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Algeopolymers

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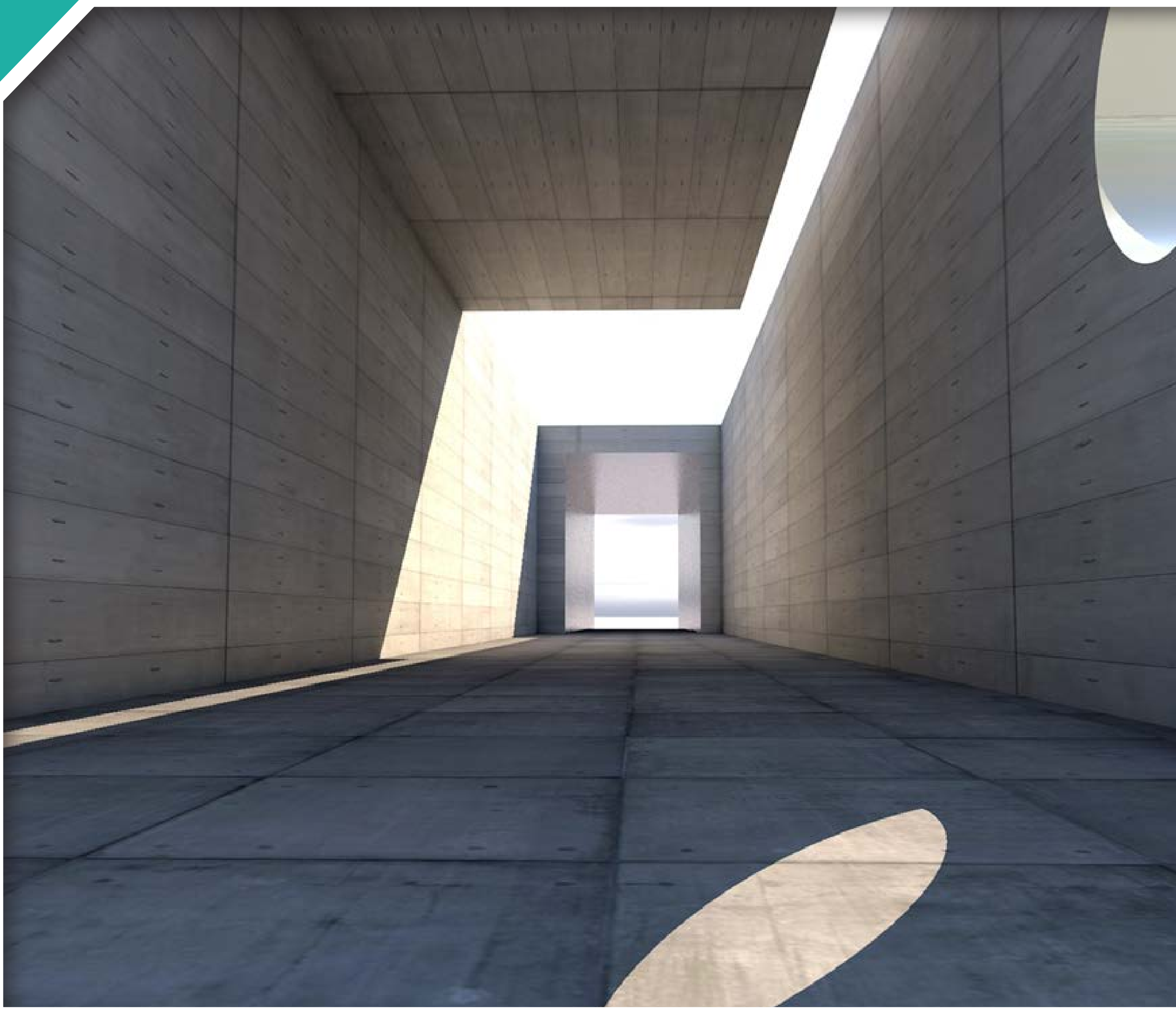

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Government of Ireland

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- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

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EPA RESEARCH PROGRAMME 2014–2020

Algeopolymers

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EPA Research Report

Prepared for the Environmental Protection Agency

by

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The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

Concrete is the second most widely used material in the world and is made of cement, sand and aggregates. Cement is a hydraulic binder that reacts with water to form a solid material. Cement manufacture requires high temperatures and produces substantial CO_2 emissions. The principal cement types (ordinary Portland cement, OPC) manufactured in Ireland are (1) CEM I – OPC; (2) CEM II/A – OPC-fly ash cement; (3) CEM II/A – OPC-limestone cement; and (4) CEM III/A – OPC-ground granulated blast furnace slag (GGBS). The production of eco-efficient blended cements (CEM II, CEM III) reduces CO_2 emissions and improves energy efficiency compared with unblended cements (CEM I).

However, a new class of materials called geopolymers has potential construction applications and produces much lower CO_2 emissions. From a terminological point of view, geopolymer cement is a binding system that is able to harden at room temperature. Geopolymers utilise the polycondensation of SiO_2 and Al_2O_3 precursors to achieve a superior strength level. Geopolymer materials are usually synthesised using an aluminosilicate raw material and an activating solution, which is mainly composed of NaOH or KOH and Na_2SiO_3.

This desk-based study focused on a state-of-the-art review related to geopolymers, including a technology overview. The objective of the research was to investigate the potential for Irish wastes (fly ash, bauxite residues, etc.) to be used in geopolymer applications and the opportunities for these geopolymer applications within Ireland.

