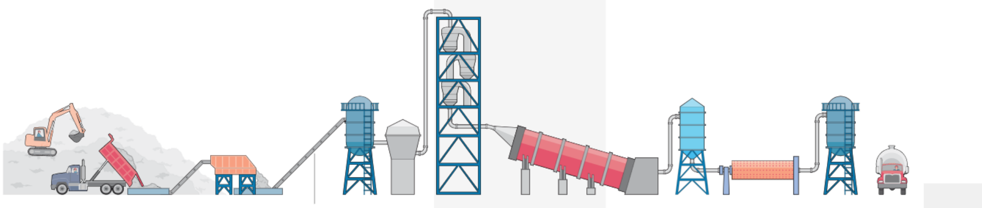


Figure 1: *Sharp increase of cement production alongside the increase in world population (UN Environment., 2018)*

In recent years, global cement production has grown rapidly (Andrew, 2019). The direct CO_2 intensity per tonne of cement increased by 1.8% per year between 2015 and 2020. By contrast, a 3% annual decline by 2030 is necessary to stay on track with the Net Zero Emissions target by 2050 (IEA, 2021). According to the United Nations, “The world’s population is projected to grow from 7.7 billion in 2019 to 8.5 billion in 2030 (10% increase), and further to 9.7 billion in 2050 (26%).” This will drive up demand for building materials (van Deventer et al., 2021). Figure 1 demonstrates the sharp increase in cement production alongside the rise in the global population. The Organisation for Economic Co-operation and Development (OECD) predicts rapid growth in the demand and production of construction materials over the next 40 years (OECD, 2019). This would have a detrimental environmental impact.

Cement is generally made up of clinker, gypsum, supplementary cementitious materials (SCMs) and fillers. There are two aspects of cement production that result in emissions of CO_2. The production of the main component of cement, clinker, accounts for the majority of the industry’s emissions (see Figure 2). Approximately 60% of the industry’s emissions result from the calcination of limestone to produce clinker, known as ‘process emissions’.

Raw materials, energy, and resources | **Clinker and cement manufacturing**



	Quarry	Crusher	Transport[1]	Raw mill	Kiln and preheater/ precalcinator[2]		Cooler[3]	Cement mill	Logistics[4]	**Total**
Energy, mega-joule/ton	40	5	40	100	3,150		160	285	115	3,895
CO_2, kilogram/ton	3	1	7	17	479 Calcination process	319 Fossil fuels	28	49	22	925

***Figure 2**: Cement production: energy required and CO_2 produced in each stage of the process. Source: Czigler et al. (2020).*

A further 40% is generated from the combustion of fossil fuels to generate the significant high temperature (850–1,600°C) required for that process (Andrew, 2019; Antunes et al. 2022; IEA, 2016; Lehne and Preston, 2018). Since a large amount of CO_2 emissions comes from calcining the limestone, eliminating emissions requires changing the fundamentals of the underlying industrial processes – not just the energy sources, but also the alternative source of materials (Material Economics, 2019).

3. Clinker Substitution as a Solution

According to IEA (2021), key strategies to cut carbon emissions in cement production include improving energy efficiency, switching to lower-carbon fuels, advancing process and technology innovations such as Carbon Capture and Storage (CCS), and promoting material efficiency (to reduce the clinker-to-cement ratio and total demand). The latter two contribute the most to direct emissions reductions in the IEA's most ambitious emissions reduction scenario, the Zero Emissions by 2050 Scenario (IEA, 2021). Although CCS implementation requires access to suitable transport and storage infrastructure, it can be considered a less disruptive change, meaning less reliance on altering processes and feedstocks. This technology can be considered a viable path towards Net Zero emissions, but only if emissions to the atmosphere are permanently avoided. Furthermore, some studies argue that implementation of CCS in the cement industry is necessary to halt CO_2 emissions in the short run, not as a long-term solution (Plaza et al., 2020; Wennersten, 2015).

Since the amount of clinker used in cement is directly proportional to the CO_2 emissions generated during cement production, reducing the cement-to-clinker ratio can significantly reduce process emissions. Clinker can be substituted or replaced with supplementary cementitious materials (SCMs). SCMs are by-products of industrial operations that have the potential to be used in blended Portland cements or as a primary and additional source for cementitious binders. In 2017, in Europe around 23% of the clinker was substituted by alternative materials such as ground granulated blast furnace slag (GGBS) from steel blast furnaces and fly ash from coal-fired power plants. The existing SCMs rely heavily on specific industrial waste mainstreams, which are currently either under major revision or threat. As a result of rising recycling level and adoption of scrap-bases electric arc furnaces in the steel sector, the availability of slag is going down. The quantity of fly ash is also going down due to the phase-out of coal-fired power plants. At the same time, various industrial by-products that are constantly accumulating in huge quantities impose a negative environmental impact. Potential usage of these by-products has attracted attention from concrete technologists. Research is also ongoing to look at potential SCMs which could be used in the future such as pozzolan materials from waste streams and slag from other industries (CEMBUREAU, 2020; IEA, 2021; Material Economics, 2019). Using alternative cementitious binders provides three main benefits. First, it reduces the need for new natural resources, particularly excessive extraction and consumption of limestone and clay (Xue et al., 2021). Second, it lowers the CO_2 emissions of cement production. Finally, it contributes to a circular economy by utilising industrial by-products, which prevents landfills from being used as dumping sites and avoids hazardous environmental impacts (Benhelal et al., 2021; Jain et al., 2021). Directive (EU) 2018/851 states that “Waste management in the Union should be improved and transformed into sustainable material management, with a view to protecting, preserving and improving the quality of the environment, protecting human health, ensuring prudent, efficient and rational utilisation of natural resources, promoting the principles of the circular economy”.

4. Naturally Occurring Radioactive Material

The International Atomic Energy Agency (IAEA) Safety and Security Glossary defined Naturally Occurring Radioactive Material (NORM) as radioactive material containing no significant[1] amounts of radionuclides other than naturally occurring radionuclides (IAEA, 2022).

The activity concentrations of naturally occurring radionuclides in undisturbed rocks and soils are generally low, and as such, of no radiological protection concern. However, during the industrial extraction and processing of natural raw materials, radionuclides, most importantly daughter radionuclides like ^{226}Ra and ^{210}Po, may accumulate and become unevenly distributed between various products, by-products, and residues. For example, commercially exploited minerals (e.g., phosphate rock and bauxite) may contain uranium (^{238}U), thorium (^{232}Th), their decay products, and potassium (^{40}K) at elevated concentrations, raising radiological safety concerns (IAEA, 2022). If the concentration exceeds defined legislative levels (which may vary among countries worldwide), it is classified as NORM (IAEA, 2024a). For a detailed methodology on the systematic identification of NORM and data collection

[1] The exact definition of ‘significant amounts’ would be a regulatory decision.

practices, reader may refer to studies such as Michalik et al. (2023), which outline a comprehensive approach to identifying NORM, and Popic et al. (2023a, 2023b), which discuss harmonised data collection and exposure assessments across European countries (Michalik et al., 2023; Popic et al., 2023a; Popic et al., 2023b).

4.1. Reuse of NORM as a Supplementary Material

Large quantities of NORM-containing industrial by-products, such as copper slag and red mud, are generated each year, much of which is disposed of in landfills. For example, copper slag is produced at a rate of 2.2 tonnes per tonne of copper, yet its reuse rate remains low (Sharma & Khan, 2017). Similarly, for every tonne of aluminium produced, approximately 1.5 tonnes of red mud are generated. The disposal of such waste creates environmental hazards, including the leaching of heavy metals and radionuclides, which can pollute surrounding ecosystems (Wang et al., 2020). IAEA (2013) has recommended the safe reuse of NORM-containing by-products as resources in various industrial applications, including cement production, as part of a circular economy. “NORM residues should therefore be regarded more as a resource than as waste” (IAEA, 2013).

Some of the NORM-containing by-products, such as copper slag, red mud, and phosphogypsum (from the phosphate industry), have demonstrated potential for reuse as SCMs in cement production. The use of NORM-containing by-products as clinker substitutions provides dual benefits: reducing the clinker-to-cement ratio—and thus greenhouse gas emissions during cement production—and repurposing NORM-contained by-products that would otherwise accumulate as waste, while minimising the demand for virgin raw (de Brito and Kurda, 2021; Juenger et al., 2019). Nevertheless, building materials containing NORM may expose individuals to gamma radiation or radon (^{222}Rn) and thoron (^{220}Rn) gases released into indoor air (ICRP, 2019).

Over the past decade, initiatives for use of NORM-contained residues in circular economy purposes have been addressed internationally. These initiatives have gained momentum particularly following the European Commission's introduction of the European Green Deal and the Circular Economy Action Plan, alongside the latest European Union's Basic Safety Standards (EU-BSS), which explicitly outline regulatory requirements for NORM management and control. Events such as the recurring NORM X symposium held in Utrecht in 2022, have focused on reuse and recycling of NORM residues to reach the closed circular course of materials in our society. However, the IAEA Technical Meeting on the ENVIRONET NORM Project, held in September 2024, and the HERCA Working Group on Natural Radiation Sources (WG NAT) meetings in 2023 and 2024, identified ‘great confusion’ surrounding the application of radiological protection (RP) principles to reuse of NORM by-products and residues. These discussions highlighted the need to reconsider and enhance current RP concepts and regulatory approaches, not necessarily by revising existing regulations, which are often challenging to amend, but by focusing on better utilisation of the Clearance concept. Greater emphasis should be placed on improving practical industrial management and regulatory frameworks, sharing best practices, and fostering harmonisation where feasible. Such efforts would facilitate the valorisation of NORM and enable more streamlined transboundary transport of these materials within the principles of the circular economy.

4.2. Regulations on the Use of NORM in Building Material

Radiation protection requirements, including those related to NORM or the use of specific types of NORM in building materials, are mandated across all EU Member States and are primarily governed by the European Union's Basic Safety Standards (EU-BSS) Directive, under Council Directive 2013/59/Euratom. This directive establishes regulations to protect public health from exposure to ionising radiation, including that arising from NORM. The EU-BSS mandates that member states monitor and assess exposure from building materials containing NORM to ensure that radiation levels remain within permissible limits.

The cement industry is one of the sectors that may result in NORM-related radiation exposure to workers, the public, and the environment. Cement production and maintenance of clinker ovens are directly regulated as a NORM-related industry under the EU Directive 2013/59/Euratom, Article 23 and Annex VI, which outline industrial sectors involving NORM (EC, 2014). Annex VII (table A, part II) of the Directive specifies exemption and clearance levels for solid NORM, set at 1 kBq/kg for ^{238}U and ^{232}Th, and 10 kBq/kg for ^{40}K. However, this is not valid for the use of NORM in building material, as the regulation of the use of NORM in building materials considers materials that are used in bulk as a large structural part of a house for example concrete and ceramics but not cement.

Building materials may contain natural radionuclides, either originating from raw materials (e.g. sourced from extraction sites), residues from NORM-related industries, or they may consist of mixtures with some naturally radioactive components. These materials can cause public exposure to radiation through direct external gamma radiation and by releasing ^{222}Rn and ^{220}Rn into indoor air. The radioactivity concentration of building materials incorporating NORM-contained by-products depends on several factors, including the geological origin of the raw materials, the specific industrial processes involved, and the extent of their use in construction applications. For example, red mud, a by-product of bauxite processing, exhibits activity concentrations ranging from 97 to 1700 Bq/kg for ^{226}Ra, 45 to 1800 Bq/kg for ^{232}Th, and 15 to 583 Bq/kg for ^{40}K, depending on its origin and treatment process. The incorporation of such materials into construction products can sometimes lead to exceeding regulatory screening levels, as indicated by the EU-BSS standards. Recognising the variability of NORM concentrations and local conditions across EU countries, the Directive requires member states to adopt stricter national regulations where needed. For example, countries with higher natural levels of NORM in their building materials may enforce lower reference levels or impose more stringent monitoring and compliance requirements. This flexibility ensures that regulations are adaptable to national contexts while still aligning with the overarching framework provided by the Directive.

The EU-BSS Directive sets a reference level of 1 mSv per year above natural background levels for indoor gamma radiation from building materials. Article 75 of the Directive addresses different types of building materials, categorising them into natural materials and materials incorporating residues from NORM processing industries, such as certain types of stone, granite, and industrial by-products. These categories guide member states in identifying materials that may present higher radiological risks, and the Directive ensures that such risks are carefully monitored and regulated (Schroeyers et al., 2018).

To aid in identifying materials with potential radiological risks, Annex VIII introduces the activity concentration index (I), which serves as a screening tool. If the index exceeds a value of 1, further calculations are required to assess compliance with the reference level. These measurements must be performed by accredited laboratories, which are recognised by the member states and must consider factors like the material's density and thickness, as well as the building type and its intended use, ensuring that radiation exposure remains within the 1 mSv per year limit. For example, for bulk materials, the index should generally be less than 1, and for superficial materials (such as tiles), it should be less than 6 (HERCA, 2016). If the activity concentration index exceeds these limits, the materials may need further testing, particularly for radon exhalation. Furthermore, the potential incorporation of gamma radiation from building materials into the framework of CE marking[2] could align radiation with other chemical parameters, eventually requiring producers to demonstrate compliance for CE marking purposes (HERCA, 2016).

Additionally, the EU-BSS Directive introduces the concept of National Radon Action Plans, which require member states to monitor and assess radon emissions from all sources, including NORM-containing building materials, soil, and water. This ensures a comprehensive approach to managing long-term radon exposure risks in dwellings, public buildings, and workplaces. Annex XVIII further specifies that these plans must include the monitoring and assessment of radon exhalation rates from building materials, with the aim of reducing prolonged radon exposure, which is a proven lung carcinogen. Epidemiological studies demonstrate a significant increase in lung cancer risk from prolonged exposure to indoor radon at low levels of exposure (HERCA, 2016). By integrating building materials into national radon mitigation strategies, the Directive ensures a holistic approach to radiation safety.

[2] CE marking signify that products sold in the EEA have been assessed to meet high safety, health, and environmental protection requirements (European Commission, 2021).

Finally, the Construction Products Regulation (CPR) 305/2011/EU complements these efforts by setting requirements for the marketing of construction products across the EU. Annex I of the CPR mentions "dangerous radiation" as part of the basic requirements for construction works, mandating that construction materials, along with other hazardous agents, do not pose a threat to the hygiene, health, or safety of workers, occupants, or neighbours. This includes measuring the activity concentration of key radionuclides such as ^{226}Ra, ^{232}Th, and ^{40}K to ensure compliance with the reference level of 1 mSv/year as part of radiation safety assessments.

Through these comprehensive regulations, the European Union ensures that radiation risks from NORM in building materials are effectively managed, promoting a safe and sustainable built environment. While the EU-BSS Directive provides a comprehensive framework, its integration with the broader objectives of the European Green Deal and Circular Economy Action Plan requires further effort through strict and harmonised regulations through a holistic approach. Harmonisation of national regulations, better utilisation of the clearance concept, and integration of radiological protection principles into sustainability goals are essential. Establishing mandatory requirements for the reuse of NORM in construction, supported by research evidence and best practices, could foster stakeholder confidence and align regulatory frameworks with the principles of circular economy and the Green Deal. Furthermore, its effectiveness depends heavily on public trust. Addressing societal concerns about potential radiological risks is vital for fostering acceptance and facilitating the broader adoption of these materials in construction, contributing to the advancement of a circular economy and sustainable practices.

4.3. Non-technical Aspects of reuse of NORM

Despite the clear environmental benefits, societal and market acceptance remain formidable obstacles. Non-technical barriers, such as public risk perception and industry resistance to change, continue to hinder the adoption of NORM-containing cementitious materials (Schroeyers et al., 2018).

The technical feasibility and environmental impacts of using NORM-containing by-products in cementitious binders have been the focus of several studies. These investigations primarily assess the radiological safety, mechanical performance, and environmental aspects when used in construction (Adesanya et al., 2021; Marinković et al., 2017; Romero-Hermida et al., 2020; Wang et al., 2020). While technical research has shown promising results, a more holistic approach is needed to ensure the sustainable transition of the cement industry. In particular, addressing societal and market challenges alongside technical and economic concerns remains essential (Schroeyers et al., 2018).

Public perception of NORM-containing materials might pose a challenge, particularly given the concerns that may arise due to the radiological aspect. Although radiation from the final product may be negligible in terms of health risks, it may still trigger rejection due to safety concerns (Perko, 2014). According to a study by Turcanu et al. (2022), public perception of radiological risk plays a critical role in the acceptance of NORM-derived materials in construction. Furthermore, the construction industry is particularly conservative, often reluctant to adopt new products (Dewald & Achternbosch, 2015; Lehne & Preston, 2018). The conservative nature of the industry, combined growing with public concerns about radiological risks, presents a complex challenge and further complicates the acceptance of innovative materials, including those containing NORM. While the technical and environmental challenges of NORM-containing materials are well-understood, their societal acceptance, particularly in terms of stakeholders' perception, plays a crucial role in the adoption of these materials, just as with other sustainable novel technologies like alternative cements[3].

5. Technology Adoption: Social Psychology Factors

Interaction between humans and technology is inherently complex, influenced by social, psychological, and contextual factors (Arning et al., 2021a; Taiwo & Downe, 2013). This complexity has prompted the development of numerous theories and frameworks over time to understand the drivers of technology acceptance and adoption. These models, often extensions or refinements of earlier theories, offering unique insights while reflecting the iterative and evolving nature of research in this field (Momani & Jamous, 2017).

The Theory of Reasoned Action (TRA), introduced by Ajzen and Fishbein in 1975 and expanded in 1980 (Ajzen & Fishbein, 1980; Fishbein & Ajzen, 1975), is one of the earliest and foundational frameworks in social psychology for understanding human behaviour. It posits that individuals form behavioural intentions based on two factors: their attitude towards the behaviour and their perceptions of social norms. Attitude reflects an individual's evaluation of the behaviour as favourable or unfavourable, while subjective norms represent perceived social pressures from significant others to perform or avoid the behaviour. Together, these constructs shape behavioural intention, which is considered the primary predictor of actual behaviour (Ajzen & Fishbein, 1980; Fishbein & Ajzen, 1975). TRA assumes that human behaviour is volitional and influenced by systematic cognitive deliberation, making it a rational choice model (Davis et al., 1989).

Derived from the TRA, the Technology Acceptance Model (TAM), developed by Davis (1986, 1989), explains users' behaviour towards technology (Marangunić and Granić, 2015). TAM introduces two key beliefs—perceived usefulness and perceived ease of use—as predictors of a user's attitude towards a system Unlike TRA, TAM does not incorporate subjective norms, a decision that has drawn

[3] In this thesis, we use 'alternative cementitious binders' and 'alternative cement' interchangeably. We use 'cementitious binders' mainly when referring to technical aspects, while for perception and acceptance, we mostly use 'alternative cement'.

criticism from some researchers (Galletta, 1999). Others contend that subjective norms may not directly influence behavioural intention but instead impact attitudes (Wu et al., 2011). Despite being recognised as a reliable framework for understanding technology acceptance (Legris et al., 2003), similar to TRA, one of the limitations of TAM is the exclusion of external barriers. Bogozzi (2007) has argued that TAM oversimplifies the adoption process by failing to account for barriers that may prevent individuals from using a technology, despite favourable attitudes or intentions.

The Theory of Planned Behaviour (TPB), introduced by Ajzen (1985), extends TRA by incorporating an additional construct: perceived behavioural control (PBC). This construct recognises that individuals may face barriers that prevent them from performing a behaviour, even when their attitudes and social support are favourable. PBC reflects an individual's perception of the ease or difficulty of performing a behaviour, shaped by resources, opportunities, skills, and the perceived importance of these factors. This addition enhances TPB's applicability to real-world contexts where individuals are not always fully in control of their actions (Ajzen, 1991; Sharma & Chandel, 2013; Budovska et al., 2020). In the context of alternative cement, even stakeholders who support its environmental benefits may be constrained by financial or regulatory barriers. By addressing such external factors, TPB offers a more comprehensive understanding of behaviour than its predecessor. Its structural simplicity and versatility have made TPB one of the most widely applied behavioural theories (Ajzen, 2008; Lizin et al., 2017).

Each of these frameworks has limitations, which have driven ongoing refinements and the integration of elements from multiple theories over time. For example, Taylor and Todd (1995) combined constructs from TPB—attitude, subjective norms, and perceived behavioural control—with TAM's perceived usefulness and ease of use to create a more robust explanatory model. Similarly, Venkatesh and Davis (2000) expanded TAM by incorporating social influence and cognitive instrumental processes, further enhancing its applicability. However, a common limitation of these theories is that they typically assume that individuals plan their behaviours rationally and systematically. This perspective fails to account for spontaneous or habitual actions, which are critical aspects of human decision-making. Consequently, these frameworks do not fully capture the complexity of behavioural dynamics in real-world contexts (Conner, 2020; Moons & de Pelsmacker, 2015; Shih & Fang, 2004).

Investigating the acceptance of sustainable technology adds complexity to understanding the perception of novel technologies. Despite widespread positive attitudes towards environmental sustainability, consumer behaviour often fails to align with these attitudes (Shaw et al., 2016; Trudel, 2019). Beyond the theories previously discussed, Schwartz's (1977) Norm-Activation Theory (NAT) and Stern's (2000) Value-Belief-Norm (VBN) Theory are among the most influential frameworks in environmental psychology (Sopha, 2011). These theories suggest that altruistic or biospheric values, combined with moral obligations, can override immediate self-interest to promote pro-environmental actions (Steg & Vlek, 2009). However, like the other theories discussed earlier, they also face significant limitations. For instance, NAT struggles to predict behaviour in situations where external factors strongly facilitate or inhibit action (Corraliza & Berenguer, 2000; Guagnano et al., 1994). Similarly, VBN has been criticised for its weak connection between general attitudes and specific behaviours and for omitting an intention variable, which reduces its predictive accuracy (Bamberg & Schmidt, 2003; Follows & Jobber, 2000).

Various studies have identified a range of barriers to pro-environmental behaviour, including cost, quality, performance, safety, and aesthetic concerns, with each study highlighting different factors as significant (Caruana et al., 2016; Chatzidakis & Shaw, 2018; Gleim et al., 2013; Polyportis et al., 2023). For example, in the context of sustainable building materials, higher costs compared to traditional alternatives present a significant obstacle for both companies and consumers (Gounder et al., 2021; Pinkse & Bohnsack, 2021). Even as the environmental benefits of sustainable materials gain recognition, cost-related barriers persist. For instance, Simion et al. (2019) found that higher material costs significantly hinder the execution of sustainable construction projects in Romania. Similarly, Chen (2023), identified cost concerns and a lack of knowledge as key factors limiting the adoption of sustainable construction practices.

Alongside barriers, various facilitators of pro-environmental behaviour have also been identified. Regulatory frameworks are particularly influential, as they can mandate the use of sustainable building materials or provide financial incentives to mitigate higher costs (Henrion et al., 2021; Osuizugbo et al., 2020). For instance, government initiatives in Malaysia aimed at promoting sustainable buildings have significantly increased the adoption of sustainable construction practices (Kamar & Hamid, 2011). Similarly, regulatory mechanisms such as carbon pricing and stricter emissions standards can help create a more equitable competitive environment for sustainable alternatives, enabling them to compete more effectively with traditional materials (Löfgren & Rootzen, 2021).

Variations in the factors influencing acceptance of sustainable technologies can be attributed to differences in the nature of the behaviour studied, the targeted consumer segments, the country-specific contexts of the research, and the timing of the study, particularly given the rapid evolution of consumers' pro-environmental behaviour. These factors often overlap, further complicating the understanding of pro-environmental behaviour (Lindenberg & Steg, 2007; Moisander, 2007). In the context of our study, the presence of Naturally Occurring Radioactive Materials (NORM), even in low-risk quantities, may raise concerns among stakeholders, triggering rejection based on perceived health and environmental hazards (Perko, 2014). Psychometric research has shown that certain characteristics of hazards influence how worrisome and acceptable they are to individuals (Fischhoff et al., 1979; Starr, 1969). Seminal studies on this topic mapped hazards on two key dimensions: dread and unknown (Fischhoff et al., 1978; Slovic, 1987). Hazards associated with dread are characterised by catastrophic consequences, lack of control, involuntary exposure, and salient fatalities. In contrast, unknown risks are novel, poorly understood, and often perceived as distant, with delayed or geographically removed effects (Eyal et al., 2008). These qualitative characteristics often weigh more heavily in public risk perception than objective measures like mortality or morbidity, especially among laypeople (Kraus et al., 1992). For instance, technologies that are both unknown and dreaded, are frequently perceived as highly risky. Conversely, familiar and less-dreaded activities are viewed as less risky (Siegrist & Árvai, 2020). It is important to note that the factors shaping risk perception vary depending on the type of hazard. For example, in the domain of nuclear energy, Ryu et al. (2018) demonstrated that trust in regulation significantly influences risk perception, with lower trust in regulation being associated with higher perceived risk. Studies focusing on risk perception in various domains identified trust as one of main factors influencing risk perception and consequently intention (Siegrist et al., 2007).

The perceived risks do not only differ by the characteristics of the risk itself but also by the different actors. For instance, the findings of Perko (2014) indicate that experts perceive the risks associated with medical X-rays and natural radiation to be significantly higher than those perceived by the general population. However, when it comes to nuclear waste and accidents at nuclear installations, experts tend to have a lower perception of risk compared to the general population. Experts tend to prioritise quantitative characteristics, such as exposure probability and measurable consequences, over qualitative and affective aspects when forming risk perceptions (Slovic et al., 2002; Wilson & Arvai, 2006; Siegrist et al., 2007). In contrast, laypeople often rely on heuristics to evaluate risks, particularly when they lack detailed knowledge about complex topics like gene technology or climate change (Connor & Siegrist, 2011a; Slovic et al., 2004). This aligns with the elaboration likelihood model (Meijnders et al., 2001; Petty & Cacioppo, 1986), which suggests that when knowledge or motivation is limited, individuals tend to rely on a peripheral route of processing, where simple heuristics become essential. These heuristics often operate through attribute substitution (Kahneman & Frederick, 2005), whereby a cognitively inaccessible attribute, such as the objective probability of exposure, is replaced with a more readily accessible one, like the number of memorable examples of the hazard.

Studies on risk perception have consistently highlighted the role of emotions, such as dread, worry, and anxiety, alongside the positive or negative associations tied to a hazard (Raue et al., 2019; Siegrist & Sütterlin, 2014; Terpstra, 2011; Wilson & Arvai, 2006; Zhao et al., 2019). The affect heuristic further demonstrates how emotions shape perceptions of risk and benefit, often leading to an inverse relationship between the two in subjective judgements (Finucane et al., 2000). Alhakami and Slovic (1994) showed that positive emotions reduce perceived risks while amplifying benefits, whereas negative emotions do the opposite. Research by Finucane et al. (2000) confirmed that altering affect—by increasing or decreasing perceived benefits or risks—can shift evaluations, underscoring the central role of emotions in guiding these judgments independently of analytical reasoning. The role of affect is particularly relevant when considering technologies like NORM-containing cement, where emotional responses—such as fear of health risks—can influence rational assessments of risks and benefits.

The acceptance of alternative cement, like other sustainable technologies, cannot be fully understood through a purely rational lens. While logical evaluations of performance, cost, and safety play a role, emotional responses are equally significant. Recognising this complexity, our research adopted an exploratory approach, beginning with qualitative interviews to capture the diverse ways in which both industry representatives and end-users perceive alternative cement. This method was particularly crucial given the absence of prior studies addressing the societal acceptance of NORM-containing by-products in building materials. In-depth discussions with stakeholders through semi-structured interviews allowed us to uncover a broad spectrum of rational, emotional, and contextual factors influencing acceptance, ranging from technical concerns to trust and societal influence.

Based on the findings from the qualitative phase and insights from existing theories, we developed a framework to identify the key factors influencing the acceptance of alternative cement. This framework not only guided the formulation of hypotheses but also represents a contribution to the theoretical understanding of sustainable material adoption by integrating practical insights with theoretical constructs. These hypotheses were subsequently tested in a quantitative study with a larger sample to provide more generalisable insights. By starting with this exploratory phase, we generated a comprehensive understanding of the barriers and facilitators influencing the acceptance of alternative cement. This foundation, along with the framework, allowed for a more structured investigation in the subsequent phases of the research, ensuring that our approach acknowledges the multifaceted nature of acceptance and perception in the context of sustainable materials.

6. Research Objectives and Dissertation Structure

This doctoral thesis aims to investigate the factors influencing the adoption of alternative cement, with a particular focus on perceptions among industry representatives and end-users across Belgium, Czechia, and Slovenia. The objectives of this thesis are as follows:

1. To provide a comprehensive understanding of the barriers and facilitators influencing concrete industry representatives in Belgium to adopt alternative cement.

2. To compare industry representatives' perceptions of alternative cement usage across Belgium, Czechia, and Slovenia.

3. To investigate end-users' perceptions of alternative cement in Belgium, Czechia, and Slovenia, and generate hypotheses regarding factors influencing their acceptance.

4. To examine and compare the factors that influence end-users' attitudes and intentions to use alternative cement in the construction of their homes in Belgium, Czechia, and Slovenia, based on the hypotheses generated in objective 3.

The remainder of this thesis is structured into four chapters. Figure 3 provides an overview of the thesis structure and the main content. Chapters 2 to 4 are each based on one or more objectives of the thesis. In Chapter 2, we investigated the perspectives of concrete industry representatives in Belgium on the use of (NORM-contained) by-products in cement production through semi-structured interviews. Based on the themes identified in our analysis, we provide a comprehensive insight into the barriers and facilitators for the industry to switch from traditional cement to alternative cement. Regulatory certainty was found to be central among these factors.

In Chapter 3, we extended our investigation to include both industry representatives and end-users not only in Belgium, but also in Czechia, where a history of using by-products with elevated radioactivity has led to health-related issues (SURO, 2024), and Slovenia, where there has recently been strong criticism over air pollution from the country's largest cement plant (CIPRA, 2022). Through semi-structured interviews, we identified financial and performance concerns as common themes among both stakeholders across countries. However, health concerns were perceived differently, influenced by various factors.

In Chapter 4, we tested some of the hypotheses derived in Chapter 3, using the framework we designed based on existing literature and interview findings, with end-users. This allowed generalisability of our findings with a larger sample. We observed notable variations across countries in the factors affecting end-users' attitudes towards alternative cement. Moreover, our analysis emphasised the significant influence of heuristics in shaping how end-users perceive the risks and benefits. Due to the small sample size of industry representatives, we did not further investigate their acceptance through a survey questionnaire. Finally, chapter 5 provides a general conclusion.

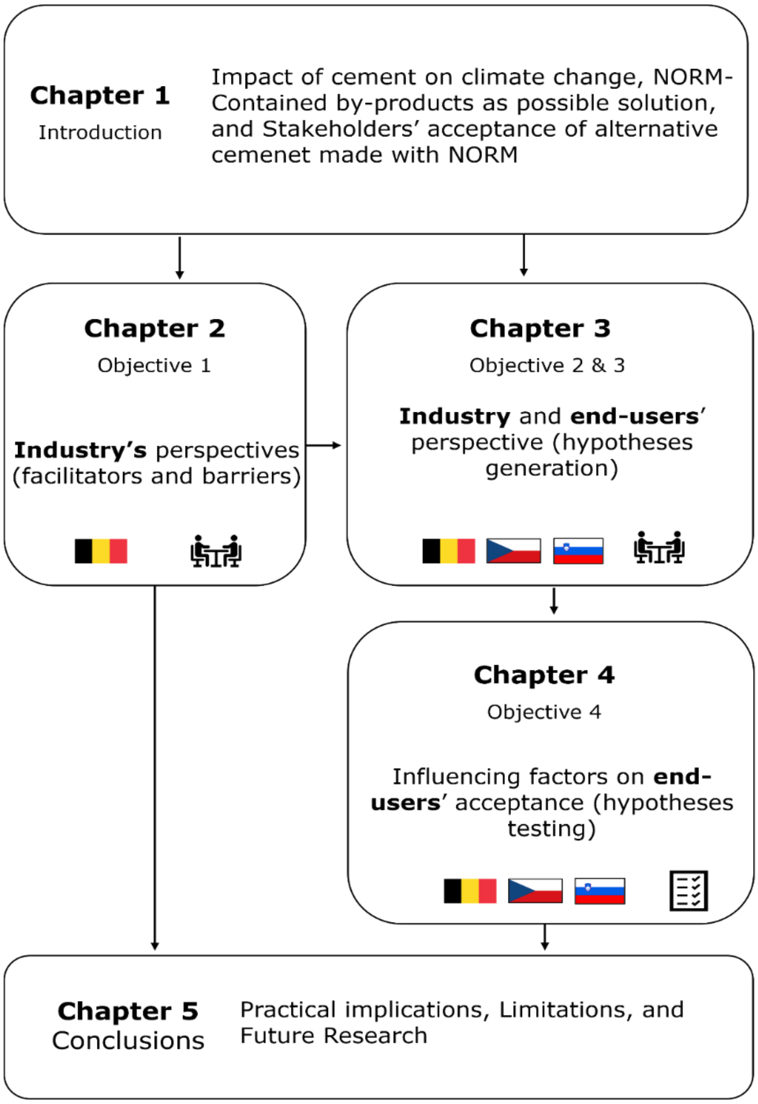


Figure 3: Overview of the thesis structure and the main content

Chapter 2. Facilitators and Barriers of the Use of NORM-contained By-products for Sustainable Cement: Industry Insight in Belgium

This chapter is based on the publication[4]: Love, N., Geysmans, R., Leroi-Werelds, S., Perko, T., Malina, R. and Schroeyers, W. 2023. Usage of alternative cementitious binders containing naturally occurring radioactive by-products: The industry's perspective, in *Journal of Cleaner Production*.

Abstract

In 2021, global cement production was responsible for around 8% of anthropogenic greenhouse gas (GHG) emissions. Alternative cementitious binders from secondary raw materials that replace traditional cement can reduce the need for the use of virgin raw materials and can thereby reduce GHGs associated with cement. Some of these secondary materials include industrial by-products categorised as NORM (Naturally Occurring Radioactive Material). While prior research has investigated the technical aspects of using NORM-contained by-products in cementitious binders, to date, no attention has been given to non-technical aspects such as perceived risks and concerns of the main stakeholders. This study brings novel insights into these overlooked aspects through a series of semi-structured interviews with concrete industry representatives in Belgium. Through a thematic analysis of the data, we found six themes that represent industry's concerns regarding the usage of NORM-contained cementitious binders: (1) availability of the by-products, (2) financial factors, (3) quality and performance, (4) common sustainability parameters, (5) customer demand, and (6) acceptance of NORM-contained by-products. Regulatory certainty was found to be a key driver in all six themes. With regard to the expected role of governments, we can synthesise three core expectations highlighted by interviewees: a) Policymakers need to revisit the current regulations regarding the performance and quality to facilitate innovation in the concrete industry such as the use of alternative cementitious binders. b) They should implement EU-level regulations that can provide a level playing field for the industry during their transition to net-zero targets, including import regulations and certification for the usage of NORM-contained by-products. c) As an important public buyer, the government should expedite the transition to alternative binders through their procurement policies for governmental buildings and infrastructure projects.

1. 1. Introduction

An analysis by the International Energy Agency (IEA) shows that global CO2 emissions rebounded in 2021 after the Covid-19 crisis to their highest level in history (IEA, 2022). Global annual production of around 4.4 billion metric tons of cement (USGS, 2022) contributes to around 8% of CO2 emissions

[4] This study has been developed within the RadoNorm project funded by the European Union's Horizon 2020 Euratom research and training programme 2019-2020 under grant agreement No 900009.

(World Economic Forum, 2024). Cement, the binding element of concrete, forms an integral part of everyday lives. It is the second most consumed substance globally after potable water (Czigler et al., 2020). Since the 1990s, global cement production has risen almost 4-fold (Andrew, 2019). Figure 4 shows that cement production outpaced world population growth since the 1950s, and that it is expected to continue to outdo it until 2050, in the absence of significant emission reduction measures (IEA, 2018).

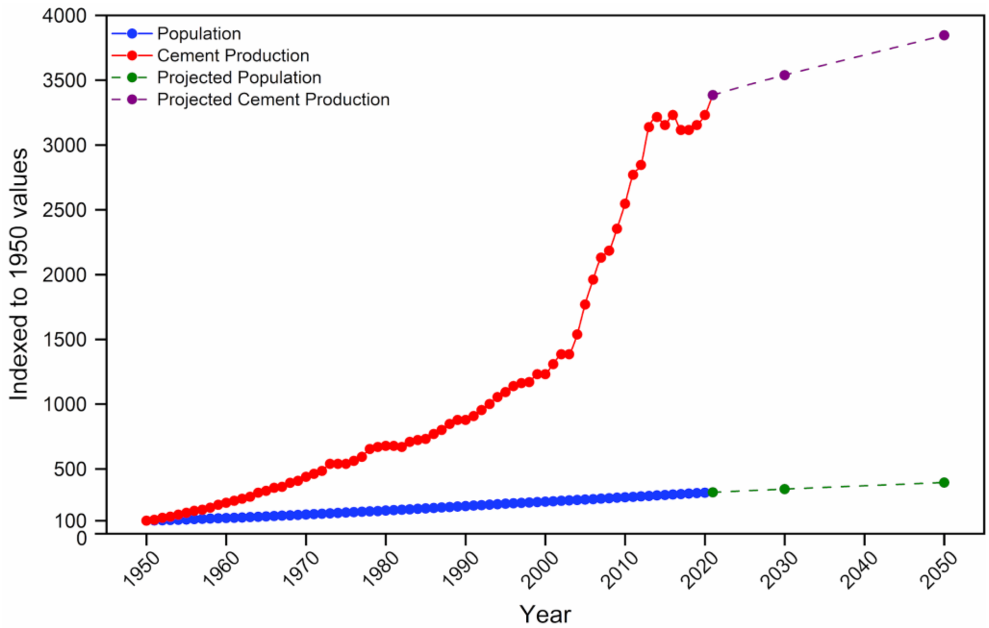


Figure 4: Growth in cement production versus population growth over time.
Data derived from United Nations (2022), USGS (2022), and IEA (2018)

As a key milestone in their roadmap to achieve net-zero target by 2050, the Global Cement and Concrete Association (GCCA) pledged to reduce 25% of the sector's CO2 emissions by 2030 (GCCA, 2021). The majority of CO2 emissions of the cement industry comes from production of clinker, the main component of cement (Andrew, 2019). Reducing the clinker-to-cement ratio is one of the key strategies that contribute the most to direct emissions reductions in the net-zero roadmap (GCCA, 2021; IEA 2021). Clinker can be substituted with supplementary cementitious materials (SCMs). SCMs are by-products of industrial operations that have the potential to be used in blended Portland cements or as a primary and additional source for cementitious binders (Benhelal et al., 2021). In Europe, around 23% of the clinker was substituted in 2017 by alternative materials such as Ground Granulated Blast Furnace Slag (GGBS) from steel blast furnaces and fly ash from coal-fired power plants (CEMBUREAU, 2020). The existing SCMs rely heavily on specific industrial waste mainstreams which are currently either under major revision or threat. At the same time, various industrial by-products that constantly accumulate in huge quantities have a negative environmental impact. Potential uses of these by-products have attracted attention from concrete technologists (Jain et al., 2021). Over the last few decades extensive research has been conducted on non-traditional materials and production techniques in the search for alternatives to traditional cement (see de Brito and Kurda, 2021; Juenger et al., 2019). With regard to SCMs as an alternative to traditional cement, the initial motive was economic, as it helped to decrease cement production cost (Kemp et al., 2017). More recently, environmental considerations for using SCMs are gaining attention (see Adesanya et al., 2021; Marinković et al., 2017). First, minimising the excessive extraction and consumption of natural resources, particularly limestone and clay through re-use of industrial by-products, contributes to a circular economy. Second, the substitution of clinker reduces CO2 emissions of cement production. Third, the re-use of hazardous materials such as metallurgical and mining residues specifically, avoids landfill being used as dumping sites (Benhelal et al., 2021; Jain et al., 2021).

With regard to hazardous materials, certain industrial operations, such as subsequent physical or chemical processing, can significantly increase activity concentrations of radionuclides. As a result, radionuclide concentrations in some by-products may exceed those in the original minerals and raw materials. If the concentration is above defined legislative levels (this varies among counties), it has become known as naturally occurring radioactive material (NORM). The activity concentration enhancement is observed in the generated industrial waste or residues (IAEA, 2013; ICRP, 2019). For example, copper slag, waste from the production of copper metal, may contain NORM. To produce one tonne of copper, around 2.2 tonnes of slag is generated. The utilisation ratio of copper slag is currently low and it is mostly discharged in landfills (Sharma and Khan, 2017). Red mud, the waste generated during aluminium production, is another example of NORM-contaminated material. For one tonne of aluminium produced, 1.5 tonnes of red mud are generated. Considering the annual production of 63.2 million tonnes of aluminium in 2017, it can be estimated that more than 100 million tonnes of red mud is generated every year which is mostly discharged into landfill (Tyagi et al., 2020). This waste not only occupies space, but more importantly pollutes the environment as a result of the leaching of heavy metals and radiation of nuclides (Wang, et al., 2020). This necessitates the safe usage of these industrial wastes. Rather than disposing of these materials in landfill as a waste, the International Atomic Energy Agency recommends the safe usage of NORM in other applications and considers them as resources rather than waste (IAEA, 2013).

Several studies examined the potential usage of different NORM-contained materials. For example, Wang et al. (2020) studied the use of copper slag as SCM and the potential hazards, while Romero-Hermida et al. (2020) examined the possibilities of reusing the phosphogypsum in building material from a health and safety risk standpoint as well as their potential polluting capacity. Finally, Temuujin et al. (2019) reviewed the latest developments related to the utilisation of various types of fly ash with a different level of radioactive elements content.

Schroeyers et al. (2018) provided a comprehensive review of the radiological aspects of by-products that have suitable properties to be used in concrete, but they also emphasised the need to understand the non-technical barriers that might delay or even terminate the actual adaptation of NORM in the construction industry. Furthermore, Turcanu et al.'s (2022) systematic review of social scientific literature illustrated the need for non-technical research on NORM. To the best of our knowledge, this gap in the literature has not been addressed, yet, which motivates our present study. Hence, this paper aims to provide insight into concrete industry representatives' concerns regarding the use of NORM-containing cementitious binders.

We define barriers as factors that hinder or impede the industry's usage of NORM-contained by-products, and facilitators as factors that help their transition towards the usage of NORM-contained cementitious binders (see Klöckner and Nayum, 2017). There is some empirical evidence on the importance of non-technical barriers for industry's adoption of innovative products available from studies on carbon capture and storage (CCS). Similar to NORM-contained by-products that due to radiological aspects might be perceived as risky by different stakeholders (Perko, 2014), CCS is also a sustainable technology that is associated with higher (perceived) risk. For example, van Alphen et al. (2007), identified human and environment safety risk as stakeholders' first condition for acceptance of CCS. Similarly, Wennersten et al. (2015) found that the barriers for implementation of CCS on a large scale are not primarily technical, but economic and social, such as public acceptance of the technology. Furthermore, Huijts et al. (2007) argue that the public acceptance also affects the political attitude towards CCS technology.

Authorities in EU Member States claim that building materials are regularly controlled and ensure that radiological exposure related to building materials is below legal norms. In this way authorities ensure the radiological safety of new building materials before market introduction (Mc Laughlin et al., 2022). However, understanding industry's concerns regarding NORM-containing cementitious binders is particularly important in the context of the construction industry given the conservative (i.e., non-innovating) nature of the concrete industry (Dewald and Achternbosch, 2015). According to Chatham House's 2018 report, the inherent resistance to product/process innovation in this industry is driven by the capital intensity of production processes, the lack of consumer demand for new products, and safety concerns (Lehne and Preston, 2018). As such, a thorough understanding is needed of what perspective industry has with respect to NORM-containing clinker substitutes.

Prior studies have extensively investigated the technical performance and environmental impacts of the usage of alternative by-products (including NORM) in cementitious binders in comparison to traditional cement (see the examples in Table 1). The current study investigates the usage of alternative by-products from an acceptance perspective, which is a dimension that has been neglected so far. It explores the industry's concerns regarding the usage of alternative binders, which helps build a bridge between the technical aspects of the product and market acceptance. No study, to date, has explored the acceptance of NORM-contained by-products which makes this paper the first study in this domain elucidating non-technical barriers of substituting traditional cement with alternative binders.

Table 1

Selected prior studies: Technical and environmental aspects of SCM

Authors/date	Purpose of the study
de Brito and Kurda (2021)	A review of concrete sustainability by discussing the non-traditional materials and techniques that can be used for the selected strategy, their limitations and future trends
Juenger et al. (2019)	A review of recent research on emerging SCM sources and improved knowledge of SCMs on long-term concrete performance and durability
Adesanya et al. (2021)	A review of utilisation and properties of waste-based activators in Alkali-activated materials
Marinković et al. (2017)	A comparative environmental assessment of several different green concrete mixes: recycled aggregate concrete with a cement binder, high-volume fly ash concrete with natural and recycled aggregates, and alkali activated fly ash concrete with natural aggregates
Romero-Hermida et al. (2020)	A study on characterising the products obtained from the treatment of phosphogypsum residue by means of two recovery routes, and also evaluating the concentrations of heavy metals and radionuclides in the materials obtained and their leachates
Temuujin et al. (2019)	A review of the latest development of utilisation of the various fly ashes with a different level of radioactive elements content for value added application
Wang et al. (2020)	A reactivity index of different types of copper slag and the safety of reusing copper slag as a SCM (i.e., the soundness, radioactivity and leaching of heavy metals)

2. Methods

Due to the novelty of our research topic and its exploratory nature we selected a qualitative research method. In their book on research design, Creswell and Creswell (2017) asserted that when a subject has never been addressed and no prior knowledge is available, the exploration of phenomenon merits a qualitative approach. Qualitative research is especially useful when the researcher does not know the important variables to examine and, therefore, explores a phenomenon, rather than using predetermined information from the literature (Creswell and Creswell, 2017). In line with that, Miles et al. (2020) argued that the richness and holism of qualitative data makes it a suitable strategy for exploring a new area and developing hypotheses.

Among different qualitative techniques, a semi-structured format interview was selected in this study to obtain an in-depth understanding of Belgian concrete industry representatives' concerns regarding the usage of NORM-contained by-products. Semi-structured interview combines structure and flexibility. Interviews are constructed with a limited number of open-ended key questions that help to define the areas to be studied, while allowing both researcher and participants flexibility to bring up unanticipated topics and explore the topics raised in detail (Knott et al., 2022; Neuman, 2011). The in-depth format of this method allowed us to fully explore the factors that underpin participants' concerns and the underlying reasons. The effectiveness of the interview method in studying unexplored contexts has been validated by other scientific studies. For example, Densley Tingley et al.'s (2017) study explored reasons for declining reuse of structural steel in the UK. Through conducting interviews with 13 construction industry members, they identified five barriers. They pointed out contrast between their identified barriers and the most commonly identified barriers in the global literature that mainly had a technical focus. This would not be possible using the predetermined questions in a survey method. This highlights the importance of in-depth interviews with the experts on the phenomenon of the study when a specific context has not been explored previously.

2.1. Interview Protocol Design

A two-step approach was used to design the interview protocol. First, inspired by the available literature, we created a list of questions that might be interesting to explore during the interviews. Second, we conducted discussions with 7 experts (other than participants of the study) in fields such as sustainable building materials, green buildings, and valorisation of by-products in order to obtain insights into general industry challenges. Based on these discussions we modified the questions list and designed the interview protocol that covered: 1) company's current decision making process for the choice of cement used in their production; 2) sustainability related topics such as how they define sustainability and if they are taking any actions to reduce their environmental impacts; 3) challenges towards sustainable solutions, particularly the usage of cementitious binders; and 6) their perception of the usage of NORM-contained by-products. Prior to the third and fourth section, the participants were given general information regarding cementitious binders made with [NORM-contained] industrial by-products. Providing this kind of information was necessary to assess and discuss possible concerns they might have regarding the usage of these binders. We tried to present this information as objectively as possible (see interview protocol in appendix A).

2.2. Sampling and Data Collection

A snowball sampling strategy was used in order to contact employees who are involved in decision making of the cement used in the concrete industry in the Flanders region of Belgium. Snowballing strategy involves asking participants for the referral to other people they know who fit the selection criteria. This approach is often used for small populations to find respondents that are not easily identifiable or reachable (Miles et al., 2020).

We first interviewed a limited number of participants from both ready-mix and precast concrete related associations/federations. Then we asked these participants for the names (referrals) of the employees from local concrete producing companies that can provide us valuable insight into our research (Lune and Berg, 2017). Using snowball sampling strategy, we were able to identify the potential participants that were involved in the decision-making process in the type of the cement they use and to some extent were familiar with the usage of SCMs. As indicated in Table 2, employees' position in the company varied (from CEO to innovation or quality manager). Interviewing a diverse group of experts who had different functions in the company, allowed us to capture possible different experiences and perceptions within the confines of the research topic (Knott et al., 2022).

Table 2.

Interview information

ID	Interviewee position	Duration and type	Company category	Association/ federation
E1	Innovation Manager	65mins video call	Precast	
E2	Innovation manager	57mins video call	Precast	
E3	Director	42mins video call	Precast	
E4	CEO	35mins phone call	Precast	
E5	Technical developer	62mins video call	Ready mix	
E6	External quality adviser	62mins video call	Ready mix	
E7A	Director	56mins video call	Ready mix	
E7B	Quality Responsible			
E8	Managing director	37mins video call	Ready mix	
E9	Managing director	55mins video call	Ready mix	X
E10	Director	46mins video call	Ready mix	X
E11	Director	67mins video call		X
E12A	Head of laboratory	62mins video call		X
E12B	Project Leader			
E13	Environmental advisor	54mins video call		X
E14	Technical advisor	39mins video call		X

Note: For company number 7 and 12, two employees with different functions attended the interview to provide more insight

Given the fact that participation in interviews was voluntary, it can be expected that employees from companies that have a relatively strong focus on sustainability, were more likely to participate in the interviews than employees from other companies. However, we do not regard this self-selection as problematic given that the interviews conducted allow us to generate insights from sustainability-front runners into the industry challenges to reach net-zero carbon.

After obtaining ethical approval from Hasselt University's Ethical Commission, we conducted online/telephone (due to COVID-19) interviews with employees of fourteen Belgian concrete producing companies and related associations. Prior to the interviews, participants received a consent form, assuring that their data will be managed safely and treated anonymously. The interviews were conducted in English and they took place between September 2021 and January 2022 (average duration = 53 minutes). Table 2 depicts key information on all interviews. Data collection and analysis happened in tandem. We stopped recruiting participants once we reached data saturation. Data saturation is a common principle used in qualitative research. This is the point at which each interview confirms previous findings and no new information is emerging to evoke new insight (Braun and Clarke, 2021a; Knott et al., 2022). Therefore, conducting more interviews would not have resulted in finding more themes as the new participants were repeating the same concerns previous participants mentioned. Interviews were audio-recorded and subsequently transcribed. The transcriptions were transferred to the Nvivo software for organising and coding the data.

2.3. Data Analysis

In qualitative studies the important consideration is not if the sample is large enough to permit statistical analysis in order to test research hypotheses. It is whether the research design and recruitment strategy allows for collecting rich data to generate hypotheses (Gerson and Damaske, 2020). Unlike quantitative research which is based on statistical interpretation, qualitative research is based on themes and pattern interpretation through a text analysis (Creswell and Creswell, 2017).

Data analysis took place iteratively and in parallel with data collection. We used thematic analysis informed by Braun and Clark’s (2021b) guidelines to identify, analyse and report patterns within the data. Before coding, the first author familiarised herself with the data by transcribing and reading the interview transcripts multiple times. An inductive coding strategy was used in which codes and themes were developed directly by engaging with the content of data as opposed to starting from existing concepts or ideas. Initial rounds of coding were generated directly from the transcripts based on surface meaning communicated by participants. These semantic codes relied on close-to-text open coding and each code captured a single idea associated with a segment of data. Codes were labelled in a way that they could work independently from the data. Then similarities and differences across codes were examined to generate broader categories by relating codes to one another that were then developed through axial coding. These latent codes captured the assumptions underpinning the surface meaning of codes. During an iterative non-linear process codes were refined and changed over the course of progressive rounds of coding. This implied repeatedly renaming the codes, splitting and collapsing them together. Finally, common recurring patterns were identified and organised into themes. Each theme consisted of more than a single idea or manifestation across the data. Some of the identified themes consisted of sub-themes that share the same concept as the theme but focuses on specific elements. Table 3, summarises the themes and sub-themes identified.

Table 3.

Themes and sub-themes created in Nvivo

Themes and sub-themes	Interview*	Reference**
Availability of by-products	8	15
Financial Factors		
Investment costs	11	18
Need for clear regulations	10	28
Political lobbying of cement producers	4	10
Quality and Performance		
Distinction among application	5	12
Strict standards and certification	9	22
Importance of having standards/certifications	5	7
Harmonised product regulations	8	19
Common sustainability parameter	7	26
Customer demand		
Lack of willingness to pay	14	31
Government setting example	5	8
Acceptance of NORM-contained by-product		
Familiarity with hazardous material	7	10
Being certified	11	23

Higher perceived risk	3	8
Workers' safety	6	10
End of product life	11	36
Communicating NORM	6	13

*Interviews: number of participants that referred to particular theme

**References: number of times a reference to a theme has been made

3. Findings and Discussion

Through analysis of the interviews, six themes were generated that represent the concrete industry's concerns regarding the usage of alternative cementitious binders, particularly those made with NORM. These include (1) availability of the by-products, (2) financial factors, (3) quality and performance, (4) common sustainability parameters, (5) customer demand, and (6) perception of NORM-contained by-products. Table 4 summarises the key themes and participants identified barriers and suggested facilitators in each theme. Regulatory certainty was found to be a key driver in all six themes. In this section, we discuss each theme and associated sub-themes in depth.

3.1. Theme 1: Availability of By-products

Even when participants were convinced of the technical suitability of the alternative binders, they repeatedly highlighted the unstable supply of by-products as a barrier: "I heard that there is a possibility to activate copper slag, so I don't have concerns. My concern is [whether] enough is available? If we start tomorrow with a new binder, will that kind of binder also be available, let's say two years later" (E8).

Participants also emphasised the importance of local availability: "Often we forget on an academic level that all these kinds of binders and all these kinds of exotic things, there is not a lot of volume locally" (E12B). Some participants raised concern that current regulations allow companies to import by-products from outside Europe meaning that 'on paper' they reduce their CO_2 emissions, while in reality they emit CO_2 while transporting the materials from another continent: "If we want good quality slag it is possible, we buy the slag from Brazil and Japan. But this will have a big impact on CO_2. [...] We can't find a by-product far away from location and spending CO_2 on the way" (E7B). Jin et al.'s (2015) study showed that despite being identified as the third biggest barrier for using SCMs among ready-mixed concrete suppliers, availability of the by-products was not mentioned by any precast suppliers as a barrier. Despite not being able to statistically claim due to the nature of the qualitative study, we can see a similar pattern in our study. The concern regarding the availability of by-products was mentioned by 1 out of 4 precast participants[E3]. While this concern has been mentioned by all of the ready-mix companies[E5-E10]. This can be further explored in future studies.

Table 4

Summary of findings

Theme	Potential barriers identified by participants	Suggested facilitators by participants*
Availability of by-products	-Insufficient quantity of locally available by-products -Lack of regulations that halt the import of by-products from outside Europe	Import regulations for building material
Financial factors	-Investment costs -Lack of government pressure, e.g., CO_2 taxes -Political lobbying of cement producers	Increase of CO_2 taxes and penalising non-sustainable concrete
Quality and performance	-Distinction among applications -Current stringent quality and performance related regulations -Lack of harmonised EU level product regulations	Balanced EU-level regulations that allow innovative products, while guarantee product safety
Standardised sustainability parameter	-Lack of standardised sustainability parameters at the EU level -Greenwashing	EU-level standardised sustainability parameters
Customer demand	-Customers' lack of willingness to pay -Lack of customer obligation to consider sustainability aspects -Lack of public procurement of sustainable concrete in governmental buildings and infrastructure	Obligation to consider certain sustainability aspects in private and public procurement
Acceptance of NORM-contained by-products	-Certifications and standards that prove these materials are safe to use and have no negative impact on human health -End of product life -Communicating NORM to customers	

*All suggested facilitators for each theme are linked to the regulatory certainties

Companies' concerns related to the availability of the by-products are closely linked to the lack of regulatory certainties. In order for companies to switch to new binders, not only do they need assurance of the availability of these secondary materials that substitute clinkers. They also need regulatory certainty regarding the import regulations related to these materials to allow fair competition among the companies. Current inadequate import policies concern industry experts.

3.2. Theme 2: Financial Factors

Investment costs. The required investment in infrastructure to use these binders in production processes is another factor that interviewees brought up: “Do they need new forming technology, or can we just add them in our existing process? We have these mixers we use, if we just can add [alternative binders] instead of cement, it's very easy for us. So of course, an important driver is the investment needed to meet these kinds of binders” (E4). Current CO_2 prices are not high enough to force the companies to invest in new production processes, which is why some companies work with their old technology and invest in carbon capture technology: “The investment in CCS is in line with what I have to pay more, if I stay producing in classical way [not making changes to their production process]. Naturally, if the cost is still more expensive, then perhaps I will invest in a new production process to have lower CO_2” (E5). A similar pattern related to cost and technology implementation has been also identified in the literature by Wennersten et al. (2015). Investment cost is a big barrier for cement and concrete companies due to the low profitability of the cement: “The profitability of the sector is quite limited. [...] We are not Google or Apple or whatever, it's very capital intensive. So, we need to have long term perspectives and very clear legislation” (E9). This is parallel with Neri et al.’s (2021) study on the chemical and metalworking sector’s adoption of sustainability measures, in which investment cost and limited access to capital were among the identified barriers. They reported a trade-off between short and long term financial perspective which is also evident in our study.

Need for clear regulations. Participants are concerned that “there's still little pressure on the cement industry to become greener” (E5) and “no impulse from the government” (E7A). The authorities can expedite transition through regulations: “If you as the government change the rules, then it's easy for the companies to say, okay, now I'll invest in another technology because if I stay working with my own technology, I will not make any money between now and five years. So, I have to invest. But if nobody comes with real rules, or adapts the rules to make it more sustainable or lower CO_2, why should the companies adapt?” (E5). More specifically participants mentioned that authorities should facilitate this by increasing CO_2 taxes:

“We don't have the margins; we have to look at the economic part. We are looking in the future to reduce CO_2 in the hope that the government asks for it and makes a law that you have to do it.” (E8)

"I think they should raise taxes on these kinds of cement products, to give the cement product less of a chance." (E4)

Confirming our findings Löfgren and Rootzen (2021) argued the effectiveness of increasing carbon price as it will level the playing field between products with high and low carbon content. Corroborating this, Ajayi et al.'s (2015) study showed that increases in the landfill tax in the UK, pushed companies towards reducing construction waste and increasing materials reuse.

Political lobbying of cement producers. Some participants mentioned that the "government is not penalising the cement companies for still producing their cements as before [because] the lobbying of the big multinational [cement companies] is still really strong" (E5). The cement lobby is working against clinker substitution due to high investment in their current production sites. Participants suggested that "the government can help us to use their influence to look at this BENOR certification and say guys look, you should be more open and we need you to look at the available alternatives in an open way. Now they are using their power to keep every new player away" (E4). One participant mentioned that there was similar resistance from cement companies towards usage of slag: "I think the first time slag came commercially on the market in Benelux was 2004-2005, there were some manoeuvres for not making it easy to get it in normalised concrete" (E6). In order to reach net-zero, the government needs to act objectively: "But at the end, it's the government that has to make the path and really do it in an objective way and really think about it and not do too much lobby work. Otherwise, we will not arrive at the goal of slowing CO2 to make the construction sector more sustainable" (E5). These quotes align with Lehne and Preston's (2018) report which stated that cement producers are reluctant towards the technologies that lowers the value of clinker production installations due to high investment in these infrastructures.

Being a capital-intensive industry, rather than taking actions on their own initiative, companies need regulatory certainty. This implies that the government objectively (without the influence of cement production lobbyists) pressurises all the companies to take action (for example through increasing CO2 taxes).

3.3. Quality and Performance

Distinction among applications. Quality and performance of the binders was stated as crucial by participants as product failure might have fatal consequences. They repeatedly expressed that currently there is no miracle solution to fully replace traditional cement: "I don't expect that there's going to be a one-million-dollar solution or a miracle happening. I mean, there's going to be several alternatives, each with its own criteria and its own piece of the puzzle. At the moment there is nothing in sight that could really replace cement at industrial scale for the next five to ten years" (E10). With regard to this, some participants suggested the distinction among applications: "It's very important to look at which applications you will use. In my opinion, it will be a mistake to try to replace the cement as it is now. I think you have to make a distinction between low end and high-end applications" (E8).

Product regulation and certification. Regulations regarding quality and performance of the concrete were referred to as "working in another time frame" (E12A), which "slow down the process of introducing new cement" (E9) and "make the introduction of the innovative product quite difficult" (E11). Participants particularly referred to strict regulations in Belgium: "I think in the Belgian market it will be a very big barrier. It will take a long time because we are very strict. If you look at regulations and standards for new products, we really want to be 200% sure it will work in all circumstances" (E8). One participant mentioned that current certifications require "putting too much cement in our concrete. So, in our concrete the strength is too high versus what's been asked by the job and for the contractors" (E10). Participants explained that despite being willing to "we cannot lower the amount of cement because the moment we lower the amount, the certificates will be gone" (E1). "It is necessary to use alternative cement to reduce the cement quantity but we are always limited by the minimum of the norm. So, it is also a big constraint" (E7B).

To accelerate the transition to net-zero carbon, participants believe that lifting barriers of existing regulations is crucial: "We need to move forward as fast as possible, which means the constraints concerning historical views on concrete should be opened up quickly in order to allow companies to advance on it" (E10). These quotes are supporting the findings of van Deventer et al.'s (2021) review paper on low- CO2 cement in which they argued that regulations have been slow to prioritise climate over construction expediency. Unsupportive regulations, combined with complicated and difficult to achieve standards, were also identified as a barrier for the application of recycled C&D waste products in construction projects (Park and Tucker, 2017).