The key findings from the literature review indicated that geopolymers are manufactured from natural raw materials such as kaolin but also waste materials including fly ash and GGBS, which are already accepted as blending materials in traditional cement. Novel approaches using liquid-crystal display glass, electroplating sludge, waste incineration residue, waste glass, electric arc furnace dust and their mixtures with fly ash have also been tested. Bauxite residue waste has also been utilised in geopolymers; however, in this case the waste is usually blended with fly ash and incorporated at a maximum of 15% weight. Alternative methods to incorporate higher amounts of bauxite residue involve high-temperature heat treatments.

In order to gain an insight into the state-of-the-art applications of geopolymers that are commercially available within the market and the extent of incorporated waste materials as core ingredients, a survey of relevant stakeholders was undertaken, including the geopolymer, cement and alumina sectors, as well as research and academic organisations. The findings highlighted that geopolymers based on natural materials are commercially available and focused on niche markets such as precast, foams and mortar applications, and often form part of the product portfolio for large multinational construction companies, with small and medium-sized enterprises and start-ups more focused on novel compositions of geopolymers incorporating various wastes and at various technology readiness levels. The survey also highlighted that much of the research is focused on technology development and the incorporation of wastes; however, the barriers to market were perceived to be lack of legislation approval and acceptance rather than technological challenges. Increasing the market penetration of geopolymers in general remains a challenge, in addition to the incorporation of waste materials, because of the issue of approval and acceptance, with clear standards regarding the new types of cement materials not available.

A national stakeholder workshop was held to explore the potential use of Irish wastes in geopolymer and cement applications. The traditional cement sector views geopolymers as a potential disruptive technology that is in competition with traditional cement. However, because of a lack of standards and acceptance for structural applications, geopolymers are currently limited to niche markets, as already described. The workshop therefore took a two-pronged approach, investigating the short-term potential for the blending of wastes as supplementary cementitious materials (SCMs) into traditional cements and the long-term potential for the incorporation of wastes into geopolymer applications.

It was found that a driving force for the incorporation of SCMs (waste to energy fly ash, biomass fly ash, bauxite residue) into cements included the potential limited future supply of coal power plant fly ash, which is traditionally used to manufacture CEM II products with a reduced carbon footprint. The longer term potential of geopolymers in the market faces two challenges: (1) the lack of acceptance and standards for the use of geopolymers in widespread structural applications and (2) the lack of standards regarding the incorporation of wastes into such materials. A roadmap for the future exploration of the incorporation of Irish wastes into geopolymers and blended cements was proposed, including steps for a drilled-down workshop with Irish industry to share technical information, a feasibility assessment and a test bed for blended Irish waste/cement, to build a case for updating the European standard EN 197-1:2000 to officially sanction the use of these wastes in cement applications. This would be followed by a feasibility assessment of geopolymers based on Irish wastes and engagement with the relevant organisations on standards development, such as the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM, from the name in French) technical committee (the leading academic and commercial practitioners in alkali-activated materials), to advocate for the inclusion of relevant Irish wastes into any such standards being developed in the future.

1 Introduction

Concrete is the second most widely used material in the world and is made of cement, sand and aggregates. Cement is a hydraulic binder that reacts with water to form a solid material. In the cement manufacturing process, the right mix of minerals from mined natural rocks, e.g. limestone, is calcined in a kiln at 1450°C to form a new compound, clinker. In the final stage the clinker is milled into a fine cement powder called ordinary Portland cement (OPC) (CMI, 2018).

Construction of the built environment contributes to a considerable amount of total global greenhouse gas (GHG) emissions and involves the use of natural resources (Mikulčić *et al*., 2016). Cement manufacture requires high temperatures with consequent high energy consumption and emissions (Toniolo and Boccaccini, 2017). The amount of CO_2 released during limestone calcination and fossil fuel combustion is about 1 ton for each ton of cement production (Al Bakri *et al*., 2013; Islam *et al*., 2015). In addition, the global demand is expected to increase because of the rapid infrastructural development of emerging economies (Schneider *et al*., 2011, Benhelal *et al*., 2013). According to the World Business Council for Sustainable Development (WBCSD) report in 2009, global cement production is forecast to reach 3.7–4.4 billion metric tons by 2050 (Schneider *et al*., 2011, Benhelal *et al*., 2013).

On the other hand, cement is the essential ingredient in concrete, which is vital for economic development worldwide. Therefore, the challenge for the global cement industry is to balance the increasing demand for cement with its commitment to continuous improvements and recognition of its responsibility to use resources wisely for the benefit of future generations (CMI, 2018). The three principal levers available to the cement industry to improve the sustainability of cement production and cement products are energy efficiency investments, fossil fuel replacement and clinker replacement (CMI, 2018).

One approach to decarbonising the cement and construction industry is to use supplementary cementitious materials (SCMs) as a component of the cementing binder system. These raw materials typically are slag, silica fume, pozzolans, fly ash, burnt shale and limestone and they are already standardised by European standard EN 197-1:2000. In most cases, clinker is only partially replaced (Hemalatha *et al*., 2016), which can be an approach for the cement industry to decrease CO_2 emissions in the short term (blended cement). In the long term, alternative binders to OPC, such as geopolymers or alkali-activated cements, which are able to harden at room temperature without high temperature treatment, offer an opportunity to use large amounts of wastes as well as minimise the environmental impact (Komnitsas and Zaharaki, 2007; Toniolo and Boccaccini, 2017; Maddalena *et al*., 2018).

Blended cements are produced locally in Ireland and more than 80% of the cement used in Ireland is blended (CMI, 2018). The principal cement types manufactured in Ireland are (1) CEM I – OPC; (2) CEM II/A – OPC-fly ash cement; (3) CEM II/A – OPC-limestone cement; and (4) CEM III/A – OPC-ground granulated blast furnace slag (GGBS) (CMI, 2018). Blended cements are advantageous from a regulatory perspective as the existing standards for OPC can be adapted or built on (Maddalena *et al*., 2018).