Harmonised product regulations. Participants' concern regarding product related regulations was not just at the national level, but also the EU level: "The European concrete standard is not harmonised. It means that there is a European standard for concrete, but each country has its proper regulations on top of it […] For new products, it's possible that it's allowed in France, and if you go to Belgium, you have to redo maybe the same things[tests]" (E8). In order to reduce global CO2 emissions, a holistic global view is needed: "CO2 will not look to the boundaries of the country. It's a global issue" (E5). Current regulations do not accommodate this: "Each company that produces cement in Belgium has to buy what we call CO2 allowances. But that is only for production in Europe, which means that cement that's been bought out of Europe and introduced into Belgium is not taxed. So, import of cement is not taxed. I mean, if you make cement in Belgium or you make it, for instance, in Russia or in Turkey or whatever, the CO2 exhaust will be more or less similar. So, by importing that you reduce it, let's say on paper, but in real life, it's going into the air" (E10). The lack of import regulations was also a barrier regarding the by-products (see section 3.2.1). Not only is it financially discouraging for the companies, but also, it does not help the global CO2 problem. The importance of coordination at all governmental levels has been also discussed in Henrion et al.'s (2021) study on the current status of concrete technology and policy in the United States. Further Löfgren and Rootzen (2021) argued that lack of enforced global agreement and differing policy stringency could be a market risk when companies compete in a global market.

Balanced regulations. On one hand the existence of stringent and slow-adapting regulations was identified as barriers. On the other hand, absence of regulations was referred to as a barrier (see section 3.2.6). There is a need for a balanced product regulation which accommodates sustainable products, while guaranteeing product safety: “There must be a balance between going fast and being efficient, but still making sure that from a scientific point of view, analysis is done properly” (E9). Our findings confirm the previous studies that described the regulations and standards’ role as enabler (ensuring quality) and disabler (hindering the use of innovative sustainable products) (Park and Tucker, 2017; Senaratne et al., 2017; Shooshtarian et al., 2020).

3.4. Theme 4: Standardised Sustainability Parameters

Lack of a unified and aligned approach allows companies to make environmental claims that are only based on certain aspects and in many cases, they neglect, or even increase other environmental impacts: “Everybody is talking numbers, but nobody knows the numbers really clearly. So that's also a big, big hindrance” (E2). Participants highlighted the need for common sustainability parameters: “We need a standardised procedure to define what sustainability is. And the biggest issue is that everybody is doing something and everybody is claiming that is sustainable or ecological. They also use different parameters [...] and there's a lot of greenwashing. But the big problem is how do you define it? So, if nobody says how you have to define it, everybody can say a bit of anything, and the customer doesn't know who is right anymore.” (E5)

The lack of consensus on what sustainability means, results in greenwashing (environmental claims that are exaggerated, false or deceptive) through stating “facts and figures that are so ridiculous and so unimportant” (E6). Many companies seek sustainable concrete with a purpose of greenwashing as opposed to genuine efforts to reducing environmental impacts:

“They want a little bit of sustainability awareness in our product.” (E1)

“Some of them just want something new that sounds green.” (E12A)

Participants suggested that the Belgian government should impose a similar approach to the Environmental Cost Indicator (Milieu Kosten Indicator - MKI) in the Netherlands which was explained by participants as ‘a standard and calculation method which is recognised by everybody’. As it was discussed in section 3.2.3, this should be implemented at the EU level: “It [MKI] is the way to go. But you should launch that on a European level and not on an individual [national] level. And that's a bit of my concern that by the individual initiatives of each country the open market is a bit problematic.” (E5)

The importance of standardised sustainability parameters has been also highlighted in other fields of studies. For example, van Schoubroeck et al. (2018) highlighted the lack of a holistic view on sustainability indicators for the biobased chemicals. Similarly, Bosch et al. (2015) argued that lack of standardised sustainability parameters for biomass assessment resulted in different schemes with a lack of comparability, which resulted in confusion, mistrust and consequently slower growth.

Alongside the regulatory certainty related to the quality and performance of alternative material, regulations also need to provide a harmonised measurement system to avoid inaccurate sustainability related claims. Lack of standardised parameters not only allow unfair competition (for example through greenwashing) but as we will see in the next theme, it will create mistrust among customers.

3.5. Theme 5: Customer Demand

Lack of willingness to pay. Overall, participants explained that currently there is talk about sustainable products, but not much tangible request: “On the floor, in 99.6% [of cases], nothing has changed so far. So, most of them [concrete producers] do business as usual and just want concrete that's cheap and okay in terms of quality” (E12B). Participants “don’t think that consumers are going to be willing to pay more for green concrete” (E13). E11 reiterated this point by saying that: “They would like to get it for free, but if you ask them if they would like to pay, it is different”. The lack of demand for recycled material was also identified as a constraint in Park and Tucker’s (2017) literature review on the issues different stakeholders encounter around reuse of construction waste in Australia.

Participants explained that “there is no real obligation from owners to have real sustainability on the top of the agenda [therefore], people are not directly willing to pay a lot for it” (E10). It was suggested that to stimulate demand “you have to push it from the governmental side” (E8) by imposing sustainable consumption law on private buyers: “So you need to oblige the end-user to do it, in order to create a demand” (E14).

Government setting example. Government also plays a crucial role as public buyers: “I think there is a role for the government because the government is always one of the main end-customers. They construct a lot. [...] They can start by demanding more [on the level of] sustainability. That will create an immediate effect on the industry” (E3). Paramount role of sustainable public procurement has been the focus of many recent studies (Cheng et al., 2018; Stokke et al., 2022). In line with this, Simcoe and

Toffel's (2014) study claimed that government procurement policies have spill-over effects that stimulate private-sector adoption of sustainable activities.

Lack of regulations that oblige customers to comply with sustainability aspects when purchasing concrete, creates uncertainty regarding demand for sustainable products. Regulations that can assure public and private obligations to comply with sustainability aspects will encourage companies towards the usage of alternative binders.

3.6. Theme 6: Acceptance of NORM-Contained By-products

Familiarity with hazardous material. We asked participants if they would consider the usage of NORM-contained by-products. Mostly, those participants that were open to adopt it, had previous experience with the same or similar challenges, such as having to measure radioactivity thresholds previously; having experience in dealing with waste containing heavy metals; or being aware of the natural radioactivity level in some parts of Belgium, including the radon level: “We are used to have waste containing dioxins, organics or some heavy metals. [...] We've done leaching tests for years, so there is sufficient experience there to state that it is safe. I don't have experience with radioactivity, I don't know. But of course, let's say this will have to be handled” (E9).

Being certified. Some participants' initial reaction to the word ‘radioactivity’ was demonstrated through facial expressions or phrases such as “[radioactivity] is not a positive thing to deal with!” (E10) However, the initial reaction softened as the conversation carried on. This is evident during the conversation with E4, from: “I am reluctant to it.” to: “If it's really investigated well, it is within the standards, and we are sure that it cannot have a negative impact on our marketing, then we would consider using it”. It is also apparent that standards play an important role in participants’ acceptance. Certifications and standards that guarantee the safety of these materials, was the main facilitator: “I think we as an industry, if the product is approved and certified, then we will agree, and then we will be ready to use the product” (E3). Clear regulation has been also identified as a key potential enabler of the large-scale use of CCS technology (Benhelal et al., 2021). Currently in many EU countries, there are standards ensuring the safety of building materials or the built dwellings from the radiological perspective. However, there is a lack of a harmonised approach meaning different EU members might regulate this field differently (Mc Laughlin et al., 2022). This is also something that requires a unified approach.

Higher perceived risk. A few participants who had higher perceived risk, were more hesitant towards the usage of NORM-contained by-products: “That's a difficult one. Let's say that it looks okay if everything is done under very precautious circumstances, but being in ready-mix concrete, it's a raw material and everything is raw around it. So, what if a silo dedusting system fails? What with people that are in maintenance and are shooting down the concrete in the big mixers and getting the dust inside. So, I think that has a lot of chances to become an idea [of which] we say in ten years, oh oh we shouldn't have done that” (E6). This argument brought forward by the participant, incorporates previous findings with regard to stakeholders’ risk aversion. For example, Shooshtarian et al. (2020) explained that stakeholders prefer taking smaller and safer steps rather than being involved in disruptive changes of moving toward a circular economy.

Worker’s safety. These materials should not impose any risk on workers: “The product you are using to make concrete in your factory, should bring no risk to the people working in that factory” (E11). Moreover, the usage of these materials should not be too complex: “The people placing concrete are the contractors [...] with not a lot of experience on several types of materials and how to deal with it. So, it needs to be something that is safe for everybody without too many procedures linked to it because otherwise in real life, it could go wrong” (E10). Most of the participants did not express concerns regarding the safety of the population who will be occupying the buildings built with NORM-contained by-products. This aligns with van Heek et al.'s (2017) study in which the expert group had no health concern regarding the safety of the CO_2 utilisation for specific plastic products by the public.

End of product life. Beside the importance of regulations concerning health and safety, regulations concerning the ultimate dismantling of the product was also important for the participants. However, they had different levels of expectations, such as not encountering serious issues when demolishing (E7A: for example, asbestos); being able to reuse it to make new concrete [or aggregate]; or higher expectation: “If you put things in concrete and say you immobilise leaching, true, but if in the third life or fourth life the leaching restarts, I don't think it's a solution” (E12A).

Communicating NORM. One of the possible major hurdles for the usage of NORM-contained by-products was identified as difficulty of communicating it to the public as it might cause them to panic and overreact: “Maybe there will be a demonstration tomorrow in front of our factory and people don't even know what is even XY, they will just think, oh, it might harm us” (E1). The complexity of radiological risk communication was also evident in Turcanu et al.’s (2022) systematic review of social scientific research on NORM. Despite being open towards these materials, industry has many concerns which need to be addressed and communicated.

The final regulatory certainty required by industry is the standardisation of the NORM-contained by-products so that companies are able to ensure the safety of these products.

4. Concluding Remarks

The present study is the first to provide insights into the concrete industry’s perspective on the challenges and concerns related to the usage of NORM-contained by-products as SCMs. More broadly, this study builds on and extends literature on cementitious binders through contributing to the non-technical perspectives. Indirectly, this research also contributes to the literature on circular economy in the building sector.

During the analysis of the interviews, it was found that the fact that these by-products are NORM-contained is only one side of a multi-faceted challenge that the industry is facing regarding clinker substitution. From the interview analysis, six themes were generated representing fundamental challenges in different business stages that hinder the transition from the traditional way to a cleaner clinker production. Overall, multiple avenues that could facilitate overcoming these challenges were recommended which can be relevant for practitioners, policymakers and researchers. Our main hypothesis that we derive from our study, is that regulatory certainty is the key requirement for the industry's acceptance of alternative (NORM-contained) by-products. We also hypothesise based on the interview analysis that there is a need for a holistic approach targeting all relevant stakeholders through a policy mix: for the concrete producers through lifting barriers of existing regulations, certifying sustainable innovative materials, and imposing higher rate green taxes; and for the demand side by imposing sustainable public procurement rules and sustainable consumption law.

The global nature of climate change requires a global approach. For example, it was emphasised by the interviewees that import/export regulations that facilitate the deceiving of the system by reducing the CO2 in their own country, while increasing it at global level, need to be revised. Furthermore, the regulations regarding the performance and quality of the concrete not only need to facilitate the entry of innovative sustainable solutions, but also need to be harmonised (at least) at the EU-level to foster up-scaling of innovative solutions in an open market. To avoid the risk of activating sustainability-oriented strategies that are not effectively sustainable, the development of EU-level standardised sustainability parameters becomes fundamental. This would provide effective guidelines for the industry. Consequently, it would minimise potential risk of greenwashing by providing reliable, comparable and verifiable sustainability claims. With regard to the NORM-containing by-products, certifications and standards play a crucial role in minimising the risk companies need to take in the usage of these by-products by guaranteeing the safety of their products.

Like most qualitative studies, the goal of this research was not to generalise, but rather to explore industry's concerns regarding the usage of (NORM-contained) by-products and hear possible solutions from industry's perspective. Due to the nature of qualitative research, we could not give weight to the identified themes related to industry's concerns. We encourage a quantitative study as a future work to not only test the hypotheses generated from this exploratory study, but also to deduce the relative importance of the themes and generalise the findings of this study. With regard to additional qualitative research, we suggest future research opportunities to build upon and expand our findings by cross country studies, as the focus on Belgium could limit the representativeness of the results in a wider EU context. Our findings showed that industry is concerned about communicating the usage of NORM in their product, particularly to the public. Therefore, another potential area of future research would be to explore public perception (as opposed to industry perception) of the usage of these materials in buildings. Finally, we suggest a follow-on study to understand the perspective of public authorities on the implementation of the identified facilitators in this study which has regulatory certainty at the core.

Chapter 3. Cross-country Perceptions of NORM-contained By-products in Alternative Cement: Industry and End-user Concerns

In the previous Chapter (2), we provided a comprehensive insight into industry representatives' perspectives on the use of alternative cement. In the following Chapter (3), by expanding our investigation to two additional EU countries, we explore whether these perspectives are country-specific. Furthermore, we examine whether the identified barriers and facilitators are unique to the industry or if they also exist among end-users.

This chapter is based on the paper[5]: Love, N., Geysmans, R., Leroi-Werelds, S., Železnik, N., Perko, T., Schroeyers, W. and Malina, R. 2025. Stakeholders' perspective on sustainable cement made with naturally occurring radioactive by-products: A cross-country comparison, which is currently under minor revisions in *Journal of Environmental Management.*

Abstract

The use of industrial by-products as substitutes for raw materials in cement production not only reduces raw material use, thereby contributing to the circular economy, but also offers an avenue for reducing greenhouse gas emissions. This study investigates the perceptions of industry representatives and end-users across Belgium, Czechia and Slovenia regarding alternative cement made with industrial by-products categorised as naturally occurring radioactive materials. Based on 66 interviews, three main concerns were discerned: health, performance, and economic. Health concerns varied across countries, whereas performance and economic concerns were consistent. Health concerns can be mitigated by fostering trust in authorities. Performance concerns can be addressed through certification and practical examples. Economic concerns arising from the perceived higher costs connected to sustainability and lack of urgency for immediate change can be mitigated through incentives and regulations. This study informs communication and policy strategies tailored to address stakeholders' specific concerns in each country.

1. Introduction

Innovative solutions for energy and material efficiency in the cement sector are key to reducing the 8% of the global GHG emissions for which the cement industry is responsible (World Economic Forum,

[5] This study has been developed within the RadoNorm project funded by the European Union's Horizon 2020 Euratom research and training programme 2019-2020 under grant agreement No 900009.

2024). The predominant source of GHG emissions in cement production comes from the manufacturing of clinker, which is the main component of cement. These emissions result from the chemical reactions and fuel combustion during the production process. Reducing the clinker-to-cement ratio by increasing clinker substitution could make the greatest contribution to reducing emissions in the cement industry (IEA, 2023). Commonly used substitutes for clinker include fly ash from coal-fired power plants (Vargas and Halog, 2015), granulated blast furnace slag from steel blast furnaces (Oge et al., 2019), and calcined clays, which are natural clays subjected to thermal treatment (Scrivener et al., 2018). However, a reduction in the supply of some commonly used by-products is expected due to major changes in their respective industries (GCCA, 2023). Consequently, alternative industrial by-products with the potential to substitute clinker have been investigated extensively (Duchesne, 2021; Juenger et al., 2019; Miller, 2018; Snellings et al., 2023; Yang et al., 2015).

Among these potential clinker substitutions, by-products such as copper slag from copper metal production and red mud from aluminium production are categorised as naturally occurring radioactive material (NORM), owing to their elevated radionuclide concentrations. Industrial processes such as subsequent physical or chemical processing leads to a notable increase in radionuclide levels. Consequently, the radionuclide content of these by-products often exceeds that of the original minerals and raw materials. When these concentrations exceed a certain level (this varies among countries), the by-products are categorised as NORM. Using NORM-contained by-products as clinker substitutions has two potential benefits: it can reduce the clinker-to-cement ratio and, consequently, GHG emissions during cement production; and industrial by-products will be repurposed, rather than accumulating as waste in landfills (Wang et al., 2020).

A significant body of research has explored the technical feasibility and environmental impact of using NORM-contained by-products as clinker substitutes (see Kumar et al., 2021; Phiri et al., 2021; Wang et al., 2021). However, the successful development and deployment of emerging technologies also depends on understanding and addressing stakeholders' concerns (Siegrist and Hartmann, 2020). Kirchherr et al. (2018) classified a lack of consumer interest and awareness as one of the main barriers to a circular economy in the EU context. Their findings indicate that while technological advancements are necessary, they are not sufficient to adopt sustainable practices. The importance of societal acceptance has been highlighted for other disruptive technologies such as hydrogen (Emodi et al., 2021), low-carbon technologies (Arning et al., 2020), and renewable energy (Batel, 2020). In the context of alternative cement made with NORM-contained by-products, societal acceptance is critical, especially due to potential concerns about radioactivity.

To our knowledge, the societal aspects of using alternative cement made with NORM-contained by-products have, to date, been explored solely in the context of the Belgian concrete industry (Love et al., 2023). Our study broadens this scope by extending the investigation to include end-users' perceptions beyond industry insiders, as well as expanding the geographical context to the Czech Republic (Czechia) and Slovenia. This allows us to assess whether previous findings are context-specific or generalisable to other national contexts. We pose the following research questions to further explore the complexities of the transition to alternative cements:

RQ1: What key factors influence industry representatives' and end-users' perceptions of alternative cements in Belgium, Czechia and Slovenia?

RQ2: To what extent do country-specific factors in the three countries shape industry representatives' and end-users' perceptions of alternative cement?

Thus, this study identifies the challenges in transitioning to alternative cement, contributing to the ongoing discourse on sustainable replacements for traditional cement. By investigating societal aspects, we extend the analysis scope of the literature, which is currently strongly focused on technical and environmental issues as previously outlined. Insights into stakeholders' perceptions of alternative cement provide a foundation for strategies that can inform the design of public policies and communication strategies.

2. Methods

To explore perceptions of industry representatives and end-users of alternative cement, we adopted a qualitative research method that provided comprehensive insights into uncharted research areas, enabling a detailed understanding of the topic without predefined variables (Creswell and Creswell, 2017; Knott et al., 2022). Among the different qualitative techniques, we conducted semi-structured interviews because this format strikes a balance between structured and flexible discussions, guided by key questions, while allowing for the emergence of new relevant topics during the interviews (Gibson and Brown, 2009). This approach was particularly effective in our study, owing to its exploratory nature. Appendix B provides the interview protocol and design steps.

2.1. Sampling and Data Collection

To extend the previous research conducted in the Belgian context (Love et al., 2023), our study compares perceptions in Belgium with two other countries within the EU: Czechia and Slovenia. This ensured consistency across evaluations, leveraging the fact that all EU Member States adhere to European climate law, which mandates significant reductions in greenhouse gas emissions to achieve the 2050 net-zero target (European Council, 2024). Czechia and Slovenia were chosen for their distinct socio-historical contexts.

Czechia has historically used concrete containing industrial by-products with elevated levels of natural radioactivity, which has led to increased indoor radon levels, prompting the demolition or remediation of affected dwellings. These incidents contribute to approximately 15% of lung cancer-related deaths in Czechia (Hulka and Thomas, 1999; SURO, 2024). This history provides a different dimension to our comparative analysis of the perceptions of alternative cement.

Slovenia's high recycling rate, as reported by the European Environment Agency (2023), underscores a societal inclination towards resource efficiency, which could translate into a positive reception of alternative cement solutions that promote sustainability. However, recent criticism of Slovenia's largest cement plant regarding air pollution (CIPRA, 2022) provides context that enriches our comparative study: a robust recycling ethos in Slovenia coexists with the health challenges related to cement production.

Building on our comparative framework, participant recruitment involved tailored sampling strategies for end-users and industry representatives, detailed in Table 5.

Table 5.

Sampling strategies for both stakeholder groups

	End-users	Industry representatives
Definition	Individuals in the process of building or renovating their houses.	Professionals involved in their company or organisation's decision-making processes regarding the type of cement used. This includes roles within concrete companies, construction companies, and related federations that represent industry perspective.
Sampling strategy	**Purposive sampling**: End-users who have recently built or renovated their houses were targeted due to their recent involvement in choosing building materials for their construction projects **Convenience sampling**: Participants were selected based on their accessibility and availability to the researcher, optimising research efficiency, and resource utilisation.	**Snowball sampling**: Networks of initial participants were used to identify additional relevant individuals from other companies, ensuring that those selected could offer detailed insights into our research questions.
	Quota sampling: To ensure representation from each of the three countries under study, the above strategies were combined with quota sampling, balancing the input from both stakeholder groups across geographical locations.	

In line with ethical research practices, ethical approval was obtained from the Social-Societal Ethics Committee at Hasselt University. Informed consent was obtained from all participants before the interviews, highlighting the principles of voluntary participation, autonomy, and confidentiality. These interviews, conducted online between September 2021 and April 2023, had an average duration of 45 minutes. Each interview was audio-recorded and later transcribed and translated to English. Table 6 presents the number of participants in each category. We relied on the concept of data saturation to determine when data collection was sufficient, which meant that no new insights emerged, while ensuring the richness and comprehensiveness of the collected data (Gerson and Damaske, 2020).

Table 6.

Distribution of participants

	Belgium	Slovenia	Czechia	
End-users	12	11	10	
Industry	14	9	10	
Total	26	20	20	**66**

2.2. Analysis of Interview Data

In line with the recommendations of Knott et al. (2022), we initiated our analysis concurrently with data collection, allowing early findings to shape the direction and focus of the subsequent interviews. Employing this iterative approach ensures a cohesive alignment between the collected data and the findings that emerge (Spencer et al., 2014).

Thematic analysis was chosen for its ability to explore data in depth and utilised to scrutinise commonalities, relationships, and differences within our dataset. This method, ideal for our study's iterative approach, facilitated the identification and interpretation of emerging patterns and themes, offering in-depth insights into the data collected (Gibson and Brown, 2009). Informed by Braun and Clarke's (2022, 2006) guidelines, this approach enabled us to extract meaningful insights, particularly into understanding the nuances and perspectives revealed in the interviews. The first author engaged in an initial round of open coding by labelling sections of data with each code to encapsulate a single idea from the data. The coding process was iterative, involving reading and rereading the interview transcripts, and applying and refining the codes. This process continued until we ensured that the coding frame was consistently applied across the dataset. This allowed us to create a new understanding by identifying thematic patterns that convey significant meanings across the dataset (Knott et al., 2022). Our analysis alternated between closely examining the data for detailed insights and stepping back to synthesise and articulate broader analytical findings. We ensured that our interpretations remained firmly grounded in the data, reflecting a deep understanding of participants' perspectives (Glaser and Strauss, 2017). Throughout this iterative process, we combined deductive and inductive logic, which is often referred to as an abductive approach, a hallmark of thematic analysis (Fereday and Muir-Cochrane, 2006). Our approach was attentive to the emergence and comparison of themes and patterns across different stakeholders and across countries. NVivo software was used to manage interview data and facilitate the coding process.

3. Results and Discussion

Three main themes emerged, representing key concerns associated with the use of alternative cement: (i) health, (ii) performance, and (iii) economic. Each theme represents a fundamental aspect of the decision-making process on both the supply (industry representatives) and demand (end-users) sides of the market. For each theme, we highlight key sub-themes to shed light on the specific aspects that influence these concerns.

3.1. Health Concerns

This theme entails stakeholders' concerns about the potential health impacts of alternative cement, which is a key factor because of the widespread use of cement in buildings and hence potential long-term exposure risks. Our analysis highlighted a divergence in health-related concerns among participant groups. The greatest concern emerged among end-users in Czechia, who demanded long-term evidence regarding the "non-toxicity" [3.E.C] of alternative cement, stating, "My decision depends on whether buildings or apartments have already been constructed with this material. Otherwise, I would likely be hesitant and choose to wait. It could take years to establish the non-existence of negative health effects of such materials" [10.E.C]. Industry representatives in Czechia demonstrated less concern but emphasised the need to guarantee its safety "for the occupants and users of the building as well as for the construction workers" [6.I.C].

Both industry and end-users in Slovenia were among the groups with elevated health concerns. An industry representative said, "Yes, of course, I would be worried. The average citizen does not initially measure it, know about it, or feel its effects, only after becoming ill. What is the reason they became ill? They don't know. [...] Consumer safety is paramount. If we work with residential construction, this cement must be medically indisputable and safe" [8.I.S]. Participants in Slovenia and end-users in Czechia believed that alternative cement "should not be used for a house" [7.E.S] because "health effects only manifest over years" [9.E.S]. Echoing this, one end-user in Slovenia stated, "If I were to do it, I would begin with certain construction examples, such as garages that no one lives in. I would conduct measurements there and, with assistance from independent institutions, demonstrate that radiation is essentially non-existent. This could pave the way for its application in ordinary constructions. I would certainly not start with residential buildings" [2.E.S]. In Czechia, the elevated health concerns among end-users prompted additional caution, even with non-residential applications: “I don’t know if I would want that in my immediate proximity. I’d rather have it quietly in that fence. I don’t think I’d mind that, but still I’d want to get that painted, or I’d like to treat it somehow so the radiation wouldn’t leak out” [2.E.C].

Our analysis indicates the least pronounced concerns in Belgium. Both stakeholder groups had broad concerns. For example, they mentioned that alternative cement should be “safe for use in production” [13.I.B], and “within limits” [3.E.B].

3.1.1. Perceived Trustworthiness of Certifications

This sub-theme emerged as one of the main factors shaping perceptions of health risks, with a notable contrast between Belgium and Slovenia. In Belgium, the lower health risk perception among both stakeholder groups was linked to their higher trust in certification. End-users in Belgium exhibited trust in the safety of products in the market. As one participant said, “If that is extreme, then it will not be allowed to be put on the market” [9.E.B]. Another participant explained, “If it is really too radioactive, then it should never be used. I trust the inspection authorities on that” [8.E.B]. Through certification, companies can guarantee the safety of their product:

“I think we, as an industry, if the product is approved and certified, then we will agree, and then we will be ready to use the product.” [5.I.B]

In Slovenia, scepticism towards certification underscores a more cautious approach. Both stakeholder groups’ higher perceived risk is linked to lower trust in certification. Despite acknowledging its necessity, certification did not equate to the safety of the product, primarily because of an underlying mistrust in certifying authorities: “As soon as you hear radioactive, you lose interest, right? I mean, that’s quite a problem, even though it’s low. No, it’s low now, but then in 10 years, they’ll figure out that it’s not that low” [11.E.S]. To alleviate their health concerns, both stakeholder groups sought additional assurances such as detailed information and explanations, as well as approval from other trusted entities:

“If experts unanimously agree that it’s safe and poses no harm, then I have no problem with it.” [6.E.S]

This theme was less pronounced in Czechia, particularly among end-users. Despite the link between certification and health concerns, due to negative past experiences in the country (see Section 2.1), some participants stated that these materials would not be allowed in the market:

“It is not allowed, and we have standards for that. Radon is monitored here and people are sensitive to that. Lung cancer and radon have been dealt with a lot in the country, even among us – some houses were demolished or so-called undercut to shield them” [4.I.C].

3.1.2. Experience with Similar Materials

Stakeholders' health concerns were also influenced by their past experiences with similar materials. This theme emerged most frequently during the interviews in Czechia. Some of the end-users recounted past experiences, with one noting, "Due to historical reasons in Czechia, especially from those who lived in houses constructed with radioactive fly ash ; I know many who developed lymph node cancer" [5.E.C]. Another added, "So it could cause cancer over time" [9.E.C]. Awareness of previous negative incidents has led to elevated health concerns regarding the use of alternative cement. In line with this, industry representatives stated that customers would not accept the use of alternative cement: "But that risk seems familiar and, if the public knows, I believe the majority of people would not want it" [3.I.C]. This sentiment is echoed in concerns that switching to alternative cement will not be justifiable: "It wouldn't be worthwhile. [...] We have radioactivity linked to cancer, and even a lower price would not solve that if it was written there or people had that information" [4.I.C]. To address the current negative connotation of these materials, one participant suggested "using them in government contracts" [6.I.C].

Similar patterns were observed in Belgium and Slovenia, even though participants there were mostly unaware of the prior use of NORM-containing by-products. Participants raised health concerns when they associated the use of NORM-contained by-products with previous problematic use of hazardous materials in the market. For example, in Belgium, although most participants were receptive to using alternative cement, one expressed scepticism about its use, even with certification. This participant referred to a building material initially regarded as safe, but later discovered it to pose harmful health risks: "For example, asbestos used to be a good building material. [...] But something will probably come up at some point where people will say, 'ah well, we shouldn't have used that either" [11.E.B].

Participants with a history of successfully managing hazardous materials tended to feel more confident about the use of alternative cement. Previous experience helped them overcome potential obstacles associated with the use of by-products containing NORMs; thus, they expressed fewer health concerns: "We have conducted leaching tests for years, so there is sufficient experience there to say that it is safe. Frankly, I don't have any experience with radioactivity. I don't know. But, of course, let's say this will have to be handled appropriately" [8.I.B]. This is also evident in the following quote from an end-user:

"I would primarily research that. I had a similar issue with my kitchen countertop made of granite or stone, which is also supposed to be radioactive, but I looked into it and found that the levels are so low that they're insignificant. I would make a similar decision here." [6.E.S]

Health concerns related to disruptive technologies have been highlighted in several studies. Arning et al. (2020) identified health concerns as a key factor in public scepticism towards carbon capture and utilisation. Etale et al.'s (2020) study on the willingness to use recycled water in Australia and South Africa indicated that greater trust in institutions leads to lower perceived health risks. Our findings also align with Scovell's (2022), in which positive experiences with similar technologies were identified as the contributing factors to acceptance. Similarly, negative personal experiences have been shown to increase risk perceptions (Siegrist and Árvai, 2020; Xie et al., 2019).

3.2. Performance Concerns

This theme emerged among all participant groups. There were no major differences in their concerns regarding the workability and performance of alternative cement. Validation of long-term durability and resilience emerged as key factors that reduce the participants' performance concerns. Performance-related durability and resilience are essential for materials such as cement, because they ensure that buildings can maintain stability over time. One participant stated, "It must have the same properties, which perhaps won't change over time, and won't be affected by weather and such" [5.E.C]. A flaw in the product can endanger human life: "Construction is about safety. If you construct something that ultimately lacks strength, resilience, or durability, you create potential danger" [9.I.B]. Therefore, "introducing a revolutionary binder into the market [...] may be a bit riskier than other products where there are no such [safety] concerns" [3.I.S].

Furthermore, some participants perceive "environmentally friendly options as slightly more complicated" [5.E.S], which often led them to favour traditional cement. Participants stressed that alternative cement must be convenient to work with. One participant from the construction companies emphasised, "In construction, there is a saying that paper can handle everything. I mean, it's nice to say that this is such and such a cement and that it has such and such properties when it was worked with it in the lab, but when this is actually used on construction sites, things can vary a bit and it may be, for example, that some cement types are less popular because it causes certain inconveniences on the site" [1.I.S]. Workability concerns were particularly pronounced among end-users in Belgium, who were more actively involved in the construction of their houses. Participants emphasised the need for alternative cement to be "easy to use" [9.E.B] and not require "any specialised protective equipment" [1.E.S]. A common sentiment among these participants was the need for the cement to be straightforward to work with:

"We do some of the construction work on our house ourselves. We should be able to easily work with that material, not fight with it." [5.E.C]

3.2.1. Validation of Long-Term Durability and Resilience

To address participants' performance concerns, validation and guarantee of the long-term durability of alternative cement is required. Participants emphasised that alternative cement must "align with specifications" [8.E.C] and "comply fully with established standards and regulations" [6.I.C]. While compliance with standards lowers participants' performance concerns, some industry representatives highlighted that “sometimes, the regulation itself is the main problem” [2.I.S]. They pointed out that “various bureaucratic hurdles and lengthy processes” [3.I.S] often dissuades the adoption of sustainable practices, as “most people don't even find it worthwhile” [6.I.C]. Participants urged streamlined and effective regulations that do not themselves become barriers.

End-users, typically those less experienced with cement, place their trust beyond certifications, valuing “the opinions of those who use it to determine whether the product is good or not” [4.E.S]. This is evident in the following statement: “This isn’t where you rely on the government or even scientists, as they can’t test it! The experience of those builders is what matters” [5.E.C]. In addition to contractors, other frequently mentioned trusted entities include architects, reputable institutions, building shops, and acquaintances.

End-users generally expect the house they build to “be functional for the rest of [their] life” [5.E.C]. Given the novelty of alternative cement and their structural importance, the above-mentioned enablers should be accompanied with practical examples of the use of alternative cement in other buildings: “So this is a novelty. I think I’d wait first to see what the results and references would be” [1.E.C]. A prevalent concern among participants was “the absence of references” [5.E.S]. They emphasised the need for it to be “historically proven” [5.E.C] “to see if it actually does what it claims” [2.E.B]. One industry representative articulated:

“So, with these cements, we are not sure because they are so new. [...] I would not recommend them because we don’t know what they mean in the long run.” [4.I.S]

Our findings align with those of previous studies investigating barriers to the circular economy, which suggested revising existing restrictive product regulations. These were identified as significant impediments, owing to their misalignment with the principles of sustainable production. They recommended the introduction of new regulations to promote sustainable production (Geissdoerfer et al., 2023; Gue et al., 2020; Kirchherr et al., 2018).

3.3. Economic Concerns

This theme highlights the economic challenges stakeholders encounter when shifting towards sustainable alternatives. Incentives and obligatory pathways emerged as sub-themes identified as key enablers for overcoming economic concerns. Economic concerns were consistent across countries and both stakeholder groups generally acknowledged that “if nothing is done about environmental issues, they will only worsen” [9.E.B]. However, there was also a common perception that “what is more environmentally friendly is more expensive” [5.E.S], which prevents this recognition from translating into action. One participant outlined the dilemma, stating, “We also want our children to have a better future.

But for the moment, changing would lead me to bankruptcy” [9.I.B]. There was a conspicuous “lack of urgency” [12.I.B] among participants to adopt environmental actions. This hesitancy stems from viewing sustainability as a long-term goal, rather than an immediate priority. For instance, one participant remarked, “Over a horizon of 30 to 50 years, I believe changes will be necessary; maybe I will not be alive by then, but maybe I will” [3.I.C]. Immediate economic challenges overshadow the urgent need to address environmental issues. Participants emphasised that “It is an uncertain time for choosing even more expensive materials that might be ecologically better in the long run” [2.E.B]. Echoing this, one industry representative mentioned that “Currently, there is a slight decline in this [opt for sustainable alternatives] due to the economic crisis, high inflation, a problem with the supply of materials, and the Ukrainian War. I don’t think any big ecological turbulence in traditional construction can happen now” [4.I.C].

Furthermore, industry representatives noted a lack of demand for sustainable materials, explaining that customers are generally positive about sustainable options “until they have to pay for it” [8.I.C]. During the interviews with end-users, this lack of demand was linked to the fact that “When building a house, funds are usually limited, making it difficult to focus on every detail, including environmental impact” [6.E.S]. Another underlying reason was that construction of the house is “primarily the biggest expense we [end-users] have in life” [10.E.S]. Hence, opting for a novel, yet unverified product introduces considerable financial uncertainty: “You always have to take out a mortgage on it, and then with this new thing, to find out that somehow it's a problem with the construction, I would just be concerned” [5.E.C]. Industries find a shift towards sustainable alternative cement, which is impractical without guaranteed customer demand:

“We cannot use cement that is much more expensive as it would make us non-competitive with our colleagues.” [8.I.S]

3.3.1. Incentives

Both stakeholder groups mentioned that they opt for sustainable solutions only “if it yields a profit for them elsewhere” [3.E.B]. In the absence of financial motives, they were less inclined to invest in sustainable cement. One end-user stated, “I’ll go for solar power because then you have some financial benefits or savings. At the same time, you do something good for the environment, so it’s a win-win. The question is, if it was only about the environment, you pay three times more, and do something good for the environment, there would be fewer decisions made in that direction” [11.E.S].

Both stakeholder groups mentioned government incentives as a form of encouragement, but also that “currently, there is no leverage or stimulation” [5.E.C]. One participant said, “If you want to do it, you have to pay for it without receiving something. There is no impulse from the government” [11.I.B]. Some industry representatives pointed out that incentives can also take the form of “company image” [2.I.B] or “PR” [6.I.S]. However, the absence of standardised parameters complicates the process of making credible sustainability claims. As one participant explained, “Everyone interprets sustainability differently, and even I am uncertain about how to understand and declare it in the context of our company” [6.I.C]. This ambiguity often leads to greenwashing: “Customers no longer know whom to believe” [9.I.B]. This was also pointed out during the interviews with end-users: “It’s challenging to be a judge here, and very difficult to process all the different information coming from all sides. There’s a lot of deception and misleading people as a result” [7.E.B].

Participants repeatedly mentioned that “It is essential to maintain consistency in how environmental product declarations are expressed” [4.I.C]. The lack of “a universally recognised calculation method” [6.I.B] demotivates companies to invest in sustainable solutions: “It often feels like a matter of saying something that sounds good, the use of alternative fuels, and alternative materials in order to increase or maintain profits. We know that is the case in every company. My personal opinion is that everything has too much to do with these profits. This sometimes obscures the truth about our motives and whether there is genuine commitment to sustainability. Where is this boundary, and where is this truth, or are these just some nice words?” [6.I.S].

3.3.2. Obligatory Pathways

This sub-theme was mentioned more frequently during the interviews with industry representatives. The participants highlighted that, without direct benefits from using alternative cement, regulatory measures are essential to facilitate a transition. One participant stated, “Clearly, the industry will not adapt unless there is a necessity or advantage to do so. Why should we torture one another? [...] Regulation and standardisation are absolutely necessary. Without them, change is not possible” [6.I.S]. Echoing industry’s perspective, an end-user mentioned that “People are unlikely to significantly reduce consumption unless faced with a shortage or a ban” [7.E.S]. Participants indicated that the most effective way to switch to sustainable cement is through obligations, particularly due to higher associated costs: “Clear rules are necessary, and who better to set them than politicians, since it is unpopular and currently also expensive” [3.E.C]. Some industry representatives stated that there is no significant mandate for enforcing the use of sustainable cement in concrete production: “In other areas, there are even requirements, not just desires [...], whereas for concrete, this trend is very low or almost non-existent” [7.I.S]. To render the use of traditional cement financially unviable, representatives advocated for increasing CO2 taxes and emission allowances: “Should the emission allowances increase so high that it will stop being profitable to use natural cement” [9.I.C]. They argued that legal obligations would “guarantee the same rules of the game for everyone” [3.I.S] and establish “a single and fair market” [6.I.C] within which “no one could abuse them” [3.I.C].

Moreover, participants highlighted that "The sustainability aspect is not yet a requirement in public procurement" [9.I.C]. This situation further discourages companies from adopting sustainable solutions, as, currently, "the government needs to sign contracts with the cheapest contractor" [6.I.B]. Participants suggested that authorities need to "put an environmental criterion into their tender" [5.I.S].

Our findings confirm those of Sáez-Martínez et al. (2016), who highlighted the central role of regulations in driving sustainable solutions, while Tokbolat et al. (2020) indicated the role of perceived benefits of sustainable investments. Niaki et al. (2019) even found financial motives to be the primary motivators for adopting sustainability practices. Furthermore, prior studies (Adams et al., 2017; Guerra and Leite, 2021) confirmed the role of consistent and clear environmental regulations.

4. Concluding Remarks

This study investigated the perceptions of industry representatives and end-users across Belgium, Czechia, and Slovenia, regarding the use of alternative cement made with NORM-contained by-products. It also sought to identify country-specific factors that affect these perceptions. Through our analysis, we identified three key concerns among both industry and end-users that influence their perception of alternative cement: health, performance, economic. Notably, while health concerns varied, performance and economic concerns were expressed consistently across the countries. Country-specific differences related to health concerns underscore the need for tailored approaches when promoting alternative cement in different contexts.

In Czechia, reassuring end-users about the safety of alternative cement requires transparency and careful communication that addresses the historical context and its impact on current perceptions. While the industry's apprehension largely reflects end-users' negative attitudes, there is a prevailing belief that certifying authorities will not approve the use of NORM-contained by-products in alternative cement in Czechia. A strategic response is required to alter this perception, potentially through using alternative cement in government projects and implementing additional safety measures, such as radon testing. Such measures are required to gradually change negative perceptions and assure both the industry and end-users of its safety. Similarly, in Slovenia, perceived health concerns were high, although they resulted from low trust in regulatory authorities. Effectively addressing these concerns requires engaging with trusted institutions and leveraging the best practices of countries with stringent safety regulations. Conversely, in Belgium, a high level of trust in the safety of certified products underscores the need for communication strategies that emphasise regulatory approval. However, over-emphasising certification might lead consumers to question its necessity, especially if risks are perceived as low (see Siegrist and Hartmann's (2020) study on novel food technologies). Therefore, a nuanced approach is needed to avoid the inadvertent signalling of potential risks.

Performance concerns were consistent across the countries. Addressing these concerns requires going beyond merely complying with the established standards. Communication strategies should focus on highlighting endorsements from trusted institutions specialising in building materials, such as reputable construction companies, to enhance end-user trust in the reliability of alternative cement. Additionally, demonstrating practical real-world examples that showcase the durability and resilience of buildings constructed with alternative cement is critical in their decision-making process. The practicality and ease of use of alternative cement should also be emphasised in communications.

Finally, to effectively address the economic concerns of stakeholders regarding the transition to alternative cement, a comprehensive approach from governmental bodies is required. Authorities need to implement globally standardised sustainable parameters and employ stringent regulations, along with incentives, to ensure a balanced yet impactful approach. This combination of regulatory measures and incentives is necessary in order to encourage stakeholder participation and prevent greenwashing practices that can arise in the absence of clear guidelines. Such governmental actions can help ensure the fair and equitable adoption of sustainable practices across the industry. Furthermore, government involvement in public procurement can create economies of scale, serving as a catalyst for the successful implementation of alternative cement in major projects.

This study has highlighted the indispensable role of authorities in facilitating the transition to alternative cement. It calls for a concerted effort that includes customised communication, nuanced policy strategies, and strategic incentivisation, all of which are reflective of each country's unique context and stakeholder concerns. By exploring non-technical perspectives, this study enriches the existing body of literature on alternative cement and extends our understanding of sustainable practices within the construction industry.

To sum up, we derive four hypotheses from our work that could be tested in quantitative study as future work. H1: Trust in certifying authorities reduces perceived health risks. H2: Associating the use of alternative cement with previous health-related problems increases the perceived health risk. H3: Practical examples of the use of alternative cement in building materials reduce the perceived performance risk. H4: The absence of financial incentives hinders the adoption of alternative cement.

Due to the nature of qualitative research, it is not feasible to assign weights to the identified themes pertaining to their various concerns. We recommend conducting a quantitative study as future work. Such a study would test the hypotheses derived from this exploratory study, evaluate the relative significance of these themes, and potentially enable the generalisation of the findings. Furthermore, we suggest conducting a study in a non-European context.

Chapter 4. Factors Influencing End-users' Acceptance of NORM-Contained Sustainable Cement: A Cross-country Study

This chapter is based on the submitted paper[6]: Love, N., Perko, T., Leroi-Werelds, S., Geysmans, R., Schroeyers, W. and Malina, R. 2024. Sustainable Cement Produced with Naturally Occurring Radioactive Material: Insights into End-users' Perceptions and Adoption

Abstract

The cement industry is a significant contributor to global anthropogenic greenhouse gas emissions, accounting for approximately 8% of total emissions. To mitigate these emissions, the use of industrial by-products as substitutes for raw materials in cement production not only reduces reliance on virgin raw materials but also contributes to the circular economy by repurposing waste. Alternative cement, made from secondary raw materials such as naturally occurring radioactive materials (NORM), provides a promising solution for lowering greenhouse gas emissions associated with traditional cement production. However, the public acceptance of such innovations is critical for their successful adoption. This study investigates end-users' perceptions of alternative cements made with NORM-contained by-products across Belgium, Czechia, and Slovenia. We explored how perceived risks and benefits, psychometric risk characteristics, and affective responses influence attitudes towards this sustainable cement. Data were collected through a survey of 1,224 participants, all of whom had recent experiences in building or renovating their homes. The findings reveal significant cross-country differences in how these factors impact attitudes and intentions to use alternative cement. Our results highlight the importance of tailored communication strategies that address specific national concerns and emphasise the most valued benefits in promoting the adoption of sustainable cement alternatives.

1. Introduction

Innovative solutions for energy and material efficiency in the cement sector are crucial for reducing approximately 8% of Global Greenhouse Gas (GHG) emissions attributed to the cement industry (World Economic Forum, 2024). The predominant source of these emissions is clinker production, which is the primary component of cement and involves energy-intensive chemical reactions and fuel combustion processes. Reducing the clinker-to-cement ratio using Supplementary Cementitious Materials (SCMs) is a key strategy for mitigating these emissions (IEA, 2023). Commonly used SCMs include fly ash from coal-fired power plants, granulated blast furnace slag from steel production, and calcined clay (Oge et al., 2019; Scrivener et al., 2018; Vargas and Halog, 2015). However, shifts in these industries may

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reduce the availability of these by-products, necessitating the exploration of alternative SCMs (GCCA, 2023).

Among potential SCMs, by-products such as copper slag from copper production and red mud from aluminium production can be categorised -depending on the national legislation- as Naturally Occurring Radioactive Materials (NORM), due to their elevated radionuclide concentrations. Industrial processing often increases radionuclide levels. Using NORM-contained by-products as clinker substitutes can potentially reduce both the clinker-to-cement ratio and GHG emissions while repurposing industrial waste that would otherwise accumulate in landfills (Wang et al., 2020). However, Love et al.'s (2024) study showed that the use of NORM-contaminated by-products might lead to health concerns among end-users, which could negatively impact their acceptance of this 'alternative' cement.

Extensive research has explored the technical feasibility and environmental impacts of using NORM-contained by-products in cement production (Kumar et al., 2021; Phiri et al., 2021; Wang et al., 2021). However, the successful deployment of such technology depends not only on its technical viability, but also on societal acceptance (Siegrist and Hartmann, 2020a). In the EU, a significant barrier to adopting sustainable practices is a lack of consumer awareness and interest (Kirchherr et al., 2018). Public acceptance is key, especially when bringing potentially disruptive technologies and products to the market (Arning et al., 2020; Batel, 2020; Emodi et al., 2021). Assessing public perceptions at an early stage, before a product is introduced in the market, is therefore key to identify potential risks and address concerns or controversies proactively (Satterfield et al., 2009).

To our knowledge, end-users' perceptions of using alternative cement made with NORM-contained by-products has been explored solely in a qualitative study conducted by Love et al. (2024) in the context of Belgium, the Czech Republic (Czechia), and Slovenia. Their study identified three key concerns among both industry professionals and end-users that influences the perception of alternative cement: health, performance, and economics. Additionally, it identifies country-specific differences in health concerns linked to two affect heuristics: trust and negative emotions (ibid.). The study reported on in this paper extends Love et al.'s (2024) qualitative insights, by quantitatively assessing and validating their findings across a broader population in these countries.

Our study is the first to quantitatively assess how perceived risks and benefits influence end-users' attitudes towards using alternative cement in the construction of their homes across Belgium, Czechia, and Slovenia. We also explored the underlying factors that shape these perceptions and examined their relationships. By understanding these dynamics, our findings can inform the design of public policies and communication strategies that can effectively promote the adoption of sustainable alternatives to traditional cement, thereby contributing to the reduction of GHG emissions in the cement industry.

2. Conceptual Framework

We designed a conceptual framework based on the literature on the acceptance of new technologies and empirical findings from prior qualitative research (Love et al., 2024). These insights informed the selection of constructs and relationships in the model, which allowed us to answer our research question. We tested the conceptual models based on data from a questionnaire that assessed end-users' perceptions of using cement made with NORM-contained by-products.

2.1. Risk and Benefits

Extensive research has demonstrated that perceptions of risks and benefits are two of the most reliable predictors of technology acceptance across a range of innovations (L'Orange Seigo et al., 2014; Venkatesh et al., 2012; Visschers and Siegrist, 2013). Risk is often defined as a hazard or threat that has the potential to cause harm, whereas benefit is seen as a positive outcome that might result from a technology or activity (Siegrist, 2000; Slovic, 1987). These perceptions significantly influence individuals' willingness to adopt innovation. For instance, in the case of carbon capture technologies, quantitative research has consistently shown that perceptions of both risks and benefits reliably predict public acceptance (Arning et al., 2020; Huijts et al., 2012; Wallquist et al., 2012). Despite the risks of CO_2 leakage, blowouts, explosions, and CCS-triggered earthquakes, this technology is also seen as beneficial because of its potential to mitigate climate change (Ashworth et al., 2009; Oltra et al., 2010; Palmgren et al., 2004; Upham and Roberts, 2011; Wallquist et al., 2009).

Prior studies indicate that a significant discrepancy exists between the perceptions of risks and benefits held by experts and laypeople, which can hinder the successful implementation of new technologies (Hansen et al., 2003; Krystallis et al., 2007; Savadori et al., 2010). For instance, research has shown that experts may accept innovative food technologies because of their potential to improve quality, safety, and security, whereas non-experts often rely on heuristics to assess these innovative products (Hansen et al., 2003; Tversky and Kahneman, 1992). Given that the general public, as end-users, ultimately determine the societal uptake of these technologies, their perspectives are crucial. To maximise the societal benefits of innovative technologies, bridging the gap between expert assessments and public perceptions is essential. This can be achieved through evidence-based communication strategies that help sceptical consumers better understand the risks and benefits as assessed by experts, thereby reducing the likelihood of rejection based on non-factual grounds (Bearth and Siegrist, 2016). By focusing on laypeople's concerns and perceptions, policymakers and industry leaders can foster greater acceptance and smoother integration of new technologies into society.

Alongside the perceived risks identified in Love et al.'s (2024) interviews—namely, health risks related to potential toxicity from NORM, performance risks regarding the long-term durability and structural integrity of alternative cement, and financial risks regarding the potentially higher costs associated with sustainable materials—we also investigated perceived benefits. These benefits include environmental advantages, such as reducing greenhouse gas emissions and promoting a circular economy through the repurposing of industrial by-products; performance benefits, including the potential for improved material properties; and financial benefits, such as potential cost savings over the lifecycle of buildings. These perceived benefits may positively influence end-users' attitudes towards adopting alternative cement, counterbalancing these concerns. Given the established influence of risk and benefit perceptions on technology acceptance, we hypothesise the following:

H1: End-users' intentions to adopt alternative cement made with NORM-contained by-products will be positively influenced by perceived benefits and negatively influenced by perceived risks.

Hypothesis 1 is further divided into specific hypotheses, each addressing the influence of different risks and benefits on end-users' attitudes towards adopting alternative cement. Table 7 details these specific hypotheses.

Table 7.

Breakdown of H1

Construct	Hypotheses
Perceived risks and benefits	**(H1) Perceived risks and benefits -> Attitude**
Health risk	(H1a) Health Risk -> Attitude
Financial risk	(H1b) Financial Risk -> Attitude
Performance risk	(H1c) Performance Risk -> Attitude
Environmental benefit	(H1d) Environmental Benefit -> Attitude
Financial benefit	(H1e) Financial Benefits -> Attitude
Performance benefit	(H1f) Performance Benefits -> Attitude

2.1.1. Psychometric Risk Characteristics

Given the nature of the product in our study, it is crucial to understand the factors that influence participants' health risk perceptions. The non-experts may focus on specific risk characteristics, such as the catastrophic potential of a technology, which can significantly influence their risk perceptions (Arning et al., 2024). Previous research has demonstrated that people's perceptions of various hazards differ based on specific characteristics of those hazards. The psychometric paradigm seeks to explain why individuals perceive risks as high or low by identifying hazard characteristics that elicit different responses (Fischhoff et al., 2000).

The psychometric paradigm highlights several qualitative factors that characterise public risk perception, including familiarity, voluntariness, individual controllability, catastrophic potential, and the impact on vulnerable groups such as children and future generations (Fischhoff et al., 2000). Each factor can independently shape risk perception, and certain combinations of these factors can substantially influence the perceived risk. For example, individual control is a critical factor; people are more concerned about airplane crashes than car crashes, often overestimating their control and competence as drivers (Slovic, 1987). Similarly, the catastrophic potential of a hazard—where significant damage or a number of fatalities could occur at once—can elevate perceived risk, regardless of the actual probability (Slovic, 1987). While these psychometric dimensions are robust across different cultural contexts (Chuk-ling Lai and Tao, 2003; Savadori et al., 1998), the importance of specific risk characteristics can vary depending on the hazard (Han et al., 2022; Siegrist et al., 2007).

Most studies on risk perceptions have identified two principal dimensions: 'dread risk' and 'unknown risk' (Siegrist et al., 2005; Slovic, 1987). Dread risks are those that are difficult to observe or control, can result in significant fatalities, are encountered involuntarily, and have catastrophic potential. Unknown risks, on the other hand, are novel, not fully understood by either respondents or science, or are perceived as such, with effects that are temporally or spatially distant (Eyal et al., 2008; Siegrist et al., 2005). For instance, risks that are both unknown and dreaded, such as genetic modifications and pesticide residues, are perceived as severe, whereas known risks, such as alcohol consumption, are seen as less severe (Siegrist and Hartmann, 2020a).

Psychometric scaling studies suggest that, for non-experts, the qualitative characteristics of a hazard often outweigh the objective measures of mortality or morbidity when evaluating potential risks (Kraus et al., 1992). This helps explain why technologies such as nuclear power, geoengineering, or genetic modification—generally unknown and viewed with dread—are perceived by the public as highly risky. In contrast, known and less-dreaded hazards, such as sunbathing, are considered less risky (Siegrist and Árvai, 2020). Given the nature of alternative cement made with NORM-contained by-products, we anticipate that end-users' risk perception will be influenced by key psychometric factors, such as unknownness and dreadfulness. These factors have been shown to significantly affect risk perception, and consequently, the acceptance of new technologies. Therefore, based on the established psychometric dimensions of risk perception, we hypothesised the following:

H2: Alternative cement made with NORM-contained by-products will be perceived as highly unknown and will evoke a greater sense of dread, both of which will increase perceived health risk.

Table 8 outlines the hypotheses derived from H2, detailing the components of the psychometric dimensions of dread and unknown and how these dimensions are expected to influence the perceived health risks associated with alternative cements made with NORM-contained by-products.

Table 8.

Breakdown of H2

Construct	Hypothesis
Dread: composed of potential severity, controllability, observability, dreadfulness, and impact on future generations.	(H2a) Dread - > Health Risk
Unknown: composed of immediacy of effect, familiarity, and known (to those exposed to them, science, and regulatory authorities).	(H2b) Unknown - > Health Risk

2.2. Role of Heuristics

Non-experts often lack the necessary resources, such as time, motivation, or specialised education, which impacts their perception and evaluation of the risks and benefits of new technologies. For instance, end-users building their homes may not have access to comprehensive information regarding the environmental impact of cement or naturally occurring radioactive materials. Additionally, they may not have the capacity to process this information systematically, leading them to rely on heuristic or peripheral methods of evaluation.

In such situations, people often rely on heuristics—mental shortcuts—rather than engaging in systematic information processing when evaluating new technologies or hazards (Bearth et al., 2019; Loewenstein et al., 2001; Perko et al., 2014; Västfjäll et al., 2014). For example, when assessing risk, individuals might replace a complex attribute, such as the actual probability of harm, with a more readily accessible one, like a recent memorable event. People employ a wide range of heuristics in decision-making situations (Siegrist and Hartmann, 2020a). Even when aware of the safety measures in place, individuals might still feel uneasy or reject certain technologies due to emotional responses or a lack of trust in the authorities responsible for risk assessment and regulation (Bearth et al., 2019; Siegrist, 2008). This study focuses on two key heuristics—affect and trust—which are likely to be particularly relevant to understanding perceptions of alternative cement, as these perceptions might be strongly influenced by emotional responses and the level of trust in the entities promoting or regulating technology (Siegrist and Árvai, 2020).

2.2.1 Affect Heuristic

The concept of the affect heuristic builds on earlier work by Kahneman and Tversky in the 1970s, who pioneered the study of cognitive biases and heuristics in decision-making (Kahneman and Tversky, 1979; Tversky and Kahneman, 1974). Alhakami and Slovic (1994) later identified an inverse relationship between judgments of risks and benefits, further establishing the significance of the affect heuristic. They suggested that the way people perceive risks and benefits is influenced by their emotional response. Specifically, when people perceive a technology or activity as highly beneficial, they tend to view the associated risks as lower regardless of the actual risk level. Conversely, when they perceive something as risky, they often see fewer benefits, even if benefits are present. This underscores the role of affect in shaping how risks and benefits are perceived rather than indicating a direct relationship between them. For example, this is evident in Arning et al.'s (2024) study, where strong negative emotions linked to misconceptions about new technology amplified perceived risks and decreased acceptance. In Huijts' (2018) study, emotions like fear enhance perceived risks, while joy amplifies perceived benefits, thus playing a critical role in the acceptance of new technologies.

Finucane et al. (2000) further explained that in complex decision-making, individuals often rely on their overall emotional impressions, judging hazards based on the emotional tags associated with them. Hazards that evoke strong feelings of dread and are processed heuristically, are perceived as riskier than those that are not (Siegrist and Hartmann, 2020a). For instance, consumers who associate negative feelings with genetic modification are less likely to purchase genetically modified foods than are those with positive associations (Siegrist, 2008; Siegrist and Hartmann, 2020a).

When individuals feel favourably towards an activity, they tend to perceive the risks as low and the benefits as high. Conversely, unfavourable feelings lead to perceptions of high risks and low benefits. Both cognitive and affective processes influence these judgements, depending on contextual factors. This can explain why non-experts perceive certain technologies as more concerning than experts, who rely more on analytical evaluations than on emotional impressions due to their technical knowledge (Perko, 2014; Slovic et al., 2010). This aligns with the elaboration likelihood model (Petty, 1996; Petty and Cacioppo, 1986), which suggests that individuals lacking knowledge or motivation are more likely to use a peripheral route that relies on simple heuristics (Meijnders et al., 2001).

The affect heuristic can simplify decision-making but also introduce biases (Siegrist and Sütterlin, 2014). This can lead individuals to overlook important risk information and skew their risk perceptions (Sunstein, 2003). For example, if a hazard evokes strong negative emotions, people may disregard data indicating a low risk. Wilson and Arvai (2010, 2006) illustrated this effect: when participants encountered scenarios involving wildlife overpopulation and nonviolent crime, they perceived higher risks in situations that triggered strong negative emotions, even though objective data showed that wildlife overpopulation posed a greater threat. This finding highlights the impact of emotional responses on risk perception. Moreover, Nakayachi (2013) noted that information about a specific risk can heighten fear not only about that risk, but also about the broader category to which it belongs. However, as Siegrist and Árvai (2020) argue, relying on heuristics to inform risk perceptions does not imply irrationality nor does it necessarily result in biased judgements. If the underlying information and processes are closely calibrated to reality, heuristics can lead to accurate estimates. Given the role of emotions in shaping risk and benefit perceptions, we hypothesised the following:

H3: The affect heuristic significantly influences end-users' perceptions of the risks and benefits associated with alternative cements made with NORM-contained by-products. Specifically, negative affect increases perceived risks and decreases perceived benefits, whereas positive affect decreases perceived risks and increases perceived benefits.

Table 9 presents the hypotheses derived from H3, illustrating how the affect heuristic—through both positive and negative emotional responses—is expected to influence the specific perceived risks and benefits associated with alternative cements made with NORM-contained by-products.

2.2.2 Trust Heuristic

Trust is a critical factor in understanding the acceptance of new technologies, particularly in situations of high uncertainty and novelty, where intuitive affect-based processing often dominates due to a lack of available cognitive resources for analytical judgement (Siegrist et al., 2007). In such cases, trust plays a crucial role in guiding the initial evaluations and attitudes towards novel technologies. When product attributes are not easily observable or verifiable by consumers (e.g., organic foods), they rely on trust in the source of the information (Siegrist, 2021). Similarly, when consumers lack specific knowledge, they depend on trust to assess the technology's risks and benefits (Siegrist and Hartmann, 2020b).

Table 9.

Breakdown of H3

Construct	Hypothesis
Negative and positive affect	**(H3)** **Positive and negative affect - > perceived risks and benefits**
Negative affect	(H3a) Negative Affect -> Health Risk
	(H3b) Negative Affect -> Financial Risk
	(H3c) Negative Affect -> Performance Risk
	(H3d) Negative Affect -> Environmental Benefit
	(H3e) Negative Affect -> Financial Benefit
	(H3f) Negative Affect -> Performance Benefit
Positive affect	(H3g) Positive Affect -> Health Risk
	(H3h) Positive Affect -> Financial Risk
	(H3i) Positive Affect -> Performance Risk
	(H3j) Positive Affect -> Environmental Benefit
	(H3k) Positive Affect -> Financial Benefit
	(H3l) Positive Affect -> Performance Benefit

Prior studies suggest that trust does not directly influence perceived risks and benefits, but is related to affect (Midden and Huijts, 2009; Terpstra, 2011). Trust may shape feelings towards a technology, which in turn influences acceptance judgements (Huijts, 2018; Midden and Huijts, 2009). Siegrist (2021) posited that the relevance of trust or affect in evaluating a hazard may depend on contextual factors. For example, in scenarios involving multiple stakeholders, where it is unclear who to trust, affect may play a more significant role in acceptance than trust. Conversely, trust may become more important when fewer stakeholders are involved. As evident in Love et al.'s interviews, different actors, such as regulators, scientists, and architects, were mentioned as trusted entities regarding alternative cement. Therefore, we expected trust to influence attitude through affect.

Trust is often measured as a single concept that reflects how effectively risks are managed, although the method of measuring it can vary. Earle (2010) distinguished between two types of trust: social trust (intention and integrity) and confidence (ability and competence), both of which are heuristic in nature (Sintov and Hurst, 2023; Vainio et al., 2017). Social trust is based on perceived value similarities, reflecting trust in actors' intentions to act in the public's best interest, whereas confidence is grounded in past experiences or perceived competencies (Johnson and Rickard, 2023). For example, end-users might have confidence in the competencies of actors producing safe alternative cement but lack social trust, doubting whether these actors are transparent about risks or prioritise profit over consumers' health.