Another approach to decarbonising the cement and construction industry is to use geopolymers. Geopolymers, sometimes called alkali-activated binders, are a relatively new class of construction materials (Davidovits, 2008). These alternative binders are usually synthesised using an aluminosilicate raw material, which is mainly composed of SiO_2 and Al_2O_3, and an alkali-activating solution such as NaOH or KOH and Na_2SiO_3 (Duxson *et al*., 2007a). These cements have been discussed as a component of the current and future toolkit of a sustainable cementing binder system over the past few years (Provis, 2017).

Geopolymers are able to harden concrete at room temperature without high temperature treatment, consequently reducing CO_2 emissions; they therefore provide an eco-friendly innovative alternative to cementitious binders (Skvara *et al*., 2006). Geopolymers are well known for their excellent properties compared with OPC, which are the following: high compressive strength, low shrinkage, fast or slow setting, acid resistance, fire resistance and no emissions of toxic fumes, low thermal conductivity, excellent heavy metal immobilisation, high temperature stability and low manufacturing energy consumption for construction purposes and engineering applications (Palomo *et al*., 1999; Duxson *et al*., 2007a,b; Yao *et al*., 2009; Zhang *et al*., 2010; Mao-chieh *et al*., 2012; Burciaga-Díaz *et al*., 2013).

In principle, any waste material containing SiO_2 and Al_2O_3 can serve as a precursor for the production of alternative binders (Ye *et al*., 2014). Fly ash, from coal-pulverised power plants, is the most commonly used by-product (Van Jaarsveld *et al*., 1998; Phair *et al*., 2004; Zhang *et al*., 2008; Nikolići *et al*., 2013; Ogundiran *et al*., 2013; Guo *et al*., 2014), but mine tailings, electric furnace slag and municipal solid waste incineration fly ash have also been investigated (Yunsheng *et al*., 2007; Komnitsas *et al*., 2013; Nikolići *et al*., 2013; Ogundiran *et al*., 2013; Guo *et al*., 2014; Waijarean *et al*., 2014). Further precursors could be waste glasses (Hao *et al*., 2012; Lin *et al*., 2012; Novais *et al*., 2016) or bauxite residue, the by-product of alumina production, as they are Al- and Si-rich materials (Zhang *et al*., 2016). Bauxite residue has been used in combination with other aluminosilicate minerals such as metakaolin and fly ash in research trials (He and Zhang, 2011; He *et al*., 2012; Hajjaji *et al*., 2013; Kumar and Kumar, 2013; Mucsi *et al*., 2015; Kaya and Soyer-Uzun, 2016; Nie *et al*., 2016; Zhang *et al*., 2016).

Overall, the key factor that is likely to determine the likelihood of the uptake and utilisation of geopolymers is the local availability of precursors and activators (Provis, 2017). If geopolymers are part of a sustainable cementing binder, the transport of bulk materials must be minimised (McLellan *et al*., 2011).

The discussion to follow will be focused on a state-of-the-art review of geopolymers, including a technology overview. A review of the existing literature regarding different wastes used in alternative binder applications, including a database with process parameters listed where available, is presented. The objective of this research was to investigate the potential for Irish wastes that are not currently used in practice to be used in the cement industry and to identify the market barriers to adoption. The state of the art of these types of applications was assessed using a survey of relevant stakeholders. The survey questions focused on the state of the art and best practices regarding wastes (e.g. fly ash, mine tailings, bauxite residue) used in alternative binder systems and capturing knowledge of the construction sector alternative binder value chain. The strengths and limitations of geopolymer production were assessed through a national stakeholder workshop with the Irish construction sector and relevant stakeholders using the “Six Thinking Hats” approach and the findings are presented here.

2 Literature Review

2.1 Background of Cement Manufacture

2.1.1 Types of cement

Cements are inorganic materials that exhibit characteristic properties of setting and hardening when mixed to a paste with water. Inorganic cements can be categorised as follows, according to the way that they set and harden: non-hydraulic cements (e.g. lime), which harden only in air and will not harden under water; and hydraulic cements (e.g. OPC), which, when mixed with water, form a paste that sets and hardens by means of hydration reactions and processes and which, after hardening, retain their strength and stability even under water (McArthur and Spalding, 2004). OPC and some other cements based on it are overwhelmingly the dominant hydraulic cements produced today; therefore, the chemistry and mineralogy of OPC will be described in the following overview.

2.1.2 History of OPC

Although the use of cementitious materials in construction is a very ancient practice, the story of modern cement making dates back to the early 19th century and the work of Leeds stonemason Joseph Aspdin, who in 1824 filed the first patent for “Portland” cement. He heated a mixture of finely ground limestone and clay in his kitchen stove and ground the mixture into a powder to create a hydraulic cement that hardens with the addition of water. He named the product OPC because it resembled a stone quarried on the Isle of Portland off the British coast. The cements currently referred to by the same name are technologically more evolved (Costa, 2015).

2.1.3 Chemistry and mineralogy of OPC

Ordinary Portland cement is a finely ground mix of OPC clinker and a small amount (3–7%) of gypsum and/or anhydrite (van Oss, 2005). Tables 2.1 and 2.2 show the typical chemical and mineralogical composition of OPC.

2.1.4 Cement manufacturing process

The best available cement manufacturing technology with the lowest energy consumption is the use of a rotary kiln together with a multi-stage cyclone preheater system and a calciner. Figure 2.1 illustrates the different stages of cement production.

The cement manufacturing process can be divided into two basic steps: clinker production in the kiln at 1450°C followed by grinding clinker with other minerals to produce cement. According to the IEA Cement Technology Roadmap (2009), the following steps are

Table 2.1. Typical chemical composition of OPC

Chemical formula	Cement chemist notation	Percentage by mass in OPC
CaO	C	63.4
SiO_2	S	20.9
Al_2O_3	A	5.7
Fe_2O_3	F	2.9
MgO	M	1.9
$K_2O + Na_2O$	K+N	0.6
Other (incl. SO_3^-)	$\bar{S}$	3.6
H_2O	H	1.0

These mineral formulas are averages.

Source: van Oss (2005).

Table 2.2. Typical mineralogical composition of OPC

Oxide formula	Cement chemist notation	Description	Percentage by mass	Mineral function
$(CaO)_3SiO_2$	C_3S	Tricalcium silicate (alite)	50–70	Hydrates quickly and imparts early strength and set
$(CaO)_2SiO_2$	C_2S	Dicalcium silicate (belite)	10–30	Hydrates slowly and imparts long-term strength
$(CaO)_3Al_2O_3$	C_3A	Tricalcium aluminate	3–13	Hydrates almost instantaneously and very exothermically. Contributes to early strength and set
$(CaO)_4Al_2O_3Fe_2O_3$	C_4AF	Tetracalcium aluminoferrite	5–15	Hydrates quickly. Acts as a flux in clinker manufacture. Imparts grey colour

Source: van Oss (2005).

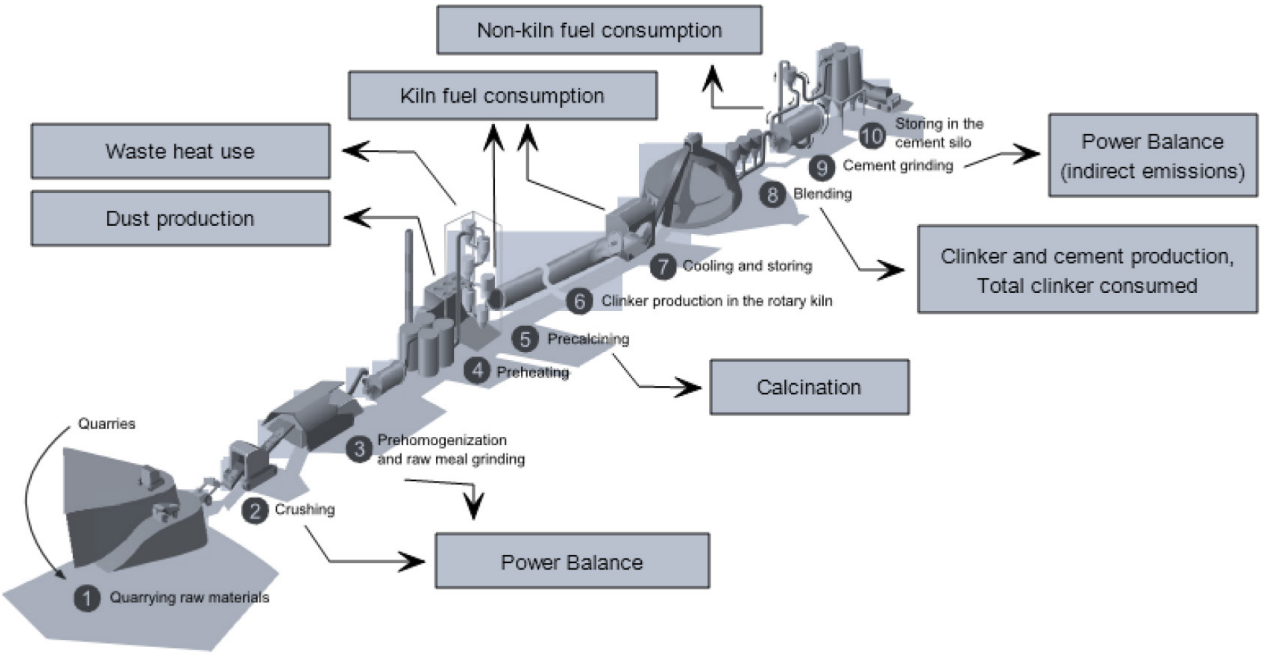

Figure 2.1. The cement manufacturing process. Reproduced from IEA's 2009 publication entitled *Current Technology Roadmap*. © 2009, OECD/IEA and The World Business Council for Sustainable Development. (URL: https://cement.mineralproducts.org/documents/wbcsd-iea%20cement%20roadmap%202009.pdf; accessed 11 July 2019).

involved in the cement manufacturing process (see Figure 2.1):

- *Quarrying raw materials*. Naturally occurring calcareous deposits such as limestone, marl or chalk provide $CaCO_3$ and are extracted from quarries.
- *Crushing*. The raw material is quarried and transported to the primary/secondary crushers and broken into 10-cm large pieces.
- *Pre-homogenisation and raw meal grinding*. The different raw materials are mixed and the crushed pieces are then milled together to produce "raw meal".
- *Preheating*. A preheater is a series of vertical cyclones through which the raw meal is passed, coming into contact with swirling hot kiln exhaust gases moving in the opposite direction. In these cyclones, thermal energy is recovered from the hot flue gases and the raw meal is preheated before it enters the kiln.
- *Pre-calcining*. Calcination is the decomposition of limestone to lime. Part of the reaction takes place in the "pre-calciner", a combustion chamber at the bottom of the preheater above the kiln, and part takes place in the kiln.

- *Clinker production in the rotary kiln*. The pre-calcined meal then enters the kiln. The intense heat (up to 1450°C) causes chemical and physical reactions that partially melt the meal into clinker.
- *Cooling and storing*. From the kiln, the hot clinker falls onto a grate cooler where it is cooled by incoming combustion air, thereby minimising energy loss from the system.
- *Blending*. Clinker is mixed with other mineral components. All cement types contain around 4–5% gypsum to control the setting time of the product. If significant amounts of slag, fly ash, limestone or other materials are used to replace clinker, the product is called “blended cement”.
- *Cement grinding*. The cooled clinker and gypsum mixture are ground into a grey powder, OPC, or ground with other mineral components to make blended cement.
- *Storing in the cement silo*. The final product is homogenised and stored in cement silos and dispatched from there to either a packing station (for bagged cement) or a silo truck.