Identifying key actors whose trust influences public perceptions of a new technology is essential for understanding and fostering support for these innovations. In the context of land-based recirculating aquaculture systems, trust in both government agencies and the corporations involved has been shown to be a critical determinant of public perceptions regarding the net benefits of the technology, which, in turn, influences their level of support (Johnson and Rickard, 2023). Similarly, trust in the food industry significantly impacts the acceptance of novel food technologies such as cultured meat (Siegrist and Hartmann, 2020b). However, contrary findings by Wilks et al. (2019) suggest that general trust may not play a significant role in the acceptance of cultured meat, indicating that specific trust in the food industry or in food scientists may be more relevant. Furthermore, Han et al. (2022) demonstrated that trust in authorities is inversely related to the risk perceptions of natural hazards, with a higher degree of trust corresponding to lower levels of concern about events such as typhoons and earthquakes. These findings underscore the complexity of trust as a factor and highlight the need to consider the specific types of trust that are most relevant in different contexts. Given this complex relationship between trust, affect, and risk perception, we hypothesise the following:

H4: The level of trust in different actors will significantly influence positive and negative affect. We expect that higher trust will be associated with more positive affect and less negative affect negative, whereas lower trust will likely be associated with more negative and fewer positive affect related to the product.

Table 10 outlines the hypotheses derived from H4, detailing how trust in various key actors is expected to influence the emotional responses—both positive and negative—of end-users towards alternative cements made with NORM-contained by-products.

Table 10.

Breakdown of H4

Construct	Hypothesis
Trust	**H4: Trust - > Negative and positive affect**
Trust in Authorities	(H4a) Trust in Authorities -> Negative Affect (H4b) Trust in Authorities -> Positive Affect
Trust in Research Institutions	(H4c) Trust in Research Institutions -> Negative Affect (H4d) Trust in Research Institutions -> Positive Affect
Trust in Scientists in universities	(H4e) Trust in Scientists in universities -> Negative Affect (H4f) Trust in Scientists in universities -> Positive Affect
Trust in Cement Manufacturers	(H4g) Trust in Cement Mfr -> Negative Affect (H4h) Trust in Cement Mfr -> Positive Affect
Trust in Construction Companies	(H4i) Trust in Construction Companies -> Negative Affect (H4j) Trust in Construction Companies-> Positive Affect
Trust in Architects	(H4k) Trust in Architects -> Negative Affect (H4l) Trust in Architects -> Positive Affect

2.3. Conceptual Model

Based on past research on public perception of novel technologies and findings of Love et al.'s (2024) qualitative study, we identified factors that are hypothesised to have a direct or indirect effect on end-users' attitudes and intentions towards the usage of alternative cement in their homes. Figure 5 presents the model we tested in the present study.

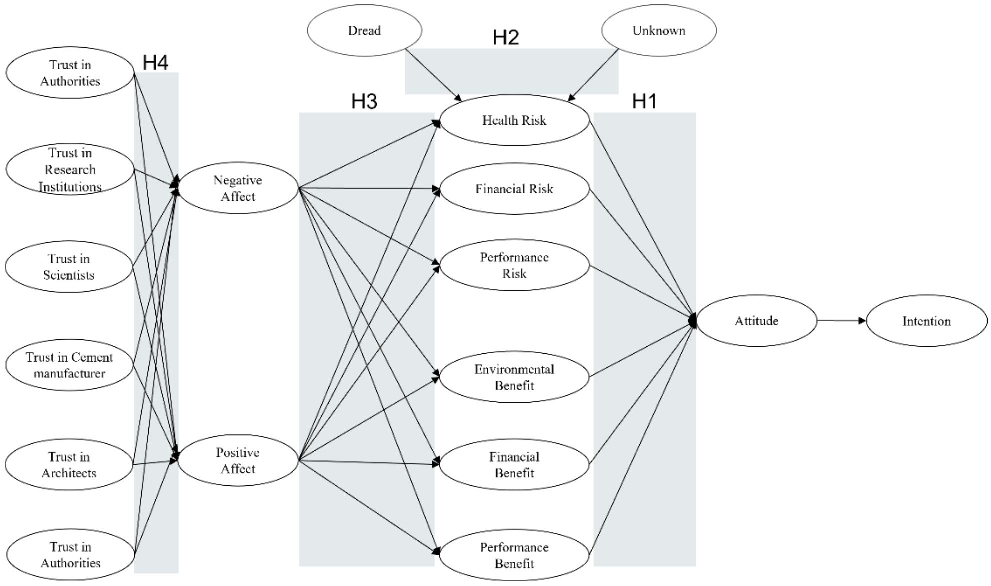

Figure 5. *Conceptual model and hypotheses*

Note: Grey represents the aggregation of overarching hypotheses indicated by H1, H2, H3, and H4.

3. Method

3.1. Participants and Procedure

The total sample size of our study was 1,224 participants, with the following distribution: Belgium (400), Czechia (409), and Slovenia (414). We utilised independent market research firms in each country for participant recruitment and survey administration. Participants were randomly selected from a pool of panellists who were either currently building or renovating their homes, or who had built or undertaken major renovations within the last 10 years. This selection criterion ensured that participants had recent, relevant experience in selecting building materials for their projects, providing valuable insights into the potential market acceptance of alternative cement. The characteristics of the participants are provided in Table 11.

Table 11.

Characteristics of participants

	Total Sample (%)	Belgium (%)	Czechia (%)	Slovenia (%)
Gender				
Male	53.3	46	53	59
Female	46.9	52	46	40
Other	0.2	1	0	0
Prefer not to say	0.6	1	0	0
Age				
18-24	3.8	4	3	5
25-39	23.1	23	30	15
40-54	30.4	30	34	27
55-69	31.4	31	26	38
Over 70	11.4	12	7	15
Education				
No diploma & primary education	2.9	5	2	2
Secondary education	58.1	56	54	64
Higher education & university	38.9	39	44	34
Perceived financial situation				
Living very comfortably	6.0	3	7	7
Living comfortably	37.3	35	35	41
Getting by	43.3	46	45	40
Finding it difficult	8.3	10	8	7
Finding it very difficult	3.2	4	3	2
Prefer not to say	2.0	2	1	3

The survey took around 10 minutes to complete in Belgium, 12.9 minutes in Czechia, and 13.1 minutes in Slovenia. Participants who did not complete the survey, showed straightlining behaviour, or provided inconsistent responses were excluded from the final sample. The response rates were 2.62% in Belgium, 29.9% in Czechia, and 13.1% in Slovenia.

3.2. Case Description

Radiation safety requirements, including those related to NORM in buildings, are mandated across all EU Member States under Council Directive 2013/59/Euratom. This directive requires Member States to transpose and “implement strategies, methods, and tools for preventing radon ingress into new buildings, including the identification of building materials with significant radon exhalation”, as specified in Annex XVIII (8). Belgium (2020), Czechia (2019), and Slovenia (2020) have transposed these requirements into national regulations, and they are actively implementing them during our study, mostly through specific “Building Codes”. This legislation ensures that NORM used in buildings does not cause additional health risks (Perko et al., 2023). However, perceived health risks may vary depending on the country-specific context as evident in Love et al. (2023) 's study.

Czechia has a history of using concrete containing industrial by-products with elevated levels of natural radioactivity, which has resulted in the demolition or remediation of affected dwellings. These incidents are estimated to account for approximately 15% of lung cancer-related deaths in the country (Hulka and Thomas, 1999; SURO, 2024). This historical context adds a unique dimension to our comparative analysis of perceptions of alternative cement.

In Slovenia, a high recycling rate, as reported by the European Environment Agency (2023), reflects a societal inclination towards resource efficiency, which may foster a positive reception of alternative cement solutions that promote sustainability. However, recent criticism of Slovenia’s largest cement plant regarding air pollution (CIPRA, 2022) introduces another layer of complexity to our study, highlighting the coexistence of a strong recycling ethos with ongoing health challenges related to cement production.

In addition to Czechia and Slovenia, Belgium was selected for this study because of its comparatively lower health risk concerns regarding alternative cement, as highlighted in Love et al.'s findings. Belgians’ higher trust in certification and regulatory bodies contributes to a distinct perception of the safety of alternative cement, providing a contrasting case to the more sceptical perspectives found in Slovenia and Czechia.

Findings by Love et al. revealed differences in end-users’ health risk perceptions, primarily influenced by their level of trust in various actors and prior experiences associated with alternative cement, which in turn evoked positive or negative feelings. To further explore and confirm these differences, we tested our model in these countries to quantitatively assess variations in perceived health risks, levels of trust in different actors, and the associated emotional responses. Additionally, we investigated whether other factors might directly or indirectly influence attitudes towards the use of alternative cement specific to each country.

3.3. Survey Design and Data Collection

In line with ethical research practices, approval was obtained from the relevant ethics board. The questionnaire used in this study was part of a larger survey. An online, self-administered questionnaire was used in three countries: Belgium, Czechia, and Slovenia, in February and March 2024. The questionnaire was initially designed in English and subsequently translated into Dutch and French for Belgium, Czech for Czechia, and Slovenian for Slovenia, then translated back into English to ensure a unified meaning across all languages.

Before the main data collection, we conducted a pilot study with 24 participants across all languages to ensure that the survey was comprehensible, accurately translated, and of appropriate length. The pilot study involved gathering feedback from these participants on various aspects of the survey, such as the clarity of questions, the relevance of the content, and the ease of completion. Any issues identified during this phase, such as ambiguous wording or difficulties in translation, were addressed and corrected. Following the pilot study, a soft launch of the survey was carried out to refine the process before the full launch.

Upon consenting to participate, respondents answered two filter questions to confirm they met the selection criteria. The survey began with several warm-up questions, followed by a brief introduction to alternative cement (see Appendix C). Immediately following this introduction, participants were asked to report their emotional responses to this alternative cement, measuring both negative and positive affects (emotions) using a 7-point Likert scale (ranging from "not at all" to "very much"). Based on recommendations from Peters and Slovic (2007), rather than a bipolar representation of the affective component (a single continuum of affect from positive to negative), the positive and negative affects were measured separately (unipolar). It is suggested that separating positive and negative affects leads to better prediction and understanding of attitudes. The affective measures were adapted from previous studies on novel technology acceptance (Huijts et al., 2014). The scale included three items for negative affect (doubt, worry, and aversion) and three items for positive affect (hope, interest, and curiosity).

The questionnaire then addressed various constructs, including intention, attitude, perceived risks and benefits, psychometric risk characteristics, and trust, all measured with a 7-point Likert scale. Attitude and perceived environmental benefits (adopted from Midden and Huijts, 2009) were measured using a single item ranging from “strongly disagree” to “strongly agree” and “not at all” to “extremely high” respectively. Intention and health risk (adopted from Mani and Chouk, 2018) were measured on a reflective scale ranging from “extremely unlikely” to “extremely likely” and from “strongly disagree” to “strongly agree”. Psychometric risk characteristics were adopted from scales used by Bassarak et al. (2017), Fischhoff et al. (1978), and Song et al. (2021), with the following items being reverse-coded: controllability, known, familiarity, and observability. The risk characteristics shaped two multidimensional constructs: Dread and Unknown. The risk characteristics that composed dread included potential severity, controllability, observability, dreadfulness, and impact on future generations. The risk characteristics that composed unknown included immediacy of effect, familiarity, and knowledge (among those exposed, scientists, and regulatory authorities). Trust was measured in two dimensions (intention and competence) ranging from “strongly disagree” to “strongly agree” (adapted from Huijts et al., 2014). Financial risk and benefits, and performance risk and benefits were formative measures ranging from “strongly disagree” to “strongly agree” developed based on Love et al.’s (2024) interview findings and tested during the pilot study.

Given that this technology is still under development, we expected participants to have little prior (objective) knowledge of alternative cement. However, their perceived (subjective) knowledge of radioactivity might influence their intention to use alternative cement in their homes. Objective and subjective knowledge were included as control variables to account for their potential influence on intention.

The final section of the questionnaire collected socio-demographic data, assessed objective knowledge through five true/false questions about radioactivity, and evaluated subjective knowledge by measuring participants’ confidence in their knowledge of radioactivity.

3.4. Data Analysis

To analyse the data, we employed partial least squares structural equation modelling (PLS-SEM) using SmartPLS software, version 4.1.0.6 (Ringle et al., 2024). PLS-SEM estimates partial model structures by combining principal component analysis with ordinary least squares regressions (Hair et al., 2019). Following the guidelines of Hair et al. (2022), PLS–SEM was chosen for this study based on several key considerations: Firstly, given the novel nature of the research topic, PLS-SEM is particularly suited to exploratory research, where the goal is to develop theories by predicting and maximising the explained variance in the dependent constructs. Additionally, PLS-SEM performs better than covariance-based structural equation modelling (CB-SEM) when dealing with complex structural models that involve numerous constructs and relationships. PLS-SEM is also adept at handling both formative and reflective constructs, offering greater flexibility in model specification. Furthermore, PLS-SEM imposes fewer demands regarding data distribution, sample size, and model complexity compared to CB-SEM. The statistical significance of all parameter estimates was evaluated using accelerated bias-corrected bootstrap intervals based on 10,000 samples (Hair et al., 2022). To test the model using PLS-SEM and compare the estimated path coefficients across countries, this study employed a three-stage approach, which included the assessment of measurement models, structural models, and multigroup analysis. Based on Hair et al.'s (2022) recommendations, we utilised percentile confidence intervals based on bootstrap procedures (with 10,000 resamples) to evaluate the statistical significance of parameter estimates. Furthermore, we used IBM SPSS Statistics (version 29.0.2.0, build 20) for descriptive statistics, and RStudio (version 2024.04.2+764) running R (version 4.4.1) for the comparative analyses.

4. Results

4.1. Model Assessment Using PLS-SEM

Following the Hair et al.'s (2019) guidelines for evaluating PLS-SEM results, we first examined the reflective and formative measurement models. Once the measurement model met all the required criteria, we assessed the structural model. Finally, we conducted a robustness check to support the stability of the results. Here we only discuss the model assessment for the total sample. Model assessment for each country can be found in Appendix C.

4.1.1 Reflective and Formative Measurement Models

Evaluation of the reflective measurement model for the two reflective constructs (i.e., intention and perceived health risks), indicated that all constructs exhibited favourable psychometric properties.

First, we examined indicator loadings. Indicator loading specifies the proportion of an indicator's variance that can be explained by the latent construct, with at least 50% of an indicator's variance needing to be explained by the latent construct. This requirement corresponds to loadings greater than 0.708 (Hair et al., 2019). Upon examination, all indicator loadings for the constructs exceeded 0.892.

Next, internal consistency reliability was assessed through Jöreskog's (1971) Composite Reliability (CR), Cronbach's alpha, and Dijkstra and Henseler's (2015) rho (ρA), both of which were above 0.7 for all constructs, thereby confirming their reliability (Hair et al., 2019). Following the reliability assessment, convergent validity of each construct measure was evaluated using the average variance extracted (AVE). Convergent validity is the extent to which the construct converges to explain the variance of its items. The AVE, calculated as the sum of the squared loadings divided by the number of indicators, reflects the portion of variance captured by the constructs. An AVE value of 0.50 or higher is considered acceptable, indicating that the construct explains at least 50% of the variance of its items (Hair et al., 2019). In this study, AVE values of 0.913 for intention and 0.837 for health Risk confirmed strong convergent validity.

Finally, discriminant validity, which represents the extent to which a construct is distinct from other constructs, was assessed. We employed Fornell and Larcker's (1981) criterion and Henseler et al.'s (2015) heterotrait-monotrait (HTMT) ratio method. The Fornell-Larcker criterion demonstrated satisfactory discriminant validity, with the square root of the AVE for Intention (0.915) and Health Risk (0.956) being greater than the correlation between these constructs (−0.577). Additionally, the HTMT value of 0.659 was below the threshold of 0.85, indicating adequate discriminant validity between intention and health Risk (Hair et al., 2019). An overview of the reflective measurement model results is provided in Table 12.

Table 12.

Results summary for reflective measurement model assessment

Construct/ Indicators*	Loadings	ρC	ρA	Cronbach's alpha	AVE	Discriminant validity
Intention (2 items)		0.969	0.953	0.809	0.913	Yes
INT1	0.938					
INT2	0.892					
Health Risk (3 items)		0.911	0.848	0.953	0.837	Yes
HR1	0.964					
HR2	0.959					
HR3	0.944					

ρC=Composite Reliability; ρA=Dijkstra–Henseler's rho; AVE=Average Variance Extracted

*We used item codes for indicators, full item wording can be found in Appendix C

Notes: n=10,000 subsample, ***p< 0.05 (one-tailed)

For the formative constructs, we first evaluated collinearity of indicators to ensure that there were no high correlations among the indicators. Collinearity among indicators was analysed using the variance inflation factor (VIF). According to Hair et al. (2019), VIF values of 5 or above indicate critical collinearity issues among the indicators of formatively measured constructs. In our analysis, all VIF values were below this critical threshold, indicating no collinearity concerns.

Next, we examined the indicator weights' statistical significance and relevance. When indicator weights were non-significant, we conducted further investigations. According to Hair et al. (2022), a nonsignificant indicator weight does not automatically signal poor measurement model quality. Instead, the indicator's contribution to the construct, as defined by its outer loading (i.e., the correlation between the indicator and the construct), should be taken into account. Furthermore, a higher number of indicators might result in lower average weights (Cenfetelli and Bassellier, 2009). Therefore, low but significant loadings (≤0.50) should only be considered for deletion if there is insufficient theoretical justification for their retention (Hair et al., 2019). Considering these criteria for both the total sample and each country separately, it was decided to retain all indicators in the measurement model, with the exception of PR2. The results of the formative measurement models for the total sample are provided in Table 13 (see Appendix C for country-specific evaluation).

4.1.2. Structural Model Assessment

The next step after satisfactory measurement model assessment involved assessing the structural model. Standard assessment criteria to consider include the coefficient of determination (R^2), the cross-validated redundancy measure based on blindfolding (Q^2), and the significance and relevance of the path coefficients (Hair et al., 2019).

We began by examining the structural model for potential collinearity issues. Before assessing the structural relationships, collinearity must be checked to ensure it does not bias the regression results. Similar to evaluating formative measurement models, VIF values for the predictor constructs should be below 5 to avoid collinearity problems. However, we identified one construct—trust in construction companies—with a critical level of collinearity (VIF = 6.201). Following the guidelines of Hair et al. (2022), we addressed this issue by eliminating the construct, which helped resolve the collinearity problem it had with another construct: trust in cement manufacturers. The variance inflation factor (VIF) for each country is detailed in Appendix C.

Table 13.

Results summary for formative measurement model assessment

Construct/ Indicators*	Weights	Loadings	*t* Value	*p* Value	Confidence interval		VIF
					5%	95%	
Financial Risk (3 items)							
FR1	0.618	0.717	3.739	0.000	0.316	0.853	1.822
FR2	-0.730	-0.153	4.697	0.000	-0.935	-0.456	1.344
FR3	0.640	0.696	3.724	0.000	0.344	0.899	1.906
Performance Risk (7 items)							
PR1	0.695	0.834	8.090	0.000	0.538	0.820	1.540
PR2	-0.060	0.371	0.566	0.286	-0.235	0.113	1.670
PR3	-0.261	0.347	2.604	0.005	-0.421	-0.090	1.799
PR4	0.220	0.583	2.034	0.021	0.033	0.387	1.731
PR6	0.260	0.648	2.314	0.010	0.075	0.445	3.194
PR7	-0.169	0.493	1.569	0.058	-0.347	0.006	2.346
PR8	0.468	0.684	4.017	0.000	0.270	0.657	2.997
Financial Benefits (3 items)							
FB1	0.508	0.858	9.374	0.000	0.417	0.594	1.537
FB2	0.080	0.638	1.333	0.091	-0.019	0.180	1.525
FB3	0.575	0.892	10.495	0.000	0.482	0.662	1.627
Performance benefit (3 items)							
PB1	0.105	0.709	1.542	0.061	-0.007	0.216	2.167
PB2	0.151	0.756	2.203	0.014	0.041	0.263	2.354
PB3	0.824	0.985	15.786	0.000	0.734	0.905	1.850
Negative Affect (3 items)							
AHN1	0.418	0.901	5.320	0.000	0.288	0.548	2.338
AHN2	0.361	0.895	4.624	0.000	0.230	0.487	2.461

Construct/ Indicators*	Weights	Loadings	*t* Value	*p* Value	Confidence interval		VIF
					5%	95%	
AHN3	0.356	0.845	5.029	0.000	0.237	0.470	1.848
Positive Affect (3 items)							
AHP1	0.451	0.901	7.212	0.000	0.347	0.551	2.082
AHP2	0.457	0.931	6.525	0.000	0.340	0.569	3.034
AHP3	0.202	0.893	2.777	0.003	0.082	0.321	2.470
Dread (5 items)							
RC_O	-0.017	-0.339	0.601	0.274	-0.063	0.030	1.208
RC_D	0.135	0.776	3.568	0.000	0.072	0.197	2.093
RC_S	0.487	0.955	9.046	0.000	0.396	0.573	3.645
RC_T	0.386	0.930	7.771	0.000	0.306	0.470	3.317
RC_C	0.133	0.490	3.903	0.000	0.077	0.189	1.237
Unknown (5 items)							
RC_K1	0.449	0.621	1.287	0.099	0.150	0.678	1.467
RC_K2	-0.203	0.033	0.037	0.485	-0.456	0.065	1.656
RC_K3	-0.007	0.302	4.835	0.000	-0.310	0.311	1.860
RC_N	0.615	0.730	4.835	0.000	0.375	0.793	1.175
RC_I	0.485	-0.339	4.058	0.000	0.269	0.660	1.068

*We used item codes for indicators, full item wording can be found in Appendix C

Note: A higher t-value indicates that the indicator is significantly related to the latent construct. Typically, a t-value greater than 1.96 (for a 95% confidence level) indicates significance.

Once we ensured that collinearity was not at a critical level, next we examined the R^2 value for three main dependent constructs which is the most commonly used measure to assess the model's in-sample explanatory power. The assessed perceived risks and benefits (perceived risks: health, financial, performance; perceived benefits: environmental, financial, and performance) explained 42.3%, 54.7%, and 61.1% of the variance in end-users' intention in Belgium, Czechia, and Slovenia, respectively. The proportion of explained variance for the other constructs is detailed in Table 14.

In all three countries, the R^2 values exceed 0.26, indicating a substantial amount of variance is explained in these constructs (Cohen, 1988). Additionally, the Stone-Geisser Q^2 statistics (calculated with 10 folds and 10 repetitions), reported in Table 14, demonstrate that the model has predictive relevance, as all values are greater than zero.

Table 14.

Model's explanatory power Adjusted R^2 [99% - CI] and Q_2

	Total Sample	Belgium	Czechia	Slovenia
Intention	R^2=0.539 [0.497, 0.574] Q^2=0.246	R^2=0,423 [0.335,0.499] Q^2=0.176	R^2=0,547 [0.481, 0.598] Q^2=0.283	R^2=0,611 [0.550, 0.660] Q^2=0.305
Attitude	R^2=0.535 [0.498, 0.565] Q^2=0.278	R^2=0,460 [0.375, 0.516] Q^2=0.203	R^2=0,527 [0.459, 0.571] Q^2=0.331	R^2=0,616 [0.554, 0.655] Q^2=0.307
Health Risk	R^2=0.615 [0.574,0.645] Q^2=0.563	R^2=0,551 [0.477, 0.599] Q^2=0.509	R^2=0,628 [0.551, 0.678] Q^2=0.565	R^2=0,654 [0.590, 0.697] Q^2=0.579

Note: All constructs had the $p < 0.001$

Finally, we assessed the significance and sign of the structural model relationships, specifically the path coefficients. The level of significance can be tested using the t-value, p-value, or bootstrap confidence intervals. Hair et al. (2022) suggested that reporting one of these significance tests is sufficient to avoid redundancy, recommending the use of confidence intervals for the additional insight they provide into the stability of coefficient estimates. In line with this recommendation, we estimated the levels of significance using confidence intervals derived from a bootstrapping procedure with 10,000 subsamples (see Table 15). For clarity, p-values are used in our explanations.

As the structural model shows, attitude positively influences intention. All perceived benefits positively influence attitude (H1d, H1e, and H1f supported). This indicates that the more benefits individuals associate with the use of alternative cement, the more positive their attitude towards using it in their homes, which in turn leads to a higher intention to use it. When examining the results by country (see Table 15), we observe variations in how perceived benefits influence attitude. In Belgium, both financial benefits ($\beta = 0.129$, $p < 0.05$) and performance benefits ($\beta = 0.137$, $p < 0.05$) positively impact attitude, although these effects are less pronounced compared to environmental benefits ($\beta = 0.349$, $p < 0.001$).

In Czechia, performance benefits ($\beta = 0.195$, $p < 0.001$), environmental benefits ($\beta = 0.164$, $p < 0.001$), and financial benefits ($\beta = 0.153$, $p < 0.001$) all moderately influence attitude. In Slovenia, financial benefits (β = 0.262, p < 0.001) and environmental benefits (β = 0.217, p < 0.001) have a moderate positive influence on attitude, while performance benefits (β = 0.098, p < 0.05) have a weaker influence.

Table 15.

Hypothesis testing results with path coefficients and confidence intervals bias corrected across countries

	Total Sample ß [99% - CI]	**Belgium (B) ß [99% - CI]**	**Czechia (C) ß [99% - CI]**	**Slovenia (S) ß [99% - CI]**	**Supported?** Yes , No
H1: Perceived risks and benefits -> Attitude					
(H1a) Health Risk -> Attitude	-0.342*** [-0.393, -0.295]	-0.255*** [-0.363, -0.164]	-0.435*** [-0.504, -0.341]	-0.353*** [-0.441, -0.278]	**Yes:** Total, B, C, S
(H1b) Financial Risk -> Attitude	0.086*** [0.047, 0.122]	0.079 [0.002, 0.174]	0.085 [-0.097, 0.145]	0.111** [0.046, 0.172]	**Yes:** Total, B, S **No:** C
(H1c) Performance Risk -> Attitude	-0.016 [-0.057, 0.031]	-0.058 [-0.145, 0.030]	0.000 [-0.093, 0.066]	-0.025 [-0.082, 0.047]	**No**: Total, B, C, S
(H1d) Environmental Benefit -> Attitude	0.247*** [0.205, 0.290]	0.349*** [0.265, 0.429]	0.164*** [0.097, 0.233]	0.217*** [0.147, 0.293]	**Yes:** Total, B, C, S
(H1e) Financial Benefits -> Attitude	0.188*** [0.139, 0.237]	0.129* [0.027, 0.219]	0.153*** [0.081, 0.237]	0.262*** [0.183, 0.340]	**Yes:** Total, B, C, S
(H1f) Performance Benefits -> Attitude	0.153*** [0.104, 0.202]	0.137* [0.032, 0.239]	0.195*** [0.114, 0.274]	0.098* [0.023, 0.170]	**Yes:** Total, B, C, S
H2: Psychometric risk characteristics -> Health Risk					
(H2a) Dread - > Health Risk	0.632*** [0.593, 0.670]	0.634*** [0.570, 0.688]	0.626*** [0.549, 0.693]	0.627*** [0.560, 0.695]	**Yes:** Total, B, C, S
(H2b) Unknown - > Health Risk	-0.009 [-0.052, 0.020]	0.100** [0.020, 0.160]	-0.029 [-0.112, 0.015]	-0.028 [-0.112, 0.016]	**Yes:** B **No:** Total, C, S
H3: Positive and negative affect - > perceived risks and benefits					
(H3a) Negative Affect -> Health Risk	0.200*** [0.161, 0.238]	0.097** [0.034, 0.158]	0.208*** [0.140, 0.271]	0.252*** [0.179, 0.322]	**Yes:** Total, B, C, S
(H3b) Negative Affect -> Financial Risk	-0.112*** [-0.168, -0.047]	0.070 [-0.178, 0.220]	-0.113 [-0.209, 0.120]	-0.128* [-0.221, -0.010]	**Yes:** Total, S **No:** B, C
(H3c) Negative Affect -> Performance Risk	0.345***	0.363***	0.243***	0.396***	**Yes:** Total, B, C, S

	Total Sample ß [99% - CI]	Belgium (B) ß [99% - CI]	Czechia (C) ß [99% - CI]	Slovenia (S) ß [99% - CI]	Supported? Yes , No
	[0.284, 0.393]	[0.223, 0.441]	[0.142, 0.354]	[0.283, 0.477]	
(H3d) Negative Affect -> Environmental Benefit	-0.223*** [-0.267, -0.181]	-0 .196*** [-0.270, -0.120]	-0.183*** [-0.258, -0.111]	-0.259*** [-0.345, -0.175]	**Yes:** Total, B, C, S
(H3e) Negative Affect -> Financial Benefit	-0.174*** [-0.224, -0.121]	-0.089* [-0.172, 0.003]	-0.199*** [-0.294, -0.110]	-0.198*** [-0.281, -0.105]	**Yes:** Total, C, S **No:** B
(H3f) Negative Affect -> Performance Benefit	-0.160*** [-0.208, -0.109]	-0.083 [-0.163, 0.011]	-0.278*** [-0.367, -0.193]	-0.142** [-0.235, -0.044]	**Yes:** Total, C, S **No:** B
(H3g) Positive Affect -> Health Risk	-0.082*** [-0.117, -0.049]	-0.105*** [-0.162, -0.051]	-0.114*** [-0.177, -0.053]	-0.033 [-0.094, 0.027]	**Yes:** Total, B, C **No:** S
(H3h) Positive Affect -> Financial Risk	0.126*** [0.067, 0.176]	0.086 [-0.100, 0.190]	0.127 [-0.139, 0.219]	0.210*** [0.104, 0.297]	**Yes**: Total, S **No:** B, C
(H3i) Positive Affect -> Performance Risk	-0.077** [-0.128, -0.016]	-0.098 [-0.186, 0.023]	-0.203*** [-0.306, -0.116]	0.012 [-0.091, 0.126]	**Yes:** Total, C **No:** B, S
(H3j) Positive Affect -> Environmental Benefit	0.550*** [0.509, 0.587]	0.590*** [0.528, 0.648]	0.572*** [0.506, 0.631]	0.477*** [0.395, 0.555]	**Yes:** Total, B, C, S
(H3k) Positive Affect -> Financial Benefit	0.424*** [0.378, 0.465]	0.500*** [0.420, 0.566]	0.314*** [0.234, 0.393]	0.469*** [0.387, 0.545]	**Yes:** Total, B, C, S
(H3l) Positive Affect -> Performance Benefit	0.405*** [0.357, 0.445]	0.427*** [0.348, 0.489]	0.313*** [0.237, 0.392]	0.423*** [0.328, 0.502	**Yes:** Total, B, C, S
H4: Trust - > Negative and positive affect					
(H4a) Trust in Authorities -> Negative Affect	0.000 [-0.065, 0.064]	-0.142* [-0.249, -0.020]	0.018 [-0.085, 0.123]	-0.012 [-0.138, 0.123]	**Yes**: B **No:** all, C, S
(H4b) Trust in Authorities -> Positive Affect	0.080* [0.017, 0.143]	0.012 [-0.105, 0.124]	-0.014 [-0.115, 0.084]	0.093 [-0.038, 0.225]	**Yes:** Total **No:** B, C, S
(H4c) Trust in Research Institutions -> Negative Affect	-0.060 [-0.152, 0.037]	-0.048 [-0.213, 0.124]	-0.038 [-0.208, 0.119]	0.082 [-0.077, 0.243]	**No:** Total, B, C, S
(H4d) Trust in Research Institutions -> Positive Affect	0.032 [-0.062, 0.131]	0.256** [0.095, 0.423]	0.098 [-0.045, 0.237]	0.101 [-0.075, 0.304]	**Yes**: B **No:** Total, C, S
(H4e) Trust in Scientists -> Negative Affect	-0.060 [-0.154, 0.034]	-0.089 [-0.267, 0.088]	-0.012 [-0.180, 0.162]	-0.161* [-0.313, -0.010]	**Yes:** S **No:** Total, B, C

	Total Sample ß [99% - CI]	Belgium (B) ß [99% - CI]	Czechia (C) ß [99% - CI]	Slovenia (S) ß [99% - CI]	Supported? Yes , No
(H4f) Trust in Scientists -> Positive Affect	0.116* [0.016, 0.211]	-0.067 [-0.241, 0.113]	0.113 [-0.031, 0.261]	0.115 [-0.069, 0.283]	**Yes:** Total **No:** B, C, S
(H4g) Trust in Cement Mfr -> Negative Affect	-0.111** [-0.182, -0.043]	-0.072 [-0.224, 0.071]	-0.128* [-0.226, -0.031]	-0.010 [-0.149, 0.132]	**Yes:** Total, C **No:** B, S
(H4h) Trust in Cement Mfr -> Positive Affect	-0.000 [-0.068, 0.062]	0.056 [-0.059, 0.170]	0.139* [0.040, 0.241]	-0.056 [-0.190, 0.083]	**Yes:** C **No:** Total, B, S
(H4k) Trust in Architects -> Negative Affect	-0.101** [-0.175, -0.023]	0.019 [-0.123, 0.165]	-0.191** [-0.307, -0.077]	-204** [-0.347, -0.064]	**Yes:** Total, C, S **No:** B
(H4l) Trust in Architects-> Positive Affect	0.190*** [0.122, 0.260]	0.125* [0.005, 0.237]	0.180** [0.073, 0.284]	0.21** [0.063, 0.356]	**Yes:** Total, B, C, S

Note: * p < 0.05, ** p < 0.01, *** p < 0.001

Regarding perceived risks, the analysis of the total sample reveals that only health risk (β = -0.342, p < 0.001) and, to a lesser but still significant extent, financial risk (β = 0.086, p < 0.001) negatively influence attitude (H1a and H1b accepted; H1c rejected). When examining the data by country, health risk consistently emerges as the most influential factor on attitude. In Czechia, health risk has the highest path coefficient (β = -0.435, p < 0.001), followed by Slovenia (β = -0.353, p < 0.001) and Belgium (β = -0.255, p < 0.01). Performance risk does not have a significant influence on attitude in any of the countries. Financial risk is positively related to attitude only in Slovenia (β = 0.111, p < 0.001).