2.1.5 Classification of hydraulic cements

Standard specifications for most cements are governed by British Standards, which use a classification system for cements based on strength classes (based on 28-day compressive strength of mortar prisms) and rate of development of early strength (McArthur and Spalding, 2004).

Compressive strengths are evaluated at 28 days to determine the standard strength class and at 2 and 7 days to determine the early strength class. The compressive strength for common cements should conform to the requirements of EN 197-1:2000 (Koksal, 2003) (Table 2.3).

2.1.6 Environmental considerations of the cement industry

Overall, issues with the mining of cement raw materials mostly relate to noise, vibrations and dust from blasting and haulage equipment, as well as aesthetic concerns. Environmental factors related to the procurement of fuels for cement manufacture are generally not an issue for the cement industry itself. A significant exception is when a cement plant burns waste fuels, which need to be gathered, transported to a location for blending and then delivered to the cement plant. Especially in cases where hazardous wastes are used, various aspects of waste fuel handling will likely require environmental permits (Woodson, 2012).

The major environmental issues around cement manufacture are associated with the manufacture of clinker and concern particulate and GHG emissions from the burning of large quantities of fuels and raw materials. The principal GHG emissions from cement plants are NO_x, SO_x and CO_2. Cement manufacture alone is responsible for a large percentage of CO_2 emissions at the global level. Global cement production grew by over 73% between 2005 and 2013, from 2310 Mt to 4000 Mt, meaning that there was also a considerable increase in CO_2 emissions from cement production during this period (CEMBUREAU, 2014).

Mikulčić *et al.* (2016) summarised all of the studies reporting CO_2 emissions related to cement production and concluded that cement production accounts for roughly 5–8% of global CO_2 emissions. This results in

Table 2.3. Mechanical and physical requirements for common cements according to EN 197-1:2000

Class	Compressive strength (N/mm^2)				Initial setting time (minutes)	Expansion (mm)
	Early strength		Standard strength			
	2 days	7 days	28 days			
32.5	–	≥16	≥32.5	≤52.5	≥60	≤10
32.5R	≥10	–				
42.5	≥10	–	≥42.5	≥62.5		
42.5R	≥20	–				
52.5	≥20	–	≥52.5		≥45	
52.5R	≥30	–				

the cement industry alone having a significant impact, which is increasing with the increased demand for concrete infrastructure.

In addition, all cement plants generate fine dust from the kiln line called cement kiln dust. The material in cement kiln dust varies among plants and comprises the raw mix at various stages of burning, particles of clinker and even particles eroded from the refractory brick and/or monolithic linings of the kiln tube and associated apparatus. Van Oss (2005) reported that typical cement kiln dust generation is equivalent to about 15–20% of the weight of the clinker produced in US plants.

Pre-combustion and combustion mitigation options for CO_2 include reduction of the clinker/cement ratio and use of alternative raw materials, or substitution of fossil fuels with alternative energy sources and energy efficiency improvements (Mikulčić *et al*., 2016).

2.1.7 Eco-efficient low-carbon cements

Eco-efficient low-carbon cements are produced uniformly by intergrinding or blending OPC with one or more SCM. Standardised SCMs are fly ash, GGBS, burnt shale, limestone or silica fume. The substitution levels depend on the type of raw material and its particular pozzolanic reactivity (Cancio Díaz *et al*., 2017).

In general, raw materials that have a pozzolanic or hydraulic character include iron-rich clays (McIntosh *et al*., 2015), various slags from ferrous and non-ferrous metallurgy if air or water cooled to a reactive state and then finely ground (Komnitsas *et al*., 2013; Pontikes *et al*., 2013), clay-rich sludges resulting from water treatment (Guo *et al*., 2010) or kaolin purification (Longhi *et al*., 2016), bauxite residue (Gong and Yang, 2000; Dimas *et al*., 2009), ground coal bottom ash (Donatello *et al*., 2014) and agricultural waste ashes (Bernal *et al*., 2016). According to Provis (2017), the key factor that is likely to determine the feasibility of uptake and utilisation of alternative cementitious materials in any specific location is the local availability of suitable raw materials.

Fly ash is the by-product of the combustion of pulverised coal in thermal power plants, which is collected by a dust collection system from the combustion gases as a fine particulate residue before the gases are discharged into the atmosphere (Ramezanianpour, 2014). The chemical composition of fly ash depends on the characteristics and composition of the coal burned in power stations (Ramezanianpour, 2014). In the USA, the typical major chemical composition of low-calcium fly ash ($<10\%$ CaO) is typically 45–65% SiO_2, 20–30% Al_2O_3, 4–20% Fe_2O_3 and 1–2% MgO. High-calcium fly ash ($\geq 10\%$ CaO) typically contains 20–50% SiO_2, 15–20% Al_2O_3, 15–30% CaO, 5–10% Fe_2O_3 and 3–5% MgO (Ramezanianpour, 2014).

The first major use of fly ash in construction applications was reported in 1948 with the publication by the US Bureau of Reclamation of data on the use of fly ash in the construction of the Hungry Horse Dam (Ramezanianpour, 2014).

Fly ash is most commonly used as a pozzolan for cement production. Pozzolans are siliceous or siliceous and aluminous materials that, in a finely divided form and in the presence of water, react with $Ca(OH)_2$ at room temperature to produce cementitious compounds (Seco *et al*., 2012). High-calcium fly ash has self-hardening properties whereas low-calcium fly ash hydrates when alkalis and $Ca(OH)_2$ are added (Ramezanianpour, 2014).

Ground granulated blast furnace slag is the by-product of the blast furnace from the iron industry, where pig iron is produced at high temperature (1500°C) from iron ore (Siddique and Bennacer, 2012). Typical GGBS includes 27–40% SiO_2, 30–50% CaO, 5–15% Al_2O_3 and 1–10% MgO (Collins and Sanjayan, 2001; Bellmann and Stark, 2009; Sisomphon, 2009). The substitution level for GGBS varies between 30% and 85% and determines the properties of the produced concrete (Suresh and Nagaraju, 2015). Concrete made with GGBS cement sets more slowly than concrete made with OPC, but also continues to gain strength over a longer period in production conditions (Suresh and Nagaraju, 2015).

Oil shale ash is the by-product of oil shale processing. Oil shale is sedimentary rock containing up to 50% organic matter. Once extracted from the ground, the rock can be either used directly as fuel for power plants or processed to produce shale oil and other chemicals and materials (EASAC, 2007). Oil shale ash is formed by burning oil shale to produce energy. Its composition and properties can vary widely, ranging from a high SiO_2 content, which is only pozzolanic in nature, to a high CaO content, which has cementitious properties of its own (Baum *et al*., 1985). Several studies have indicated that oil shale ash burnt at temperatures ranging from 600°C to 800°C would have a cementing strength; therefore, burnt shale could be used for cement production (Smadi and Haddad, 2003).

Silica fume is the by-product of silicon metal or silicon alloy production by reducing high-purity quartz with coal or coke and wood chips in an electric arc furnace (Srivastava *et al*., 2014). Silica fume is composed primarily of pure SiO_2 (>90%) in non-crystalline form, with small amounts of iron, magnesium and alkali oxides (Siddique and Iqbal Khan, 2011).

Because of its extreme fineness and very high amorphous SiO_2 content, silica fume is a very reactive pozzolanic material (Siddique and Iqbal Khan, 2011). Silica fume particles improve the properties of cementitious material (Yu *et al*., 2000; Sanchez and Ince, 2009; Aggarwal *et al*., 2015; Lazaro Garcia *et al*., 2016) because silica fume reacts with $Ca(OH)_2$ in OPC and forms an additional binder material called calcium silicate hydrate, which is very similar to the calcium silicate hydrate formed from OPC (Siddique and Iqbal Khan, 2011).

Generally, the mechanical properties of blended cements are similar to (or more advantageous than) the properties of OPC (Maddalena *et al*., 2018). In addition, production requires less energy and has a lower carbon footprint, and the blended cement shows the same level of performance as that of OPC.

2.1.8 European standard of common cements

To better understand how alternative concretes may be integrated into existing standards and practices, it is useful to review the types of common cements in the harmonised European standard EN 197-1:2000 (Koksal, 2003). In Ireland, the British Standard (BS) EN 197-1:2000 is used, which covers 27 main types of cements according to their chemical composition, including blended cements (Koksal, 2003). However, in the USA, three different types of standards are used: ASTM C 150 for OPC, ASTM C 595 for blended cements and ASTM C 1157 for hydraulic cements. Types of common cements covered by BS EN:197–1:2000 are given in Table 2.4.

2.1.9 Irish cement manufacture

A significant part of the cement production capacity in Ireland has been installed in the last 10 years, making it one of the most modern cement industries in Europe (CMI, 2018). There are six facilities across the country, including four integrated facilities and two grinding plants (Table 2.5). The separate grinding plants receive their feed materials, such as clinker, slag, fly ash and other pozzolans and intergrinding materials, from various sources and are not preceded by an integrated clinker production line, as described in section 2.1.4.

2.2 Technology Overview of Geopolymer Production

Geopolymers are inorganic materials produced by the reaction of a solid aluminosilicate (precursor) under alkaline conditions (activator) (Provis, 2017). These materials can provide comparable performance to traditional cementitious binders in a range of applications, with the added value that industrial waste or by-products are reused as source materials and CO_2 emissions are reduced (Gartner, 2004).

Table 2.4. Types of common cements covered by BS EN 197-1:2000

Type	Standard name
CEM I	OPC
CEM II	Portland-slag cement (S), Portland-silica fume cement (D), Portland-pozzolana cement (P, Q), Portland-fly ash cement (V, W), Portland-burnt shale cement (T), Portland-limestone cement (L, LL), Portland-composite cement (M)
CEM III	Blast furnace cement
CEM IV	Pozzolanic cement
CEM V	Composite cement

The capital letters in brackets denote the specific type of secondary constituent permitted in the cement; their meaning is defined in EN 197-1 for common cements.

Source: Koksal (2003).

Table 2.5. Cement plant locations in Ireland

Company name	Facility name	City	Type of facility	Types of cement
Ecocem Ireland Ltd	Dublin Plant	Dublin	Grinding plant	CEM III/A
Lagan Cement	Lansdown Cement Works	Kinnekad	Integrated	CEM I, CEM II/A-L
O'Brian Cement	Bell View Port	Waterford	Grinding plant	CEM I, CEM II/A-L
Quinn Building Products Ltd	Ballyconnell	Ballyconnell	Integrated	CEM I, CEM II/A-L
Irish Cement Ltd	Limerick	Castlemungret	Integrated	CEM I, CEM II/A-L
Irish Cement Ltd	Platin	Drogheda	Integrated	CEM I, CEM II/A-L, CEM III/A

Source: CemNet (2018).

Precursors can be of natural origin, such as kaolin, zeolite, volcanic ash or natural pozzolans, but may also be thermally treated material, such as metakaolin, fly ash, GGBS, calcined shales or bauxite residue (Nikolov *et al*., 2017). The main raw material must be activated by an alkaline second raw material, such as alkalis of sodium or potassium, water glass (K_2SiO_3) and Na_2CO_3 (Nikolov *et al*., 2017).