For psychometric risk characteristics, dread has a highly significant influence on perceived health risk for the total sample (β = -0.632, p < 0.001) (H2a supported), as well as in each individual country. However, the unknown aspect was not significant for the total sample (H2b rejected), and when examining the countries separately, it only has a negative influence on health risk in Belgium (β = -0.100, p < 0.01).

To investigate this further, we took a closer look at the familiarity dimension of unknown construct to determine if there is a significant difference between Belgium (M = 3.74), Czechia (M = 3.44), and Slovenia (M = 3.30) in participants' responses on whether the potential health risks from the usage of alternative cement are perceived as new (novel) or old (familiar) (see Table 16 for detailed responses). Results of a one-way analysis of variance (ANOVA) performed using R indicated a significant difference among the three countries, F(2, 1220) = 8.435, p < 0.001. Subsequent pairwise comparisons using t-tests with Bonferroni correction indicated that the difference is significant between Belgium and

Czechia ($p < 0.05$) and between Belgium and Slovenia ($p < 0.01$). No significant difference was found between Czechia and Slovenia ($p = 0.564$).

Table 16.

Detailed responses on the perceived newness of the health risk associated with alternative cement by country

7-Likert scale items	Belgium (%)	Czechia (%)	Slovenia (%)
1=Completely new (novel)	9.25	16.87	20.29
2	9.25	13.20	14.01
3	18.50	15.65	18.12
4	36.25	30.81	25.85
5	18.25	14.43	11.35
6	4.50	4.65	5.80
7=Very old (familiar)	4.00	4.40	4.59

Our next hypothesis (H3) concerned the influence of affect on perceived risks and benefits. For the total sample, both positive and negative affect strongly influence perceived risks and benefits (H3 accepted). Positive affect (hope, interest, and curiosity) has a strong positive influence on perceived benefits: environmental benefits ($\beta = 0.550$, $p < 0.001$), financial benefits ($\beta = 0.424$, $p < 0.001$), and performance benefits ($\beta = 0.405$, $p < 0.001$). This indicates that the more positive affect participants experienced—such as greater hope, interest, and curiosity towards new products using alternative cement —the more benefits they perceived.

Multi-group analysis (MGA) conducted in SmartPLS revealed that positive affect had the least influence on financial benefits in Czechia compared to Belgium ($p < 0.01$) and Slovenia ($p < 0.05$). Positive affect also has a weak but significant negative impact on perceived risks; however, perceived risks are primarily influenced by negative affect (doubt, worry, and aversion). Specifically, health risks ($\beta = 0.200$, $p < 0.001$), financial risks ($\beta = -0.112$, $p < 0.001$), and performance risks ($\beta = 0.345$, $p < 0.001$) are all strongly influenced by negative affect. A multi-group analysis revealed that the influence of negative affect on health risk is significantly lower in Belgium compared to Czechia ($p < 0.05$) and Slovenia ($p < 0.01$). In Belgium, negative affect predominantly influenced perceived performance risk. Negative affect also has a negative influence on perceived benefits, including environmental benefits ($\beta = -0.223$, $p < 0.001$), financial benefits ($\beta = -0.174$, $p < 0.001$), and performance benefits ($\beta = -0.160$, $p < 0.001$), indicating that the more negative feelings (e.g., doubt, worry, and aversion) participants had, the lower the benefits perceived.

Finally, we hypothesised (H4) that trust in different actors (competence to properly assess risks and benefits related to this new type of cement, as well as their intention to disclose this information) would influence the positive and negative affect evoked towards this novel technology. For the total sample, trust in authorities ($\beta = 0.080$, $p < 0.05$), scientists ($\beta = 0.116$, $p < 0.05$), and architects ($\beta = 0.190$, $p < 0.001$) led to positive affect (H4b, H4f, and H4l accepted; H4d and H4h rejected), while trust in cement manufacturers ($\beta = -0.111$, $p < 0.01$) and architects ($\beta = -0.101$, $p < 0.01$) decreased negative affect (H4g and H4k accepted; H4a, H4c, and H4e rejected).

When examining each country separately, we observed that the influence of trust in various actors on participants' feelings towards alternative cement varied among the countries. While trust in architects significantly influenced participants' emotions (affect) towards alternative cement across all countries, other actors varied. In Belgium, lack of trust towards authorities ($\beta = -0.142$, $p < 0.05$) led to negative emotions (affect) towards alternative cement, whereas trust in independent research institutions ($\beta = 0.256$, $p < 0.01$) and architects ($\beta = 0.125$, $p < 0.05$) led to positive affect. In Czechia, trust in cement manufacturers ($\beta = 0.139$, $p < 0.01$) and architects ($\beta = 0.180$, $p < 0.005$) led to positive affect, while lack of trust in cement manufacturers ($\beta = -0.128$, $p < 0.01$) and architects ($\beta = -0.191$, $p < 0.005$) led to negative affect. In Slovenia, trust in architects ($\beta = 0.211$, $p < 0.05$) led to positive affect, while lack of trust in scientists ($\beta = -0.161$, $p < 0.05$) and architects ($\beta = -0.204$, $p < 0.05$) led to negative affect.

ANOVA results suggest significant differences in trust towards actors across the three countries. In all countries, trust in cement manufacturers was lowest, followed by architects, while the highest trust was placed in scientists from universities, followed by independent research institutions. Post-hoc comparisons using Tukey's HSD test indicated that both Czechia ($M = 7.51$) and Slovenia ($M = 7.43$) exhibited significantly lower trust in authorities compared to Belgium ($M = 8.10$) ($p < 0.05$ for Czechia vs. Belgium; $p < 0.01$ for Slovenia vs. Belgium). For trust in manufacturers, Slovenia ($M = 6.88$) had significantly lower scores than both Belgium ($M = 7.38$) ($p < 0.05$) and Czechia ($M = 7.77$) ($p < 0.001$), while no significant difference was observed between Belgium and Czechia ($p = 0.147$). Regarding trust in architects, Slovenia ($M = 7.28$) again had significantly lower scores compared to Belgium ($M = 7.96$) ($p < 0.01$), with no significant differences between Czechia ($M = 7.63$) and either of the other two countries. These findings suggest that trust levels vary notably between the three countries, with Slovenia generally reporting lower trust levels than Belgium.

Finally, for the total sample, while objective knowledge had no effect on intention, subjective knowledge did influence intention ($\beta = 0.117$, $p < 0.001$). A similar pattern was observed in Belgium ($\beta = 0.200$, $p < 0.001$) and Slovenia ($\beta = 0.076$, $p < 0.05$), but not in Czechia. Figure 6 summarises the significant path coefficients for all constructs and control variables in the total sample. You can find structural model for each country in Appendix C.

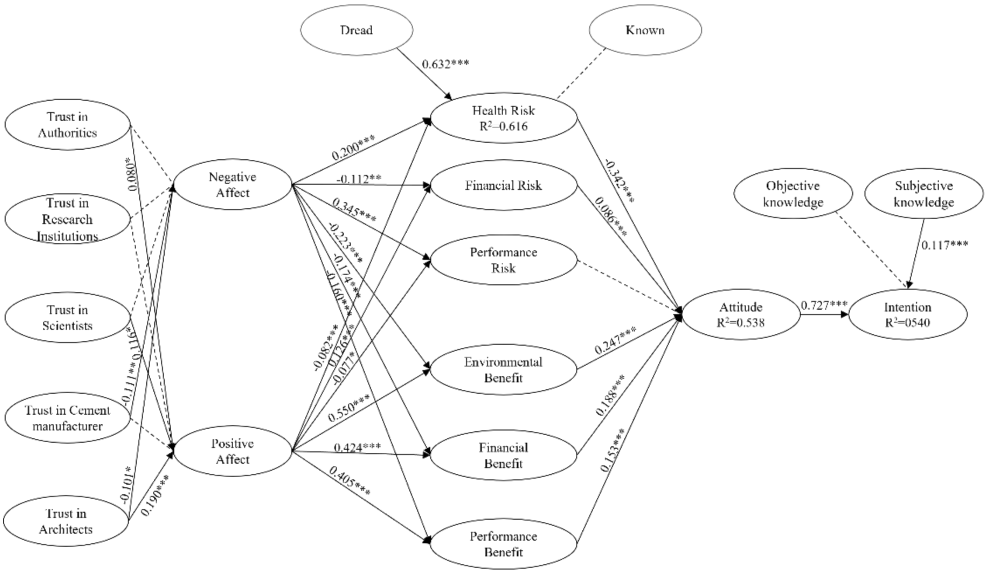

Figure 6. *Structural model for total sample with path coefficients and significance levels*

—— Significant path coefficient ----- non-significant path coefficient

Furthermore, we conducted a multigroup assessment using a non-parametric distance-based test suggested by Klesel et al. (2019) with R. This test is particularly suitable for our study because it compares the entire structural model across groups, rather than just individual parameters, providing a more comprehensive understanding of potential differences among countries. It is robust against distributional assumptions, making it ideal for detecting significant variations in complex models (Cheah et al., 2023). The results indicate a significant difference among the countries, as shown in Table 17, confirming these differences with significant results for dL and dG.

Table 17.

Distance-Based Test for Cross-Group Comparisons

H0: Model-Implied Indicator Covariance Matrix is Equal Across Groups			
Distance Measure	**Test Statistics**	**p-value**	**Decision**
dG	1.5563	0.000	reject
dL	20.1335	0.000	reject

5. Discussion

The use of NORM-contained by-products in cement production not only prevents these materials from accumulating as hazardous waste in landfills, which in high concentration poses risks to health and the environment, but also has the potential to reduce CO_2 emissions during the production process, and contribute to the circular economy. Before introducing this innovative technology to the market, it is essential to assess public acceptance of such sustainable products to ensure successful uptake. This study provides insights into the factors that influence end-users' attitudes and intentions regarding the use of alternative cement across three European countries: Belgium, Czechia, and Slovenia. Overall, the results highlight the key roles of perceived benefits, risks, and affective responses in shaping attitudes towards the use of alternative cement in residential buildings, which in turn influence the intention to use this novel technology. However, substantial differences across countries suggest that a one-size-fits-all approach may not be effective.

Our findings indicate that perceived benefits—environmental, financial, and performance—positively influence attitudes towards the use of alternative cement in residential buildings, leading to a higher intention to adopt it. This aligns with prior research, which has shown that when individuals perceive significant benefits, they are more inclined to accept new technologies (Huijts, 2018; L'Orange Seigo et al., 2014). However, our findings show that the relative importance of these benefits varies by country. In Belgium, environmental benefits were the most influential, suggesting a strong environmental consciousness among Belgian participants. This contrasts with Czechia, where performance benefits had the highest impact on attitudes, reflecting a more pragmatic approach that prioritises functionality. In Slovenia, financial benefits were most influential, indicating that economic considerations are paramount for Slovenian consumers.

With regard to perceived risks, health risks had a significant negative influence on attitudes towards the use of alternative cement in residential buildings across all countries. Differences in perceived health risks were observed. Consistent with the findings of Love et al. (2024), health risks had the most substantial negative impact on attitudes in Czechia and the least significant influence in Belgium. Furthermore, we examined the influence of psychometric risk characteristics, represented by the constructs of dread and the unknown, on perceived health risks. Dread was found to be a strong predictor of health risk perceptions across all countries, indicating that the more dreadful the perceived health risks, the stronger their negative impact on attitudes. However, the unknownness of these risks only significantly influenced health risk perceptions in Belgium, where risks were perceived as less known and more novel. This suggests that in contexts where risks are seen as new and unknown, they may be perceived as more threatening, which can negatively influence attitudes (Siegrist and Árvai, 2020). The variations in perceived familiarity of health risks among the three countries highlight the need for risk communication strategies that are sensitive to national variations in the perception of novel risks.

Despite participants being informed in the introductory text that ‘safety of the final cement will be ensured by checking that the radioactivity is below the established safety standards’, perceived health risks still had a significant negative impact on attitudes. These results not only suggest the need for clear, and transparent communication about the safety of these materials. It also underscores the important role of heuristics in risk and benefit perceptions.

Affect heuristics (emotions) played a key role in shaping perceptions of both risks and benefits. Negative affect (e.g., doubt, worry, and aversion) was more strongly associated with perceived risks, particularly health and performance risks. This was especially pronounced in Czechia and Slovenia, where it significantly impacted health risk perceptions, while in Belgium, it primarily influenced performance risk perceptions. Positive affect (e.g., hope, interest, and curiosity) was associated with higher perceptions of benefits and lower perceptions of risks, suggesting that evoking positive emotions towards alternative cement can enhance its perceived advantages and reduce concerns. Similar to Arning et al.’s (2020) study on acceptance of carbon capture technology, affective benefit perceptions were the strongest predictors. This indicates that enhancing positive emotions and managing negative emotions through effective communication could lead to enhancing the acceptance of alternative cement. Communication strategies should primarily target the positive emotions associated with sustainable alternatives. However, cross-country differences in perceived risks and benefits must be carefully considered. For example, in Belgium, efforts should focus on highlighting environmental benefits, while addressing financial and performance benefits to a lesser extent. Such tailored approaches are crucial for effectively promoting sustainable alternatives across different cultural contexts

Trust in various actors, including authorities, scientists, and architects, was found to influence affective responses towards alternative cement, which in turn influences perceived risks and benefits. Trust in architects consistently emerged as a key predictor of positive affect across all countries, underscoring the significant role these professionals play in shaping public perceptions. This suggests that these professionals could be influential advocates for the adoption of alternative cement in construction to contribute to a circular economy. Engaging architects in public communication campaigns and as intermediaries between consumers and manufacturers could enhance the credibility and acceptance of this environmental innovation. The impact of trust in other stakeholders varied across countries. In Belgium, trust in independent research institutions and architects fostered positive affect, whereas a lack of trust in authorities led to negative affect. In Czechia, both positive and negative affect were influenced by trust in cement manufacturers and architects. In Slovenia, trust in architects contributed to positive affect, while a lack of trust in scientists and architects led to negative affect. These findings suggest that building trust, particularly in architects and other key stakeholders, is essential for fostering positive emotions and, consequently, a more favourable attitude towards switching from traditional cement with high environmental impact to sustainable alternatives. The variation in trust levels towards other stakeholders across countries highlights the need for tailored marketing and communication strategies that leverage the most trusted actors in each region. For example, in Czechia, where trust in architects and cement manufacturers influences feelings towards alternative cement, emphasising certifications and scientific justifications in promotions may not be effective due to low trust in these actors at the end of the supply chain, possibly linked to the previous misuse of NORM-containing by-products in concrete production in Czechia (Hulka and Thomas, 1999; SURO, 2024).

These findings provide empirical evidence on the complex interplay of perceived benefits, risks, affective responses, and trust in shaping attitudes and intentions towards sustainable alternatives such as alternative cement. They offer insights into the communication and policy strategies that must be tailored to each context. Tailored communication strategies that focus on evoking positive emotions while considering the specific perceived benefits and risks in each country, through trusted stakeholders, are crucial for promoting the adoption of sustainable technologies such as alternative cement. For instance, in Slovenia, financial benefits and risks play a more significant role in shaping attitudes towards sustainable alternatives compared to Belgium and Czechia, indicating that simply emphasising environmental benefits and addressing health concerns may not be sufficient.

This study has the following limitations: It focused on three European countries—Belgium, Czechia, and Slovenia—limiting the generalisability of the findings to other regions with different cultural and socio-economic contexts. Future research could expand the scope to include a broader range of countries to explore whether the observed patterns hold in different settings. Moreover, our sample consisted of those who have built or renovated their home in the last 10 years which might include specific socio-economic groups. Future research could expand to the general population to also include those who will be the potential renters of the buildings made with alternative cement.

Finally, further studies could delve deeper into the psychological mechanisms underlying affective responses to novel, sustainable technologies. Understanding the factors that trigger positive or negative emotions towards sustainable alternatives, such as alternative cement, could inform the development of more targeted communication strategies that effectively address public concerns and foster acceptance, contributing to broader circular economy efforts and Sustainable Development Goals.

6. Conclusion

This study identified the associated risks and benefits of using alternative cement, which vary across countries. It also revealed the role of emotions and trust in how these risks and benefits are perceived. Our research provides empirical evidence on the factors influencing end-users' decision-making behaviour in adopting alternative cement, offering critical insights for the market introduction of sustainable products. Significant cross-country differences in the factors shaping attitudes towards sustainable alternatives underscore the importance of tailored marketing strategies before launching novel sustainable technologies into the market. These strategies should emphasise the most valued benefits (e.g., environmental benefits) in each country through communications that evoke positive emotions, while addressing consumers’ specific concerns (e.g., health risks) by involving trusted actors in each country. Additionally, financial and performance aspects should be considered. It was also clear that the country's specific context such as previous experiences with similar materials evoked certain emotions towards such sustainable products.

Chapter 5. Conclusions and Recommendations

1. Conclusions and Practical Implications

This chapter summarises the main findings of the thesis from Chapter Two, Three, and Four, by exploring the practical implications and providing recommendations for various stakeholders. Following this, the limitations of the research are discussed, and directions for future studies are proposed.

1.1. Short Recapitulation

Cement production is responsible for approximately 8% of global anthropogenic greenhouse gas emissions. The use of industrial by-products as substitutes for raw materials in cement production presents an opportunity to reduce both emissions and reliance on virgin materials. This thesis specifically focused on NORM-contained industrial by-products, which have been accumulating in landfills, posing risks to human health and the environment. By safely incorporating these materials into cement production, we can contribute to the circular economy.

While the technical aspects of using NORM-contained by-products have been explored, non-technical concerns remain under-researched. This PhD study addressed identified gaps by exploring stakeholders' perceptions in Belgium, Czechia, and Slovenia regarding the use of alternative cement made with NORM-contained by-products. The aim was to understand the factors that influence stakeholders' perceptions of these materials and identify the barriers and facilitators to their use, in order to inform policy and communication strategies.

Two key stakeholders were investigated in this thesis: industry representatives and end-users. Industry representatives included concrete producers, related associations, federations, and construction companies. End-users were defined as those who had built or renovated their houses recently, as they were directly involved in the decision-making process regarding building materials. Given the unexplored nature of this topic, we began by interviewing both stakeholder groups to identify key themes influencing their perceptions of sustainable alternative cement made with NORM-contained by-products.

First, in Chapter Two, we interviewed industry representatives in Belgium to examine the barriers preventing a switch from traditional to alternative cement, and explored potential facilitators (Objective 1). Next, in Chapter Three, we conducted a comparative study of stakeholders in Belgium, Czechia, and Slovenia (Objectives 2 and 3). Based on interviews with end-users in Chapter Three, we generated hypotheses (Objective 3) and in Chapter Four, we tested them on a larger sample using a framework designed from both the interviews and relevant literature (Objective 4). For industry representatives, the interviews (Chapter Two and Three) provided comprehensive insights into the current barriers and potential facilitators for using NORM-contained by-products in cement. The findings of our studies are summarised in the following sections.

1.2. Industry Representatives’ Perspective

Chapters Two and Three provided comprehensive insights into industry representatives, highlighting that their concerns encompass a broad spectrum of factors influencing the wider adoption of sustainable materials. These concerns are not limited to technical feasibility but also include practical barriers, with regulatory certainty standing out as a crucial element in their decision-making processes.

Although the industry acknowledges that, due to high CO2 emissions and global efforts to achieve net-zero, changes are inevitable, the perceived timeline for these changes affects their actions. Companies that view the transition as gradual do not see the necessity for major changes. In contrast, companies that anticipate stricter regulations or higher CO2 taxes are investing in technologies like carbon capture and storage, as these allow them to maintain current operations in a more cost-effective way. Many industry representatives advocated for stronger government involvement through incentives and regulations. Without financial incentives such as subsidies, tax breaks, or higher CO2 taxes, companies are unlikely to prioritise sustainability, especially when traditional materials remain cheaper and more familiar. Increased CO2 taxes and stricter emissions regulations could make traditional cement less financially viable, creating a level playing field for sustainable alternatives. This highlights the need for a robust regulatory environment that pushes companies towards sustainable practices through economic incentives, while also offering clear guidance on investment priorities.

The lack of market pressure further complicates the industry's transition to sustainable practices, as customers are generally unwilling to pay a premium for sustainable products. Here, government intervention is crucial. Regulations requiring both private buyers and public procurement to prioritise sustainability in building materials could significantly increase demand. By embedding sustainability criteria into both public and private purchasing decisions, governments can stimulate demand and signal a strong commitment to sustainability. This would encourage companies to invest confidently in greener technologies, knowing that market demand will follow. As major public buyers, governments can lead by example in construction projects by incorporating sustainability criteria, setting an industry-wide precedent and making the business case for adopting alternative binders more compelling.

The diminishing availability of commonly used by-products, such as blast furnace slag—which was initially used to lower production costs—makes the industry more open to exploring alternatives. However, companies need confidence in long-term, local availability before investing in new production processes. Additionally, import regulations that allow companies to claim reduced CO2 emissions by sourcing materials from outside Europe raise concerns about the environmental impact, as transport emissions can offset benefits. Regulatory adjustments are necessary to ensure stable, locally sourced materials and to prevent misleading sustainability claims based on imported resources.

Being a conservative industry, companies also require assurance about the long-term durability of the final product, given the stringent performance standards they must meet. The slow adaptation of regulations, especially at the national level, further adds to the industry's reluctance. For example, companies in Belgium face particularly strict certification processes, which prevent them from reducing cement content in concrete production without risking non-compliance with certification requirements. This creates tension between the desire to innovate and the risk of not complying to certifications. There is a pressing need for harmonised EU-level regulations that accommodate innovative solutions while ensuring product safety. Harmonisation would also facilitate cross-border trade and competition, enabling companies to scale sustainable solutions more effectively within an open market.

Lack of harmonised regulations is not only a barrier for cement production specifications but also when incorporating sustainable practices, as there is a lack of standardised sustainability parameters across the industry. Without a unified approach, companies are able to make environmental claims that focus on selective aspects of sustainability while neglecting others, leading to greenwashing. This not only misleads consumers but also creates unfair competition between companies that genuinely invest in sustainability and those that exploit regulatory loopholes. The call for EU-wide standardisation of sustainability parameters is crucial, as it would provide a transparent, comparable, and verifiable framework for assessing the environmental impact of products. This would also help companies make informed investment decisions, secure in the knowledge that their sustainability efforts are recognised and rewarded across the industry.

While these aspects are consistent across the countries studied, NORM-related concerns vary, influenced by factors such as historical context and trust in regulatory systems. The use of NORM-containing by-products raises health concerns that vary by region. Companies are particularly concerned about potential public backlash, as communicating the safety of these materials is a significant challenge. In Czechia, historical associations of similar materials with serious health risks, such as cancer, make it difficult to convince end-users of their safety. In Slovenia, mistrust in regulatory systems amplifies these concerns. Despite existing certification processes, companies question the reliability of these systems due to concerns about transparency or past failures. Promoting alternative cement in these regions requires not only regulatory approval but clear communication and validation from trusted entities to foster acceptance.

In contrast, in Belgium, health concerns are much lower due to higher trust in regulatory bodies and certification processes. Confidence in the safety of certified products underscores the importance of regulatory trust in safeguarding against potential risks.

In conclusion, the industry's hesitance to adopt alternative cement, particularly those containing NORM, is largely driven by a lack of regulatory certainty. Clear and consistent regulations are needed to incentivise investment in sustainable technologies, ensure product quality, and provide transparent sustainability metrics. Without these frameworks, the transition to sustainable practices in the cement industry will remain slow. Addressing regulatory concerns is essential for making alternative cement a viable and accepted solution within the industry.

1.3. End-users' Perspective

The interview analysis in Chapter Three, followed by the findings of the questionnaire derived from these interviews in Chapter Four, provided insights into end-users' perspectives. While there is broad recognition of the need for environmentally friendly solutions, perceived higher costs and lower performance of sustainable materials often prevent this from translating into practical action. The introduction of NORM-containing materials adds further complexity.

Economic considerations drive decision-making in Slovenia, where financial benefits take precedence over environmental ones. Affordability and cost-effectiveness are key priorities. Promoting long-term cost savings, such as reduced energy consumption or increased property value, may be an effective strategy. Financial pragmatism underscores the need for subsidies or incentives to support the shift towards sustainable materials. Without these incentives, Slovenian consumers are unlikely to prioritise ecological or performance benefits. Policies offering financial relief or mechanisms to bridge the price gap between traditional and alternative cement are essential.

For Czechia, performance benefits slightly outweigh environmental ones in shaping attitudes. Practical application and functionality matter most, reflecting a utilitarian approach. Therefore, simply promoting the environmental benefits of alternative cement is insufficient; companies must emphasise proven performance in real-world applications. Comprehensive case studies, pilot project evidence, and demonstrated performance quality are essential for influencing the Czech market.

In Belgium, environmental benefits are the primary influence, unlike in Czechia and Slovenia. Belgians, already inclined towards sustainability, view alternative cement primarily through an ecological lens. Promoting this technology in Belgium should therefore focus on its ability to reduce CO2 emissions and support the circular economy. The environmental narrative resonates more strongly than other factors, aligning with national values and sustainability goals.

In Belgium, health concerns have the least influence on attitudes, as trust in the safety of market products is higher. Trust in authorities and research institutions plays a key role in shaping perceptions. Therefore, if the product is to be introduced to the market, companies can focus less on health concerns and more on reinforcing environmental benefits. However, over-reliance on certification without transparent communication about risks could backfire, unintentionally suggesting underlying dangers.

In Belgium, unlike Czechia and Slovenia, the unknown nature of risks also contributed to health concerns. If the product is to be introduced to the market, trusted actors should therefore address health risks through clear, transparent communication. Engaging regulatory bodies and independent experts can help clarify perceived risks, build trust, and reduce uncertainties surrounding alternative cement. A balanced communication strategy is essential for maintaining trust and ensuring safety standards are understood.

In Czechia, health risks are the most significant concern, largely due to historical associations with the misuse of NORM in construction materials. Despite safety assurances, deep-seated mistrust hinders the acceptance of new technologies like alternative cement. To overcome these concerns, if the product is to be introduced to the market, companies must engage in transparent and targeted communication strategies that address historical fears directly. Independent health studies or long-term monitoring may help demonstrate the absence of adverse effects. Additionally, past misuse of similar materials has eroded trust in cement manufacturers and architects, who play key roles in shaping perceptions. These actors must rebuild trust by ensuring transparency and prioritising safety.

Similarly, health risks are amplified in Slovenia due to widespread mistrust in regulatory systems. Consumers here question the transparency and reliability of certification bodies, complicating efforts to assure the public of the safety of NORM-containing materials. If the product is to be introduced to the market, engaging trusted intermediaries, such as scientists, may prove more effective in fostering acceptance, as traditional regulatory assurances may not suffice.

In both Czechia and Slovenia, emotions such as doubt, worry, and aversion amplify perceptions of health risks. In countries where negative emotions strongly influence attitudes, if the product is to be introduced to the market, communication strategies should focus on reducing these emotions by building trust and confidence in the product's safety. Positive emotions like trust and optimism correlate with higher perceived benefits, including environmental, financial, and performance advantages. Fostering positive emotional associations with alternative cement could therefore be key to increasing acceptance in these regions.

Across all three countries, architects can serve as influential advocates for alternative cement. Their role as intermediaries between manufacturers and consumers positions them uniquely to shape public opinion. If the product is to be introduced to the market, companies should collaborate with architects in public communication campaigns to lend credibility to alternative cement promotion. In Belgium, where trust in independent research institutions is also high, these institutions could be valuable allies in reinforcing positive perceptions.

Public acceptance of alternative cement is complex and requires tailored, context-sensitive communication strategies. The interplay of perceived benefits, risks, emotions, and trust varies significantly across countries, making a uniform approach ineffective. Companies and policymakers must consider the specific concerns, values, and emotional responses of consumers in each country to successfully introduce alternative cement and contribute to broader sustainability goals.

In conclusion, public acceptance of alternative cement varies significantly across Belgium, Czechia, and Slovenia. If the product is to be introduced to the market, tailored communication strategies that address specific concerns—whether financial, performance, or health-related—are essential. Financial incentives are key in Slovenia, performance reliability must be emphasised in Czechia, and environmental benefits should be the focus in Belgium. Collaboration with trusted stakeholders such as architects and research institutions will help build credibility and support the adoption of sustainable technologies.

1.4. Concluding Remarks

From the findings of the studies presented in Chapters Two, Three, and Four, it is evident that the use of NORM-containing by-products in alternative cement is a complex issue requiring coordinated and multi-faceted approaches. The barriers identified, particularly in regulatory aspects, cannot be resolved in isolation. The challenges discussed in this thesis around sustainable consumption and production are not unique to this topic but reflect broader issues that are applicable to other sectors. While cement and concrete standards may differ, they are closely interwoven with sustainability regulations.

As evident in Chapter Two and Three, certification and regulation are critical for the acceptance of NORM-containing by-products. The lack of policy stimulating the valorisation of residues, particularly in alignment with the principles of the circular economy, impedes the beneficial use of these materials and obstruct the development of innovative technologies that could enable such valorisation (IAEA, 2024b). When setting regulations, both circular economy principles and the environmental hazards of these materials must be considered. Tackling regulatory issues in isolation risks creating inconsistencies, which could discourage their use. Similar challenges have been seen with the incorporation of novel by-products in cement production, where outdated regulations and certifications have deterred industry action.

A holistic, multi-stakeholder approach is required, involving industry, policymakers, and the public. Harmonised EU regulations, along with financial incentives like increased CO2 taxes and mandatory sustainability requirements in procurement, are essential for driving industry-wide change. Transparent communication about the safety and benefits of NORM materials is also critical for broader public acceptance, helping to build trust and reduce uncertainties.

A collaborative, coordinated approach is essential for achieving the Net Zero target. While the industry must be pushed to take more decisive action, demand must also be generated through regulations that require end-users to prioritise sustainability when choosing building materials. Including environmental standards in government tenders would further incentivise the industry to reduce its environmental impact. By incorporating NORM-containing materials in public projects, end-users would become more familiar with these materials, reducing the stigma around their use. This would provide both industry and end-users with the confidence and incentives to adopt them.

2. Recommendations for Stakeholders

The findings of this thesis provide several critical implications for informing industry practices, policy development, and communication strategies to promote sustainable building materials like alternative cement, particularly those made with NORM-contained by-products, if these products are to be introduced to the market.

As demonstrated in the findings from Chapters Two, Three, and Four, the adoption of alternative cement necessitates a multi-faceted strategy that addresses both the industry's need for regulatory certainty and the public's concerns regarding health, safety, performance, and financial viability. A tailored approach that considers the cultural and socio-economic contexts of different countries, along with trust-building efforts and economic incentives, is essential to overcoming barriers to widespread adoption. Policymakers, industry representatives, and communicators must collaborate to ensure that sustainability goals are met while addressing the diverse and nuanced concerns of end-users and the public.

2.1. For Industry

Industry players, particularly in the cement and construction sectors, must prioritise collaboration with regulatory bodies to advocate for clearer, consistent EU-wide regulations on alternative binders. This involves active participation in the standard-setting process and promoting policies that facilitate innovation while ensuring product safety. Investing in infrastructure to support the use of alternative materials is critical for future-proofing operations and meeting increasing CO2 reduction targets.

If the product is to be introduced to the market, our findings from Chapter Four indicate that industry actors must actively engage in public communication campaigns, collaborating with architects and other trusted institutions to educate and involve the public in recognising the benefits of alternative binders. Public engagement strategies should be tailored to local contexts, focusing on providing evidence of safety, such as independent certification and long-term studies, especially in regions like Czechia, where sensitivities around NORM-containing materials are heightened. Furthermore, companies should collaborate with trusted professionals such as architects to serve as advocates for alternative cement.

Architects are consistently trusted across all three countries and can act as intermediaries between manufacturers and end-users. Building partnerships with independent scientific institutions can also help to mitigate public mistrust, especially in regions like Slovenia where regulatory systems are viewed sceptically.

Industry players must also prioritise the protection of workers handling alternative binders, particularly those containing NORM by-products. This includes providing adequate training, implementing safety protocols, and equipping workers with the necessary protective gear to minimise exposure to potential radiological risks. Such measures are critical not only for compliance with regulations but also for fostering trust among workers, which can further influence public acceptance.

2.2. For Policymakers and Regulatory Authorities

In order to achieve the United Nations' (2015) Sustainable Development Goals (SDGs), drastic actions from policymakers and regulatory authorities are necessary at both international and national levels. The existing slow and extensive processes for developing and implementing policies and regulations act as a hindrance to achieving the SDGs. As highlighted in the findings of Chapter Two, policymakers must lead the creation of a holistic regulatory framework that addresses industry concerns, such as inconsistent import regulations and the lack of standardised sustainability metrics. Harmonised regulations and international collaboration, particularly within the EU, are essential. The global nature of climate change demands coordinated responses to ensure that CO2 reduction efforts are effective across borders. Harmonised EU-level regulations that ensure fair competition and address global CO2 impacts are crucial. Governments should also consider increasing CO2 taxes and providing financial incentives for companies transitioning to alternative cement production. Collaborative initiatives between countries, aligned with global climate policies, will ensure that innovations like alternative cement can scale and contribute to global CO2 reduction efforts.

Findings from Chapters Two and Three indicate that public procurement can play a crucial role by prioritising sustainability criteria in construction projects, stimulating demand for alternative cement and helping achieve economies of scale, which can reduce production costs. Financial constraints are also a significant barrier among end-users, shown in Chapter Four with the case of Slovenia, where financial concerns outweigh environmental considerations.

Regulatory bodies play a key role in certification. Ensuring that certification processes for alternative materials, especially NORM-contained by-products, are transparent, robust, and harmonised across countries will build trust in their safety and efficacy, both within the industry and among end-users. Regulatory bodies and governments must address the mistrust that exists, particularly in countries where it can be of higher significance (e.g. Czechia and Slovenia). Policies promoting alternative cement should be accompanied by transparency initiatives involving independent oversight and trusted institutions. Governments should also create platforms for dialogue between industry representatives and the public, ensuring that policies consider not only technical feasibility but also public sentiment and socio-economic realities. Finally, policymakers and regulatory authorities should develop clear guidelines and enforce stringent safety standards to safeguard workers involved in the production and application of alternative cement containing NORM by-products.

2.3. For Marketing and Communication Managers

Our research shows that a one-size-fits-all approach is ineffective when promoting alternative cement across countries. The relative importance of perceived benefits, risks, and trust varies significantly across Belgium, Czechia, and Slovenia, highlighting the need for tailored communication strategies, if the product is to be introduced. As discussed in Chapter Four, these strategies should not only provide factual information but also evoke positive emotions.

- Belgium: Communication strategies should focus on the positive environmental impact of alternative cement, emphasising its role in reducing CO_2 emissions and supporting the circular economy. Given the high trust in regulatory bodies, public campaigns can leverage certifications and regulations to bolster credibility mitigate the perceived risks associated with adopting alternative cement.
- Czechia: Performance benefits and safety assurances must be prioritised. Given the historical associations with hazardous materials like radioactive fly ash (Hulka and Thomas, 1999; SURO, 2024), addressing concerns with transparent and empathetic messaging is crucial. The long-term durability and safety of alternative cement should be demonstrated through practical, real-world examples. Public trust will need to be built over time with transparent and ongoing communication.
- Slovenia: Economic aspects are paramount, so communication should highlight cost savings and affordability. Government incentives or subsidies will likely be essential for driving adoption. Engaging trusted intermediaries like scientists could help foster greater acceptance, given the mistrust in regulatory authorities.

2.4. For Scholars and Academic Research

Greater attention is required to address the societal aspects of using NORM-contained by-products in cement. While performance, environmental impact, and radiological considerations are crucial, our findings suggest that societal concerns may pose significant challenges requiring further investigation. Addressing such challenges benefits from an interdisciplinary approach, as our research highlights the importance of integrating and interacting among disciplines to tackle multi-dimensional and complex topics effectively.

Our study highlights the importance of beginning investigations with qualitative studies when prior research in the field is limited, rather than solely relying on existing studies to generate hypotheses. Although qualitative studies, such as interviews, can be time-consuming, in-depth discussions with participants, regardless of the sample size, provide a robust foundation for research. For smaller samples, such as industry representatives, qualitative methods alone may be sufficient, depending on the study objectives. However, for larger samples, such as end-users, particularly when exploring a new context, we strongly recommend a mixed-methods approach. This involves generating hypotheses from qualitative studies and testing them on a broader sample using quantitative methods. The findings of our research confirm the necessity and value of this approach.

Extra care must be taken when selecting the sample population. While focusing on the general population may be more convenient, less costly, and quicker to recruit, in our study, we recognise that selecting individuals who are currently or have recently been involved in the decision-making process of choosing building materials for the construction of their homes provided a more concrete and less ambiguous context for participants to respond to study questions, as demonstrated in Chapters Three and Four. Their experiences offered more realistic and actionable insights into the challenges and facilitators associated with using alternative cement in home construction.

Based on our conceptual model in Chapter Four, which integrates the findings from Chapter Three and existing theories, in line with elaboration likelihood model (Meijnders et al., 2001; Petty & Cacioppo, 1986), we recommend recognising that consumers' attitudes towards a technology are not solely formed through systematic and rational processes but are significantly influenced by heuristics. This suggests that, in contexts where comprehensive knowledge and time are limited, perceptions of risk and benefit are shaped more by feelings than by logical evaluation. Therefore, it is crucial to address emotional responses, especially when the technology is perceived as risky (e.g., radiological risks), intended for personal use (e.g., in participants' homes where a sense of ownership or direct benefit may foster acceptance, contrasting with broader societal scepticism), or associated with societal benefits (e.g., sustainable alternatives).

To better understand consumer perceptions of technologies perceived as risky, we further recommend that future studies incorporate psychometric risk characteristics into frameworks designed to analyse consumer attitudes toward novel technologies. Our findings in Chapter Four indicate that it is not only important to determine whether a certain technology is perceived as risky and what factors influence this perception, but also that incorporating psychometric risk characteristics provides a deeper understanding of why a particular technology is perceived as risky. For example, our findings showed that in the case of alternative cement, the perception of health risks is primarily driven by the dread aspect and only in Belgium, the unfamiliarity of the risks further explained why this technology might be seen as risky. The integration of these characteristics, comprising two principal dimensions—dread and known—should be carefully contextualised to ensure their relevance and accuracy in addressing consumer attitudes. This involves not only selecting relevant characteristics related to a particular technology, such as familiarity, voluntariness, and individual controllability, but also elaborating on these dimensions when necessary. For instance, recognising the importance of certifications for end-users, we included regulatory authorities alongside science and participants themselves when measuring how much they believe the potential health risks of using alternative cement are known to these groups. As indicated in Chapter Four, major perceived risks should not be studied in isolation but in conjunction with other potential perceived risks and benefits. As demonstrated in our conceptual model, this can be complex, as multiple factors may influence the perception of the technology.

Finally, our findings in Chapter Three and Four highlights the important role of trust. In line with Siegrist (2021), we advise paying particular attention to the role of trust in shaping affective responses, especially when the technology is unfamiliar, and multiple stakeholders are involved. Building trust among all relevant actors is essential, as trust can significantly influence how consumers feel about the technology. Our findings, derived from interviews in Chapter Three, demonstrate the importance of identifying these key actors within the specific context of the study, rather than relying solely on insights from existing literature. This underscores the necessity of conducting context-specific investigations as a preliminary step in understanding the acceptance of a novel technology.

3. Limitations and Future Research

This research, though comprehensive, faced certain limitations that future studies can address. First, the qualitative nature of the study for industry stakeholders limits the ability to generalise the findings across all European contexts. While the focus on Belgium, Czechia, and Slovenia provides comprehensive insights, these results may not fully capture the complexities faced by industries in other EU countries with different regulatory landscapes or market dynamics. Expanding the geographical scope in future studies would help generalise the findings and test the hypotheses in more diverse contexts.

The study primarily focused on stakeholders directly involved in the construction industry, such as manufacturers and end-users. Future research should explore the perspectives of policymakers and public authorities, whose regulatory actions are critical in shaping industry practices, by influencing legal frameworks, market incentives, and compliance standards. Examining their roles could offer deeper insights into the feasibility of suggested policy interventions, such as harmonised EU-level standards, sustainability criteria in procurement processes, and adjustments to CO2 taxation. Moreover, while this study focused on individual stakeholders and their perceptions, future research could expand to examine broader systemic factors, as individual actions are often shaped by market structures and regulatory frameworks. A structural approach could investigate how market dynamics, such as competition or supply chain dependencies, impact the adoption of sustainable cement. Similarly, a regulatory approach could further explore how policies and compliance standards shape these market behaviours and the acceptance of alternative materials. Studying these systemic elements would provide a more holistic view of the barriers and facilitators to sustainable cement adoption.

This thesis relied on end-users who had built or renovated homes in the past decade, which might limit the diversity of socio-economic perspectives. Expanding future studies to include a wider population, such as renters and potential buyers, could yield more representative results and provide a better understanding of how public perceptions might evolve over time.

Although the research highlighted the importance of trust in certification systems and the emotional factors influencing perceptions, further psychological research is needed to understand the underlying mechanisms of trust-building and affect heuristics in the adoption of sustainable technologies. Investigating how specific communication strategies or interventions can foster trust would help tailor marketing and policy measures more effectively.

Researchers should focus on further investigating public perceptions of alternative cement, particularly regarding health and environmental concerns. Psychometric risk (Fischhoff et al., 2000) characteristics can also be explored in more depth to gain a better understanding of the aspects that contribute to stakeholders' health risk perceptions. Future studies can also explore the impact of communication strategies that leverage trusted professionals, such as architects and independent institutions. Additionally, researchers are encouraged to continue studying the economic feasibility of sustainable alternatives in the cement industry, particularly by examining how financial incentives and penalties can shift both supply and demand towards sustainable options.

Expanding cross-country comparative studies would provide a more comprehensive understanding of the barriers and challenges faced by different stakeholders across various regulatory and market environments, thereby offering insights into how diverse contexts influence the adoption of sustainable cement products. This should extend beyond EU countries. Investigating the acceptance of sustainable cement in countries like China, the largest contributor to total cement emissions (Gilfillan et al., 2020), would help accelerate the transition to the use of sustainable cement. Future studies could also test the framework designed in this thesis to determine if it is applicable in other countries. Lastly, researchers should collaborate with industry and policymakers to develop innovative approaches that balance environmental goals with practical, cost-effective solutions to ensure long-term market viability.

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Appendix A.

2.1 Appendix A

Interview Protocol

First of all, I'd like to thank you once again for being willing to participate in this interview. My name is Nazanin Love and I am a PhD researcher in Hasselt University. As I have mentioned to you previously, the aim of this research is to understand what the concrete industry thinks about a new type of cementitious binders which is currently under development, and the aspects of the product are important to them.

Our interview today will approximately last one hour during which, first, I will ask some general questions, followed by more specific questions mostly related to cement. You don't need to answer a question if you don't want to. Since you have given consent, the interview will be audio recorded. All the information will be anonymous and your responses are confidential.

Do you have any questions for me?

If it is OK for you, I will start recording the interview. This will ensure that I will note all information provided by you. Please let me know if at any point you want me to turn off the recorder or keep something you said off the record.

Main questions	Probing questions
Section 1: General	
Can you briefly introduce yourself and your company and explain your role & responsibilities in the company, please?	
Can you briefly explain what type of cement currently you use in your concrete production? And why is that?	-Except …[their answer to why]... what other factors are taken into account when choosing cement you use?

For choosing what cement to buy, how is the decision making process in your company?	-Who is usually involved in making this decision? (their role in the company) -Would this be a lengthy process if you would like to change the type of cement you use? -Do you take into account environmental sustainability in your decision making process?
Section 2: Sustainable actions	
How do you define environmental sustainability?	
In your opinion, in what ways your company affects or is being affected by environmental issues?	-How do you see your company's environmental impact? -If they didn't mention the product (cement/concrete), ask them specifically about the impact of their products -How do you see the environmental impacts of your company in comparison to other companies in your sector? -How do you see the environmental impacts of the whole concrete and cement industry? -Where do you see the role of price in this?
Do you see any changes in demand for more environmentally sustainable products in the market?	
In your opinion, what can be done to tackle/deal with [above mentioned] impacts?	
Are there actions that your company takes/has taken to reduce its impact on the environment? Can you explain it?	-Is it something that you do on your initiative or is it something that you are legally obliged to or feel the pressure to do so? [pressure by who?] e.g, change in legislation or CO_2 tax -If they mention pressure from other actors: Is it a fair expectation? Is it possible?
So far, is there anything that held you back from taking more environmentally sustainable action?	
What might encourage you more to reduce your environmental impact?	
Where do you see the role of the government in this?	

<table>
<tr><td>Do you have any plans in the future to be a more sustainable company? Why?</td><td>Currently, is there any help offered by the authorities to become more sustainable? What kind of help? Is it helpful? How?</td></tr>
<tr><td colspan="2" align="center">Section 3: Cementitious binders</td></tr>
<tr><td colspan="2"> Briefly explain the alternative cementitious binders
My research aims to bridge the industry and scientists; who are working on new types of cementitious binders made with 70-90% of industrial by-products. Because they have a flexible process and use different concentrations of various types of industrial by-products, the performance of these cement can be modified based on the specific application and industry demand. This can entail new opportunities for the concrete industry.
Since secondary raw materials are used instead of limestone, it preserves raw materials and contributes to the circular economy. It also has the potential of reducing CO_2 emissions during the production process.
Before we go into details about the by-products, based on this brief information, I would like to hear your opinion about this type of alternative cement or in general about alternative cementitious binders. (Immediately ask below question) </td></tr>
<tr><td> What are the main criteria that would affect your opinion to consider using these types of new binders in your production?
<u>If</u> they are negative towards this alternative cement, ask:
Under what circumstances might it be worthwhile for your company to switch to this cement?
OR
Do you think you might consider it in the future? What might change in the future? </td><td> [Mechanical properties?
Sustainability?
Regulation? Standards?]
-Whose approval of this product would matter to you? (Scientists, Government, Major big companies, Experts in your company, concrete federation…)
-Do you think the contractors and architects will be in favour or against this product? </td></tr>
<tr><td colspan="2" align="center">Section 4: NORM-contained SCMs</td></tr>
<tr><td colspan="2" align="center">NORM-contained cementitious binders</td></tr>
</table>

As I mentioned earlier, this cement can be made with various industrial by-products some of which you might be familiar with such as metal stag (for example copper slag) and phosphogypsum (a by-product in the phosphorus fertiliser industry). Similar to some other by-products that are currently being used, such as fly-ash, the enhanced level of natural radioactivity of these by-products adds to the importance of recycling them, for example using them in cementitious binders. The goal of developing these new types of cementitious binders is not only getting a step closer to carbon neutrality, but also improving the mechanical properties of these binders. Of course, it is not possible to have all beneficial properties at the same time. As I mentioned the properties and environmental profile would vary depending on the configuration.
Now that you have more information about the by-products used in these binders, what are your thoughts? ***Ask the same questions in previous section** If they don't mention radioactivity aspects, at the end ask this: What do you think about the fact that the by-products used in these cementitious binders have enhanced level of radioactivity?
If there are questions that you didn't have a chance to cover, ask: That covers most of what I needed to know, but there are a couple of specific questions that I want to ask before we end. We have covered everything. We are just sort of the beginning of this research and I would be really interested to hear if you have any thoughts about what you think would be interesting for us to pursue, kind of angles or questions. It can be challenging to find the right company and the right person in that company to talk to. I was wondering if there is anyone specific that you think it would be beneficial for my research to talk to? Thanks again for your time. I ensure that your data will be kept strictly confidential.

2.2 Appendix B

Interview Protocol Development

The initial interview protocol was crafted in English before translation into Dutch, Slovenian, and Czech to accommodate the linguistic differences among the three countries. The development of the industry interview protocol was shaped by an extensive review of the relevant literature and insights from both industry experts and academic researchers, ensuring its relevance and comprehensiveness. For end-users, we tailored the questions accordingly. For example, while we asked industry representatives about their decision-making process for buying cement, we posed more general questions to end-users about their choice of materials during the construction of their houses. We also simplified some of the terminologies, such as changing ‘cementitious binders’ to ‘alternative cement’. We conducted five pilot studies with end-users and made necessary adjustments; for instance, we decided not to provide examples of the by-products used because they were perceived as too technical by the participants.

By adopting a semi-structured interview approach, we oriented the conversations around a topic guide. Each section contained a series of open-ended and potential probing questions designed to encourage detailed and reflective responses. To ease participants in the discussion, we started with more general questions about their decision-making process when choosing cement (for industry representatives) and building materials (for end-users). We then gradually transitioned to a discussion on sustainable building materials. Before delving into the participants’ perceptions of cement made with NORM-contained by-products, we provided them with objective general information about the topic. This information was delivered in two steps. First, we explained the potential of using by-products in cement to reduce its environmental impact. In the second step, we informed them that some of these by-products are categorised as NORM. The flexibility inherent in our semi-structured format allowed for spontaneous exploration of emergent themes, which were not strictly confined to the initial guide. This adaptive nature of the protocol ensured that we could capitalise on the unforeseen, yet valuable, insights offered by participants during the interviews.

The researcher’s role was not merely to administer questions, but to actively navigate the conversation, maintaining a balance between the intended topics and the dynamic flow of the dialogue. This approach facilitated a deep and comprehensive understanding of stakeholders’ perceptions and attitudes towards the use of alternative cement.

Interview protocol for industry and End-users

Industry	End-users
General	
Please briefly introduce yourself and your company and explain your role & responsibilities in the company.	Please briefly introduce yourself. What type of property are you currently building or renovating? - Is it a place for yourself to live or rent out/sell? Who is and/or will be living in the house with you? - Children (number)? age? Parents?
Briefly explain the type of cement currently used in your production. And why is that? - Except for [their answer to the previous question], what other factors are taken into account when choosing the cement you use? What is your company's decision-making process for choosing what cement to buy? **<u>If</u> they struggle to answer, ask:** - Who is usually involved in making this decision? (their role in the company) - Would this be a lengthy process if you would like to change the type of cement you use? @Do you take into account environmental sustainability in your decision making process?	What criteria did you take into account when choosing the house you are currently living in? What are the most important factors that you consider in choosing the products when building/renovating your house? -Except for [their answer], what other factors do you take into account? Can you guide me through your decision-making process when deciding which products/materials you choose to use for the construction of your house? - Who is involved? (Was the architect involved? Contractor?) - Where or from whom would you seek information? - How long does it usually take you to make these decisions?
Environmental behaviour	
How do you define environmental sustainability? In what ways does your company affect or is affected by environmental issues? - How do you see your company's environmental	What comes to your mind when you hear the term 'environmental sustainability'? In your opinion, what are the major current environmental issues?

impact? [if they don't mention the product (cement/concrete), ask them specifically about the impact of their products] - How do you see the environmental impacts of your company in comparison to other companies in your sector? - How do you see the environmental impacts of the entire concrete and cement industry? Do you see any changes in the demand for more environmentally sustainable products in the market? - Where do you see the role of price in this? In your opinion, what can be done to tackle or deal with [above-mentioned] impacts? @Are actions taken by your company to reduce its impact on the environment? Please explain. - Is it something that you do on your initiative or is it something that you are legally obliged to or feel the pressure to do so? [pressure by who?] E.g., change in legislation or CO_2 tax [If they mention the pressure from other actors, ask: - Is this a fair expectation? - Is it possible?] So far, is there anything holding you back from taking more environmentally sustainable actions? What encourages you to reduce your CO_2 emissions? Where do you see the government's role in this? @Currently, is there any help offered by authorities to become more environmentally sustainable? What kind of help? Is it helpful? How? @Do you have any plans in the future to become a more environmentally sustainable company?	Do you think you and your family are affected or might be affected in the future by any of these environmental issues? - Who is affected? - Who else? (You and/or your children/next generation) - When? (In the (far) future or right now?) - Why do you think that? Who do you see being as most responsible for the current environmental issues? - Are there other actors you think are responsible? - Try to understand their opinion on the magnitude of the impacts of different actors. @If they do not mention consumers, ask: How do you see consumers' role in environmental issues? Who do you consider responsible for tackling these environmental issues? - Do you think that enough action has been taken to solve environmental issues? To what extent do you believe that your purchase or consumption decisions negatively affect environmental issues? - Why is that? - Can you give me some examples of your actions/choices that negatively impact environmental issues? - Have you recently made a decision where considering environmental impacts was a part of your decision? If so, can you explain this in an example (your way of thinking and what product was it)? How often have you come across environmentally friendly options when looking for building materials? Do you consider environmental sustainability when choosing materials/products for building or renovating your house? ↓ Can you give an example?

Why?	Explore their motivation (e.g., saving money, the planet, effects on human health?) - What has mostly held you back? - What has encouraged you? - What will encourage you more? How would you describe the environmental behaviour of the members of your household?
	@Some building materials are claimed to be more environmentally friendly; do you have any idea how/why they are environmentally friendly? - What do you think about these materials? [Just listen to what they say and if they are short ask them why that is?] **If** in the previous section they mentioned that they chose environmentally friendly products, ask: Do you know why … is more environmentally friendly than the traditional form? Have you ever purchased any cement yourself in the last 5 years? Are you aware of the environmental impact of cement production?

Briefly explaining the alternative cement

My research aims to bridge industry and scientists who are working on new types of cementitious binders made with 70-90% industrial by-products. Because they have a flexible process and use different concentrations of various types of industrial by-products, the performance of these	Now, I will talk about the product that is at the core of this research; namely, an alternative to traditional cement. This product is currently under development and has the potential to substitute traditional cement. To give you some background

cements can be modified based on the specific applications and industry demands. This can entail new opportunities in the concrete industry. Because secondary raw materials are used instead of limestone, they preserve raw materials and contribute to the circular economy. In addition, they have the potential to reduce CO_2 emissions during production. Before we go into details about the by-products, based on this brief information, we would like to hear your opinion about this type of alternative cement or, in general, about alternative cementitious binders. (Immediately ask the question below.)	information about the production of cement, there are several points I want to highlight: - A lot of raw materials are used (for the production of 1 ton of cement clinker, 1.7 tons of raw materials such as clay and limestone are needed); - To produce cement, very high temperatures are needed to melt the raw materials (1500 degrees Celsius), which require a significant amount of energy. This results in significant amounts of CO_2 emissions. In order to reduce emissions, this product will use less natural resources as it is made with 70–90% of by-products. These by-products replace natural resources to a certain extent and do not require these tremendous high temperatures; therefore, they contribute to reducing emissions during the production process. The by-products themselves come from different industries. The final result is a new type of cement that has a flexible process and uses different concentrations of various types of industrial by-products, resulting in the cement performance being modified according to its composition. Before we go into details about the by-products, we would like to hear your opinion about this type of alternative cement.

Perception of the product

What are the main criteria that would affect your opinion to consider using these types of new binders in your production? -[Mechanical properties, Sustainability Regulation? Standards] -Whose approval of this product would matter to you? (Scientists, government, major companies, experts in your company, concrete federation, etc.) **<u>If</u>** they were **negative** towards this alternative cement, ask: Under what circumstances might it be worthwhile for your company to switch to cement? **OR** Do you think you may consider this in the future? What may change in the future? Do you think contractors and architects will be in favour of or against this product?	What are your thoughts on this product? What criteria in this cement would matter to you if you were to consider it when building your house? -What other criteria will you consider in making this decision (price, quality, safety, etc.)? -What [else] might hold you back? [Why do you think ... might be a problem?] -What [else] might encourage you? Whose approval of this product do you take into consideration? (Scientists, government, construction companies, producers, family/friends) - **If** they are **unsure**: If this type of cement is used in most newly built houses, will you be more open to this product? Why?

<table>
<tr><td>- What about the public?

What types of companies do you expect would buy/use this product?

Will the actions of other companies influence yours?</td><td>- If they are negative:

Do you think your opinion might change in the future? Why?</td></tr>
<tr><td>As mentioned earlier, this cement can be made with various industrial by-products, some of which you might be familiar with, such as metal slag (e.g., copper slag) and phosphogypsum (a by-product in the phosphorus fertiliser industry).

Similar to some other by-products that are currently being used, such as fly ash, the enhanced level of natural radioactivity of these by-products adds to the importance of recycling them; for example, using them in cementitious binders.

The goals in developing these new types of cementitious binders are to become closer to carbon neutrality and to improve the mechanical properties of these binders. Of course, it is not possible to have all beneficial properties at the same time. As previously mentioned, the properties and environmental profile would vary depending on the configuration.</td><td>As I mentioned earlier, this cement can be made with various industrial by-products; some have already been used in lower quantities in cement production.

Similar to some other by-products that are currently being used in the cement/concrete

production, the radioactivity of these by-products adds to the importance of recycling

them.

The goal of developing these new types of cement is not only the environmental aspects such as reducing CO_2 emissions, depletion of raw material and recycling by-products, but also improving the mechanical properties of cement. Of course, it is not possible to have all beneficial properties at the same time. As I mentioned, the mechanical properties and the environmental profile would vary depending on the configuration.</td></tr>
<tr><td colspan="2">Ask the same questions in the previous section

Given the information that you now have, what are your thoughts about this product?</td></tr>
</table>

+ Finally ask these:	+ Finally, ask these:
@What do you think of the fact that the by-products used in these cementitious binders have enhanced levels of radioactivity? Who do you think will be most concerned about the radioactivity of the by-products used in this alternative binder? (Contractors, home-owners, government, workers, producers?)	What is your opinion on radiation? What comes to mind if you hear the word 'radiation'? Are you aware of being exposed to radiation in your everyday life? - Can you give me examples of types of radiation? Do you expect any risks related to the radioactivity of the residues used to produce this cement? Can you explain this further? - If yes: Who will be the most at risk? Can you explain this further, with an example?

<u>If</u> there are questions that you didn't have a chance to cover, ask:

This covers most of what we needed to know, but there are a couple of specific questions that I want to ask before we finish.

We have covered everything. We are just at the beginning of this research and would be interested in hearing if you have any thoughts about what you think would be interesting for us to pursue, kind of angles, or questions. It can be challenging to find the right company and the right person in that company to talk to. I was wondering if there is anyone specific that you think it would be beneficial for us to talk to? Thank you again for your time. I ensure that your data will be kept strictly confidential.	We have covered everything. We are just at the beginning of this research and would be really interested to hear if you have any thoughts about what you think would be interesting for me to pursue, kind of angles, or questions. Thank you again for participating. I ensure that your data will be kept strictly confidential.

@: This symbol means that this question might have been covered in the previous answer

2.3 Appendix C

Questionnaire

S1: Language of the questions 1.English 2.Dutch 3.French 4.Slovenian 5.Czech		
BX1	Have you built or renovated your dwelling in the past 10 years? Instruction: {If answer is No = End the survey}	• No • Yes, I am currently building or renovating my dwelling • Yes, I built my dwelling • Yes, I renovated my dwelling • Yes, I built and renovated my dwelling
BX2	Please specify how many years ago it was.	Instruction: {Drop down menu from 0 (currently building or renovating) to 10 years ago}
BX3	When choosing building materials, to what extent did you consider their sustainability (e.g., environmental friendliness)?	1.Not at all 7.Very much 1 | 2 | 3 | 4 | 5 | 6 | 7

Introductory text

We want to tell you about a new kind of cement that's being developed. While regular cement is a significant source of CO_2 emissions, which harm the environment, this new kind of cement is made using leftover materials from different industries. The reuse of this material not only helps the environment by reducing CO_2 emissions but also saves raw materials.

Our study is looking at the cement made with these leftover materials. These materials might have some radioactivity[?] but, they can be used safely to make cement. The safety of the final cement will be ensured by checking that the radioactivity is below the established safety standards.

? These materials are referred to as naturally occurring radioactive material (NORM). Certain industrial activities can increase the potential for human exposure to the NORM radionuclides, sometimes generating residues or wastes with radionuclide concentrations above natural background levels.

To what extent would the usage of this new type of cement in your dwelling evoke the following feelings in you?		
	Instruction: {randomise}	1.Not at all 7.Very much
AHN1	Doubt	
AHN2	Worry	
AHN3	Aversion	
	Hope	
AHP1	Interest	
AHP2	Curiosity	
AHP3		

1	2	3	4	5	6	7

PX1	To what extent have you heard about dwellings built with similar cement that is made from leftover materials?	1.Not at all 7.Very much 1 | 2 | 3 | 4 | 5 | 6 | 7
Instruction: {FILTER: PX1 = 2 - 7: ask PX2 & PX3}		
Navodilo: {FILTER: PX1 = 2 - 7: vprašaj PX2 & PX3}		
PX2	Can you please describe in a few words what you have heard about these types of cements? Instruction: {insert answer box and don't auto forward. **Don't force response**; allow them to go to **next** question even if they did not provide an answer}	
PX3	Do you know individuals who live or have lived in dwellings constructed with these types of cement?	• I don't know about any such cases. • I do not personally know anyone, but I have heard of such cases. • I personally know someone.