The reaction, often called geopolymerisation, is a complex, multi-step process in which the steps involved are largely coupled and occur concurrently (Duxson *et al*., 2007a).

According to Duxson *et al*. (2007a), the key processes occur in the transformation of a solid aluminosilicate source into a synthetic alkali aluminosilicate. The alkaline hydrolysis produces aluminate (AlO_4) and silicate (SiO_4) species that are incorporated into the aqueous phase. A complex mixture of SiO_4, AlO_4 and aluminosilicate species is thereby formed. The oligomers in the aqueous phase form large networks by condensation, which results in gel formation in concentrated solutions. After gelation the system continues to rearrange and reorganise, which results in the three-dimensional aluminosilicate network commonly attributed to geopolymers.

When SiO_2, Al_2O_3 or aluminosilicates in a precursor hydrolyse, –Si–O–Si– or –Si–O–Al– bonds of aluminosilicate break and release active Al^{3+} and Si^{4+} species (Zhuang *et al*., 2016). These active species react to form nuclei and aluminosilicate oligomers consisting of SiO_4 and AlO_4 tetrahedra (Zhuang *et al*., 2016). As presented by Zhuang *et al*. (2016), the chains in aluminosilicate oligomers can be in the form of polysialate –Al–O–Si– chains, polysialate siloxo –Al–O–Si–Si– chains or polysialate disiloxo –Al–O–Si–Si–Si– chains, depending on the Si/Al ratio.

The Si/Al ratio therefore significantly determines the final structure of the resulting geopolymer material, and the properties and the applications of the geopolymers are therefore also dependent on the Si/Al ratio (He *et al*., 2012). Table 2.6 shows the applications of geopolymers according to Si/Al atomic ratio (Van Jaarsveld *et al*., 2003).

There are two pathways by which geopolymers can be produced: one-part mix and two-part mix (Provis, 2017). In the one-part mix pathway, the dry powder is combined with water, whereas in the two-part mix pathway there is a need to add liquid activator.

The one-part mix involves a dry mix that consists of a solid aluminosilicate precursor, a solid alkali source and possible admixtures to which water is added, similar to the preparation of OPC (Luukkonen *et al*., 2018). The conventional two-part mix is formed by a reaction between a concentrated aqueous solution of alkalis and solid aluminosilicate precursor, that is, two parts in addition to water.

According to Provis (2017), the two-part mix pathway is probably the main pathway that is applied in most markets and the majority of products that are available on the market are produced in this manner. However, the one-part mix pathway may become a more scalable technology because of the scope for factory production and distribution of geopolymers as a bagged material; the two-part mix pathway appears to be more scalable to precast work, where handling of chemicals and curing regimes can be controlled (Provis, 2017).

Table 2.6. Applications of geopolymeric materials according to Si/Al atomic ratio

Si/Al ratio	Applications
1	Bricks
	Ceramics
	Fire protection
2	Low CO_2 cements and concretes
	Radioactive and toxic waste encapsulation
3	Fire protection fibreglass composites
	Foundry equipment
	Heat-resistant composites, 200–1000°C
	Tooling for the aeronautics titanium process
>3	Sealants for industry, 200–600°C
	Tooling for aeronautics SPF aluminium
20–35	Fire-resistant and heat-resistant fibre composites

SPF, superplastic forming.
Source: Van Jaarsveld *et al.* (2003).

2.2.1 Review of the use of wastes in alternative cementitious materials

One of the by-products most commonly used in alternative binder production is fly ash from coal-pulverised power plants, which consists of fine particles collected by electrostatic or mechanical precipitation (Van Jaarsveld *et al*., 1998; Phair *et al*., 2004; Zhang *et al*., 2008; Nikolići *et al*., 2013; Ogundiran *et al*., 2013; Guo *et al*., 2014). Fly ash is composed mainly of SiO_2 and Al_2O_3, with a favourable particle size that makes this material suitable for cementitious material production (Toniolo and Boccaccini, 2017).

Table 2.7 summarises the blends of wastes used for the production of alternative cementitious materials.

Heavy metal-containing wastes have also been investigated as a source for alternative binder production. These type of wastes include industrial residues such as mine tailings, electric furnace slag and municipal solid waste incineration fly ash (Yunsheng *et al*., 2007; Komnitsas *et al*., 2013; Nikolići *et al*., 2013; Ogundiran *et al*., 2013; Guo *et al*., 2014; Waijarean *et al*., 2014), which are rich in heavy metals and may have environmental consequences. Studies have shown that metals such as Co, Cd, Ni, Zn, Pd, As, Ra and U can be efficiently stabilised in the three-dimensional geopolymeric matrix when these materials are combined with fly ash (Komnitsas *et al*., 2013).

Metakaolin is another solid aluminosilicate source that can be used for cementitious material production (Van Jaarsveld *et al*., 1998; Phair *et al*., 2004; Yunsheng *et al*., 2007; Hao *et al*., 2012; Lin *et al*., 2012; Novais *et al*., 2016). Metakaolin is the anhydrous calcined form of the clay mineral kaolinite. According to Komnitsas and Zaharaki (2007), the calcination of raw materials for the manufacture of cementitious materials helps release SiO_2 and Al_2O_3. The metakaolin produced from the calcination of kaolinitic clay at temperatures ranging from 650°C to 800°C transforms kaolinitic clay to an amorphous phase. The calcination temperature of raw kaolinitic clay impacts the degree of crystallinity of the metakaolin obtained, as well as its reactivity (Komnitsas and Zaharaki, 2007).