[redacted]		

	Please tell us to what extent you agree or disagree with the usage of this new type of cement for the following purposes: Instruction: {randomise}	1.Strongly Disagree 2.Disagree 3.Somewhat Disagree 4.Neither Agree, nor Disagree 5.Somewhat Agree 6.Agree 7.Strongly Agree
A1	-Public utility facilities (e.g, roads, bridges, and sewages)	
A2	-Governmental buildings (e.g., government offices and courts)	
A3	-Educational buildings (e.g., daycares, schools, and universities)	
A4	-Workplaces (e.g., offices and factories)	
A5	-Healthcare facilities (e.g., hospitals and care homes)	
A6	-Leisure facilities (e.g., fitness centres and cinemas)	
A7	-Dwellings (e.g., houses and apartments)	
A8	-Private outdoor spaces of the dwellings (e.g., garage and garden walls/paths)	
[redacted]		

IN1	How likely would you be to use this cement if building or renovating your house again?	1.Extremely Unlikely 7.Extremely Likely						
		1	2	3	4	5	6	7
[redacted]								

PGB1	Please tell us how do you see the benefits of the usage of this new type of cement for (1) yourself (2) society as a whole (3) the environment	1.Not at all 7.Extremely High						
		1	2	3	4	5	6	7

PGB2 PGB3		

Please tell us to what extent you agree or disagree with the following statements regarding the financial advantages and disadvantages of usage of new cement.		
	I **think** if I use this new type of cement instead of traditional cement, I would Instruction: {randomise}	1. Strongly Disagree 2.Disagree 3.Somewhat Disagree 4.Neither Agree, nor Disagree 5.Somewhat Agree 6.Agree 7.Strongly Agree
FB1	-increase the resale value for my dwelling	
FB2	-benefit from government incentives (e.g., tax reduction)	
FB3	-save money due to energy efficiency (e.g., less water or energy consumption)	
FR1	-have to pay higher price	
FR2	-face higher maintenance costs	
FR3	-exceed my budget	

Please indicate the extent to which you agree or disagree with the following statements regarding the quality and performance of using the new cement.		
	In comparison to traditional cement, I **think** this new cement would Instruction: {randomise}	1.Strongly Disagree 2.Disagree 3.Somewhat Disagree 4.Neither Agree, nor Disagree 5.Somewhat Agree 6.Agree 7.Strongly Agree
PB1	-be ready to use quicker	
PB2	-be easier to process	

PB3	-have better quality	
PR1	-require the use of radiation protective equipment when working with it	
PR2	-be less compatible with other materials	
PR3	-be more complicated to work with	
PR4	-require special treatment	
[redacted]		
	I **think** if a dwelling is built with this new type of cement instead of traditional one, {instruction: randomise}	1.Strongly Disagree 2.Disagree 3.Somewhat Disagree 4.Neither Agree, nor Disagree 5.Somewhat Agree 6.Agree 7.Strongly Agree
PR6	-the walls will crack sooner	
PR7	-the colour of the walls will change over time	
PR8	-walls will be damaged sooner under severe weather conditions	
PR9	-the building will be functional for a longer period of time	
[redacted]		

Please tell us to what extent you agree or disagree with the following statements regarding the environmental benefits of the usage of new cement.		
	In comparison to traditional cement, I **think** this new cement would Instruction: {randomise}	1.Strongly Disagree 2.Disagree 3.Somewhat Disagree 4.Neither Agree, nor Disagree 5.Somewhat Agree 6.Agree
EB1	-release less CO_2	
EB2	-prevent waste from going to landfills	

EB3	-use less raw material	7.Strongly Agree
[redacted]		

In the following questions, we will ask for your opinion specifically on the potential health-related risks associated with the usage of the new type of cement. Click '**Next**' to continue.

Please tell us to what extent you agree or disagree with the following statements.		
HR1 HR2 HR3	Instruction: {randomise} I **believe** that the usage of the new type of cement in dwellings involves risks to **my** health The usage of this new type of cement in dwellings involves risks for the **residents'** health. I **think** that the radioactivity of the reused material used in the new type of cement is harmful to **my** health.	1.Strongly Disagree 2.Disagree 3.Somewhat Disagree 4.Neither Agree, nor Disagree 5.Somewhat Agree 6.Agree 7.Strongly Agree
[redacted]		

  HR4 HR5 HR6	If dwellings are built with this new type of cement, I think residents will be under the threat of Instruction: {randomize first two} -polluted indoor air -getting cancer -other life-threatening health issues	1.Strongly Disagree 2.Disagree 3.Somewhat Disagree 4.Neither Agree, nor Disagree 5.Somewhat Agree 6.Agree 7.Strongly Agree
[redacted]		
	How do you perceive the health risks associated with the usage	1.Not at all

	of the new type of cement for the following: Instruction: {randomise}	7.Extremely High 1 | 2 | 3 | 4 | 5 | 6 | 7
HR8	-Public utility facilities (e.g., roads, bridges, and sewages)	
HR9	-Governmental buildings (e.g., government offices and courts)	
HR10	-Educational buildings (e.g., daycares, schools, and universities)	
HR11	-Workplaces (e.g., offices and factories)	
HR12	-Healthcare facilities (e.g., hospitals and care homes)	
HR13	-Leisure facilities (e.g., fitness centres and cinemas)	
HR14	-Dwellings (e.g., houses and apartments)	
HR15	-Private outdoor spaces of the dwellings (e.g., garage and garden walls/paths)	
[redacted]		

For the following questions, please drag the bar to indicate your response ranging from 1 to 7.		
RC_K1 RC_K2 RC_K3	To what extent do you think the potential health risks regarding the usage of this cement are known to the following entities? -Those exposed to them -Science -Regulatory authorities	1.Completely unknown 7.Completely known 1 | 2 | 3 | 4 | 5 | 6 | 7

RC_N	Do you think that potential health risks from the usage of this cement are new risk (novel) or old risk (familiar)?	1.Completely new (novel) 7.Very old (familiar) 1 2 3 4 5 6 7

RC_I	Do you think that the effects of potential health risks associated with the usage of this cement are immediate, or on a very long-term?	1.Immediate 7.Very long-term 1 2 3 4 5 6 7

RC_T	To what extent do you believe that the usage of this cement in dwellings would be a health threat to the well-being of children and future generations?	1.No Threat 7.Very Serious Threat 1 2 3 4 5 6 7

RC_D	Is the health risk related to the usage of this cement something that people can think about calmly, or is it one that people have great dread of.	1.Calmly 7.Dread 1 2 3 4 5 6 7

RC_S	In your opinion, how severe would the health threat be if this new cement is used in dwellings?	1.Not severe at all 7.Very Severe 1 2 3 4 5 6 7

RC_C	To what extent do you think it would be possible to have control over the negative consequences of the usage of this cement?	1.Not at all Controllable 7.Completely Controllable 1 2 3 4 5 6 7

RC_O	In the event of any adverse health outcomes resulting from the use of this cement, how observable do you think the consequences will be?	1.Not Observable 7.Very well observable 1 | 2 | 3 | 4 | 5 | 6 | 7

Please tell us if you agree or disagree with the following statements regarding the entities listed below:			
	T_C_	T_I_	
	I feel confident that the below entities are **competent** to properly **assess** risks and benefits related to this new type of cement.	I feel confident that the below entities **disclose information** including both advantages and disadvantages of this new type of cement.	1.Strongly Disagree 2.Disagree 3.Somewhat Disagree 4.Neither Agree, nor Disagree 5.Somewhat Agree 6.Agree 7.Strongly Agree
a) Regulatory authorities			
b) Independent research institutions			
c) Scientists from universities			
d) Cement manufacturers			
e) Construction companies			
f) Architects			

[redacted]

IN3a IN3b IN3c	How likely are you to use this cement when building or renovating your dwelling, assuming this material has been used in construction for … ? -less than 10 years -25 years -50 years	1.Extremely Unlikely 7.Extremely Likely 1 | 2 | 3 | 4 | 5 | 6 | 7
[redacted]		
IN4	How likely are you to use this cement if building or renovating your dwelling assuming this material has been used in other countries with high regulatory control levels regarding the product standards?	1.Extremely Unlikely 7.Extremely Likely 1 | 2 | 3 | 4 | 5 | 6 | 7
[redacted]		

S2	What best describes your gender?	• Male • Female • Other • I prefer not to say
[redacted]		
S4	In what year were you born?	[year] Instruction: {drop down menu from 1940 to 2006}

S5	What is your highest level of education or training?	• Primary school leaving certificate • High school/high school diploma • Degree • Postgraduate • Ph.D
DWEL3	In what type of dwelling do you live?	• Studio/Apartment • Detached House • Semi-detached House • Terraced House • Other
S8_N	Do you have any children under 18 in your household?	• Yes • No
FW	Which of these phrases comes closest to describing your feelings about your household's income these days?	1.Living Very comfortably. 2.Living comfortably. 3.Getting by. 4.Finding it difficult 5. Finding it Very difficult. • Prefer not to say

SK	How confident are you in your knowledge related to radioactivity?	1. Not at all confident 7. Highly confident 1 | 2 | 3 | 4 | 5 | 6 | 7

Please tell us if you agree or disagree with the following statements.		
OK1	The human body is naturally radioactive.	• Agree • Disagree • Don't know
OK2	With time, every radioactive substance becomes more and more radioactive.	
OK3	Naturally occurring radioactive elements are present in varying concentrations in the Earth's crust.	
OK4	Radioactivity of the building material depends on the origin of soil used in construction.	
OK5	Radioactivity can be measured only with the special equipment.	

Thank you so much for taking the time to complete our survey. Your valuable insights contribute significantly to our understanding, and we appreciate your thoughtful responses.

OQ2	If you have any further comments or suggestions, please feel free to share them with us.

Formative measurement model evaluation separate for each country

Belgium

	Weights	loadings	t value	P values	5.0%	95.0%	VIF
AHN1	0.387	0.857	2.228	0.013	0.126	0.695	1.843
AHN2	0.604	0.942	3.553	0.000	0.327	0.876	2.009
AHN3	0.163	0.609	0.899	0.184	-0.168	0.433	1.321

AHP1	0.315	0.855	2.686	0.004	0.124	0.511	2.152
AHP2	0.432	0.936	3.326	0.000	0.207	0.635	3.073
AHP3	0.367	0.888	2.914	0.002	0.174	0.590	2.384
FB1	0.452	0.809	4.670	0.000	0.282	0.603	1.401
FB2	0.214	0.631	2.295	0.011	0.057	0.362	1.299
FB3	0.576	0.867	6.479	0.000	0.423	0.719	1.344
FR1	0.639	0.916	1.251	0.106	-0.071	1.247	1.582
FR2	0.298	0.662	0.444	0.329	-0.948	1.074	1.277
FR3	0.277	0.787	0.528	0.299	-0.569	1.126	1.688
HR1	0.348	0.939	40.822	0.000	0.334	0.362	3.931
HR2	0.365	0.934	39.219	0.000	0.352	0.382	3.572
HR3	0.356	0.931	45.720	0.000	0.344	0.369	3.516
IN1	0.619	0.937	26.483	0.000	0.586	0.664	1.823
IN2	0.473	0.889	26.324	0.000	0.439	0.498	1.823
PB1	-0.006	0.652	0.059	0.477	-0.190	0.168	1.972
PB2	0.190	0.701	1.554	0.060	-0.006	0.393	1.884
PB3	0.881	0.988	10.064	0.000	0.725	1.011	1.772
PR1	0.567	0.699	3.542	0.000	0.320	0.830	1.513
PR2	0.133	0.589	0.766	0.222	-0.154	0.419	1.625
PR3	-0.158	0.423	0.993	0.160	-0.433	0.091	1.628
PR4	0.105	0.537	0.586	0.279	-0.195	0.385	1.623
PR6	0.356	0.710	1.898	0.029	0.060	0.664	2.676
PR7	-0.180	0.539	1.079	0.140	-0.469	0.084	2.310
PR8	0.515	0.738	3.186	0.001	0.276	0.807	2.300
RC_D	0.104	0.748	1.373	0.085	-0.009	0.242	2.098
RC_I	0.224	0.326	1.302	0.096	-0.043	0.519	1.047

RC_S	0.408	0.920	3.539	0.000	0.216	0.598	3.209
RC_T	0.485	0.930	4.566	0.000	0.307	0.656	2.711
RC_C	0.193	0.494	2.854	0.002	0.083	0.308	1.208
RC_K1	0.479	0.779	2.268	0.012	0.124	0.811	1.385
RC_K2	-0.436	0.066	1.852	0.032	-0.836	-0.074	2.084
RC_K3	0.438	0.511	1.627	0.052	-0.011	0.876	2.457
RC_N	0.480	0.746	2.439	0.007	0.179	0.801	1.268
RC_O	-0.005	-0.136	0.089	0.465	-0.095	0.085	1.131

Czechia

	Weights	loadings	t value	P values	5.0%	95.0%	VIF
AHN1	0.420	0.912	3.456	0.000	0.221	0.622	2.569
AHN2	0.311	0.880	2.560	0.005	0.118	0.517	2.505
AHN3	0.393	0.873	3.605	0.000	0.215	0.570	1.977
AHP1	0.468	0.893	4.982	0.000	0.314	0.624	1.915
AHP2	0.601	0.939	5.855	0.000	0.422	0.764	2.856
AHP3	0.024	0.739	0.237	0.406	-0.145	0.189	2.270
FB1	0.587	0.861	5.421	0.000	0.400	0.759	1.328
FB2	0.103	0.632	0.768	0.221	-0.114	0.325	1.505
FB3	0.515	0.833	4.333	0.000	0.314	0.700	1.542
FR1	0.282	0.504	0.862	0.194	-0.298	0.762	2.335
FR2	-0.848	-0.382	1.396	0.081	-1.073	-0.520	1.277
FR3	0.809	0.660	1.568	0.059	-0.126	1.264	2.277
HR1	0.354	0.971	58.916	0.000	0.345	0.365	8.684
HR2	0.356	0.972	58.086	0.000	0.347	0.367	8.808

HR3	0.329	0.945	46.863	0.000	0.315	0.338	4.554
IN1	0.668	0.927	26.447	0.000	0.630	0.713	1.481
IN2	0.455	0.836	24.523	0.000	0.420	0.482	1.481
PB1	0.256	0.624	2.244	0.012	0.075	0.446	1.814
PB2	-0.069	0.578	0.598	0.275	-0.261	0.115	1.995
PB3	0.898	0.979	13.251	0.000	0.784	1.000	1.439
PGB3	1.000	1.000	n/a	n/a	1.000	1.000	1.000
PR1	0.895	0.864	7.149	0.000	0.728	1.116	1.631
PR2	-0.010	0.337	0.063	0.475	-0.269	0.249	1.671
PR3	-0.329	0.253	1.947	0.026	-0.628	-0.070	1.904
PR4	-0.081	0.358	0.417	0.338	-0.419	0.232	1.790
PR6	0.335	0.646	1.623	0.052	-0.002	0.686	3.672
PR7	-0.232	0.462	1.307	0.096	-0.537	0.054	2.227
PR8	0.356	0.656	1.537	0.062	-0.027	0.732	3.561
RC_D	0.132	0.662	2.408	0.008	0.042	0.224	1.534
RC_I	0.769	0.813	2.109	0.017	0.541	1.020	1.089
RC_S	0.532	0.955	6.448	0.000	0.397	0.663	3.260
RC_T	0.370	0.921	4.601	0.000	0.242	0.505	3.117
RC_C	0.144	0.421	2.308	0.011	0.051	0.257	1.296
RC_K1	0.067	0.194	0.179	0.429	-0.570	0.674	1.803
RC_K2	-0.132	-0.107	0.419	0.338	-0.639	0.384	1.729
RC_K3	-0.100	0.110	0.258	0.398	-0.726	0.526	1.842
RC_N	0.611	0.586	1.730	0.042	0.162	0.971	1.165
RC_O	-0.040	-0.082	0.847	0.198	-0.116	0.038	1.189

Slovenia

	Weights	loadings	t value	P values	5.0%	95.0%	VIF
AHN1	0.451	0.917	3.486	0.000	0.242	0.664	2.570
AHN2	0.207	0.863	1.659	0.049	-0.013	0.401	2.695
AHN3	0.448	0.910	3.853	0.000	0.255	0.634	2.332
AHP1	0.449	0.900	4.295	0.000	0.269	0.615	2.071
AHP2	0.467	0.929	4.060	0.000	0.272	0.648	3.020
AHP3	0.192	0.848	1.518	0.065	-0.005	0.407	2.696
FB1	0.507	0.898	5.836	0.000	0.361	0.652	2.007
FB2	-0.033	0.648	0.368	0.357	-0.191	0.105	1.800
FB3	0.609	0.930	6.529	0.000	0.450	0.754	2.145
FR1	0.782	0.785	4.710	0.000	0.519	1.027	1.705
FR2	-0.713	-0.020	3.867	0.000	-1.005	-0.440	1.512
FR3	0.567	0.657	2.988	0.001	0.251	0.866	1.869
HR1	0.355	0.973	75.129	0.000	0.348	0.364	8.450
HR2	0.345	0.962	57.743	0.000	0.337	0.356	6.663
HR3	0.338	0.952	64.456	0.000	0.330	0.347	5.186
IN1	0.569	0.946	47.689	0.000	0.552	0.592	2.360
IN2	0.497	0.929	58.213	0.000	0.483	0.511	2.360
PB1	0.030	0.774	0.226	0.411	-0.187	0.253	2.711
PB2	0.335	0.879	2.700	0.003	0.130	0.541	3.149
PB3	0.702	0.971	5.977	0.000	0.498	0.883	2.389
PR1	0.636	0.828	4.246	0.000	0.409	0.879	1.551
PR2	-0.193	0.265	1.127	0.130	-0.480	0.072	1.827
PR3	-0.258	0.314	1.666	0.048	-0.530	-0.024	1.882

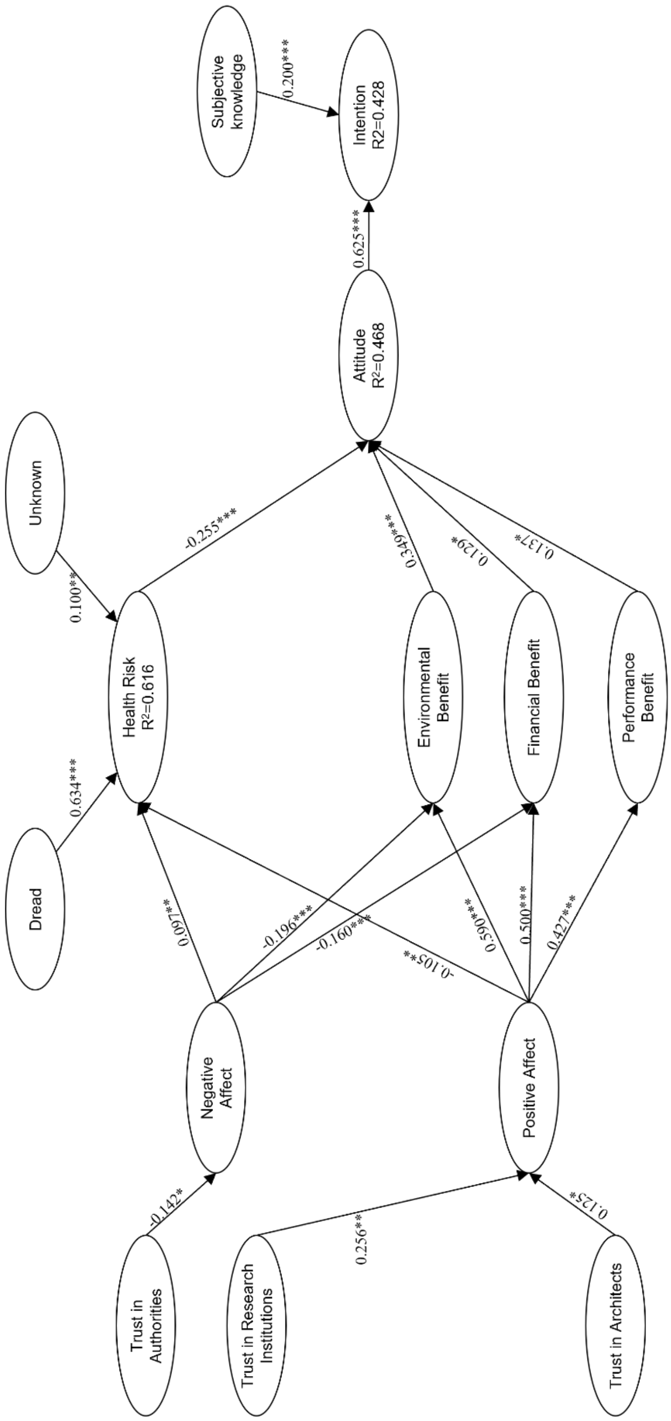
PR4	0.439	0.667	2.835	0.002	0.193	0.711	1.810
PR6	0.204	0.584	1.070	0.142	-0.087	0.549	3.462
PR7	-0.155	0.420	0.801	0.212	-0.487	0.146	2.569
PR8	0.423	0.611	2.007	0.022	0.110	0.801	3.596
RC_D	0.142	0.883	1.836	0.033	0.019	0.273	3.784
RC_I	0.476	0.541	2.811	0.002	0.212	0.753	1.061
RC_S	0.558	0.976	6.283	0.000	0.409	0.703	5.064
RC_T	0.305	0.935	3.523	0.000	0.160	0.444	4.516
RC_C	0.082	0.538	1.661	0.048	0.001	0.164	1.324
RC_K1	0.451	0.679	2.303	0.011	0.158	0.785	1.447
RC_K2	-0.110	0.150	0.514	0.304	-0.467	0.235	1.614
RC_K3	0.072	0.365	0.306	0.380	-0.310	0.466	1.832
RC_N	0.585	0.728	3.462	0.000	0.315	0.839	1.151
RC_O	0.000	-0.670	0.002	0.499	-0.108	0.100	1.907

Variance inflation factor (VIF) for total sample and each country

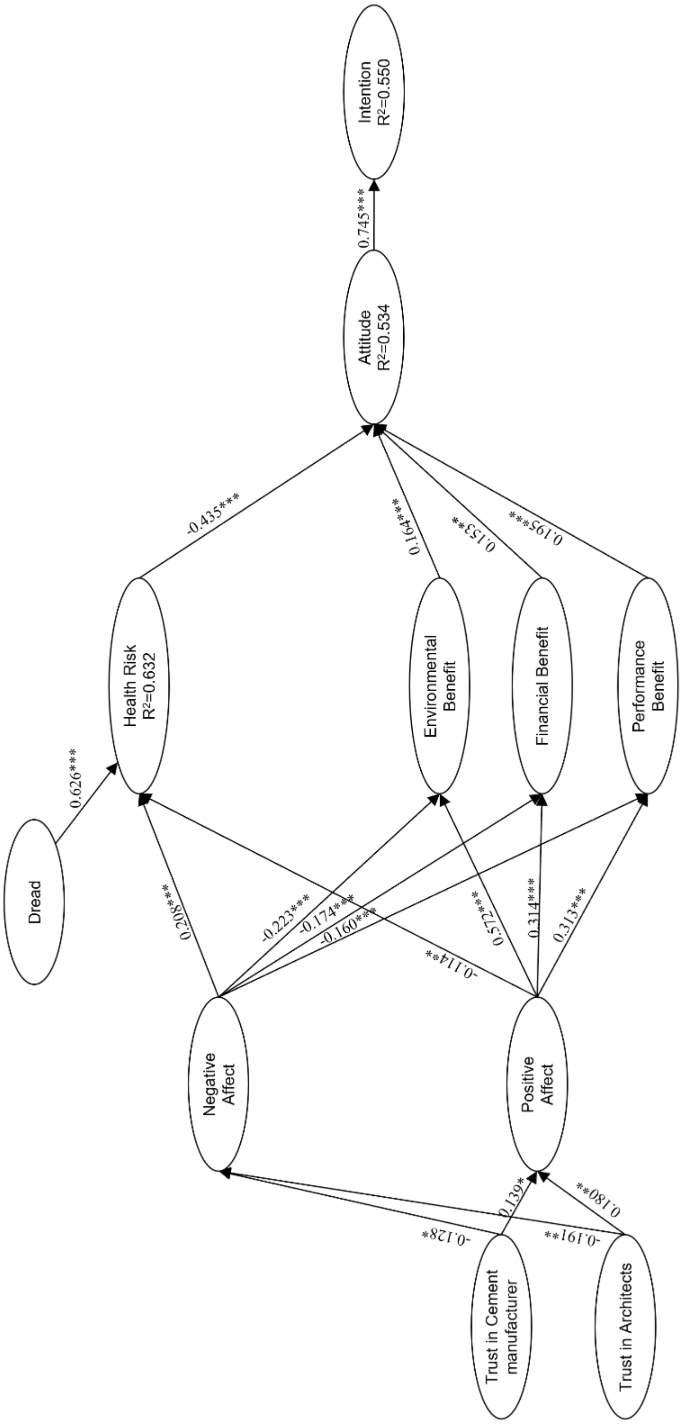
	Total Sample	Belgium	Czechia	Slovenia
	VIF	**VIF**	**VIF**	**VIF**
Attitude -> Intention	1.000	1.016	1.000	1.000
Dread -> Health Risk	1.595	1.341	1.488	1.881
Environmental Benefits -> Attitude	1.557	1.464	1.501	1.767
Financial Benefits -> Attitude	1.867	2.004	1.444	2.256
Financial Risk -> Attitude	1.052	1.161	1.067	1.105
Health Risk -> Attitude	1.746	1.701	1.697	1.883
Unknown -> Health Risk	1.120	1.081	1.076	1.197
Negative Affect -> Environmental Benefits	1.058	1.023	1.106	1.174
Negative Affect -> Financial Benefits	1.058	1.023	1.106	1.174
Negative Affect -> Financial Risk	1.058	1.023	1.106	1.174
Negative Affect -> Health Risk	1.404	1.226	1.366	1.676
Negative Affect -> Performance Benefits	1.058	1.023	1.106	1.174
Negative Affect -> Performance Risk	1.058	1.023	1.106	1.174
Objective knowledge -> Intention	1.000	1.016	1.000	1.000
Performance Benefits -> Attitude	1.789	1.916	1.501	2.059
Performance Risk -> Attitude	1.460	1.663	1.468	1.445
Positive Affect -> Environmental Benefits	1.058	1.023	1.106	1.174
Positive Affect -> Financial Benefits	1.058	1.023	1.106	1.174
Positive Affect -> Financial Risk	1.058	1.023	1.106	1.174
Positive Affect -> Health Risk	1.122	1.071	1.173	1.239
Positive Affect -> Performance Benefits	1.058	1.023	1.106	1.174
Positive Affect -> Performance Risk	1.058	1.023	1.106	1.174
Trust Scientists -> Negative Affect	3.618	4.178	3.414	3.601
Trust Scientists -> Positive Affect	3.618	4.178	3.414	3.601
Trust architects -> Negative Affect	2.511	2.398	2.126	3.224

Trust architects -> Positive Affect	2.511	2.398	2.126	3.224
Trust authorities -> Negative Affect	2.056	2.087	1.692	2.868
Trust authorities -> Positive Affect	2.056	2.087	1.692	2.868
Trust cement manufacturers -> Negative Affect	2.175	2.170	1.836	2.811
Trust cement manufacturers -> Positive Affect	2.175	2.170	1.836	2.811
Trust independent R I -> Negative Affect	3.679	4.513	3.411	3.861
Trust independent R I -> Positive Affect	3.679	4.513	3.411	3.861

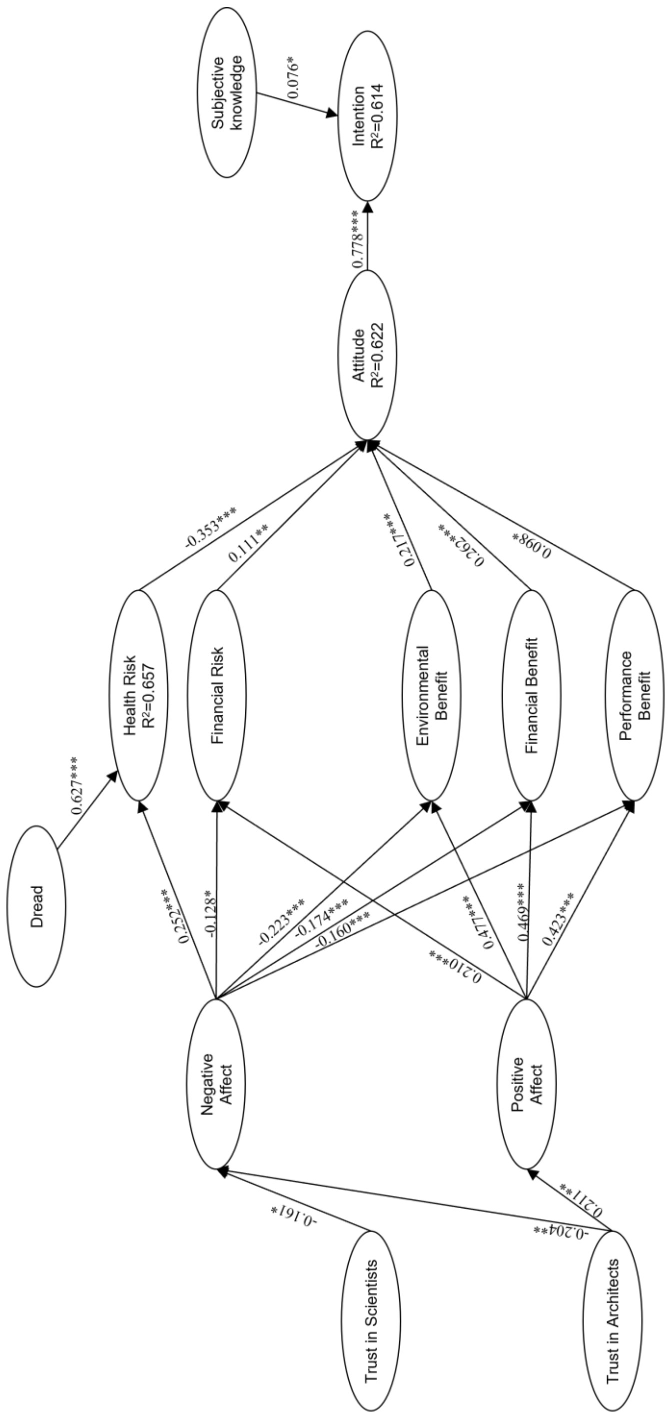
Structural model with significant path coefficients for each country for Belgium



Structural model with significant path coefficients for each country for Czechia



Structural model with significant path coefficients for each country for Slovenia


Subjective knowledge
0.076*
Intention R²=0.614
0.778***
Attitude R²=0.622
-0.353***
0.111**
0.217***
0.262***
0.098*
Health Risk R²=0.657
Financial Risk
Environmental Benefit
Financial Benefit
Performance Benefit
0.627***
Dread
0.252***
-0.128*
-0.223***
-0.174***
-0.160***
0.210***
0.477***
0.469***
0.423***
Negative Affect
Positive Affect
-0.161*
-0.204**
0.211**
Trust in Scientists
Trust in Architects