Waste glass is Si-rich material and therefore it can be considered as a precursor of geopolymers. In addition, the required amounts of Na_2SiO_3 and NaOH can be limited or eliminated completely when water glass is applied as an alternative binder (Cyr *et al*., 2012). Glass from different waste streams can be used in this process, e.g. solar panel glass, thin-film transistor liquid-crystal display glass, waste glass from end-of-life fluorescent lamps (Hao *et al*., 2012; Lin *et al*., 2012; Novais *et al*., 2016).

The type of cation involved in the activation reaction affects the microstructural development of geopolymer systems, as well as the Si/Al ratio. In the geopolymerisation reaction, the OH^- ion acts as a reaction catalyst and the alkaline metal cation acts as a structure-forming element, balancing the negative framework charge carried by tetrahedral Al (Duxson *et al*., 2007a).

Table 2.7. Summary of blends of different wastes used as alternative cementitious materials

Chemicals and raw materials used in the process				Process steps		Properties of the product		Reference
Raw materials	Origin of waste material used	Amount of waste material used	Other additives	Thermal treatment (calcination)	Curing or hardening	Compressive strength	Metal leaching/ immobilisation[a]	
Fly ash + metakaolin	Australia	–	K-feldspar, SiO_2, Na_2O, NaOH	700°C, 6 hours (metakaolin)	–	7.7–32.7 MPa	Immobilisation of Pb and Cu determined	Phair *et al.* (2004)
Electric arc slag (ferronickel plant)	Greece	82% slag	H_2O, KOH, Na_2SiO_3	–	22°C, 2 days	52 MPa	Effect of NO_3^- and SO_4^{2-} on heavy metal (Cr, Cu, Ni, Pb) immobilisation	Komnitsas *et al.* (2013)
Fly ash + metakaolin	South Africa	57% fly ash + 15% kaolinite	KOH, NaOH, Na_2SiO_3	750°C, 24 hours (metakaolin)	50°C, 24 hours	39 MPa at 28 days	Immobilisation of Pb and Cu determined	Van Jaarsveld *et al.* (1998)
Fly ash (class F) + sand	Australia	50% fly ash + 50% sand	NaOH or $1.5SiO_2$:Na_2O: $11H_2O$	–	40°C, 24 hours	45.3 MPa (NaOH activator), 60.6 MPa ($1.5SiO_2$:Na_2O: $11H_2O$ activator) at 28 days	Cr^{6+}, Cd^{2+} and Pb^{2+} leaching test	Zhang *et al.* (2008)
Fly ash (class F)	Australia	–	$1.5SiO_2$:Na_2O: $11H_2O$	–	40°C, 24 hours	60.6 MPa at 28 days	Cr^{6+}, Cd^{2+} and Pb^{2+} leaching test	Zhang *et al.* (2008)
Fly ash (class F) + lead smelting slag (LSS)	The Netherlands	10% LSS	Spent aluminium etching (AES) solutions or K_2SiO_3, blast furnace slag (BFS), NaOH	–	–	80 MPa for AES based, 100 MPa for K_2SiO_3 based at 28 days	NEN 12457-4, TCLP, SPLP and NEN 7375 leaching tests	Ogundiran *et al.* (2013)
Fly ash + electric arc furnace dust (EAFD)	Montenegro	10% EAFD	Na_2SiO_3, NaOH	–	65°C, 48 hours	–	Zn immobilisation using TCLP method 1311	Nikolići *et al.* (2013)
Fly ash (class C) + municipal solid waste incineration fly ash (MSWIFA)	China	10% MSWIFA	Na_2SiO_3, NaOH	–	22°C, 24 hours	≈52 MPa after 28 days	Cr, Cu, Zn and Pb leaching study	Guo *et al.* (2014)
Water treatment residue (WTR) + electro-plating sludge (EPS)	–	0–50% EPS	NaOH	600–900°C, 1 hour (WTR)	28°C, 24 hours	2–6 MPa after 28 days	–	Waijarean *et al.* (2014)
BFS + metakaolin	China	10–70% BFS; optimal: 50%	Na_2SiO_3, NaOH, river sand	700°C, 1 hour (metakaolin)	80°C, 5 hours	75.2 MPa (50%) after 28 days	Pb and Cu immobilisation	Yunsheng *et al.* (2007)
Thin-film transistor liquid-crystal display (TFT-LCD) + metakaolin	Taiwan	0–40% TFT-LCD	Kaolin, NaOH, Na_2SiO_3	650°C, 3 hours (metakaolin)	30°C, 24 hours	62 MPa (10% TFT-LCD), 42 MPa (10% TFT-LCD) after 28 days	–	Lin *et al.* (2012)
Waste glass (WG) from end-of-life fluorescent lamps + metakaolin	Portugal	12.5–50% WG; optimal: 37.5%	Na_2SiO_3, NaOH, H_2O_2	–	40°C, 24 hours	14 MPa after 28 days	–	Novais *et al.* (2016)
Solar panel WG + metakaolin	Taiwan	0–40% WG; optimal: 10%	Na_2SiO_3, NaOH	650°C, 3 hours (metakaolin)	30°C, 24 hours	67 MPa after 28 days	Cr, Cu, Pb and Zn leaching test using the TCLP method	Hao *et al.* (2012)

[a]NEN 12457–4: characterisation of waste: leaching – compliance test for leaching of granular waste materials and sludges; NEN 7375: leaching characteristics – determination of the leaching of inorganic components from moulded or monolithic materials with a diffusion test – solid earthy and stony materials; toxicity characteristics leaching procedure (TCLP): acetic acid leaching test; synthetic precipitation leaching procedure (SPLP): H_2SO_4/HNO_3 leaching test; and results for the various geopolymers and comparison with the Dutch Soil Quality Regulation emission limits (Ogundiran *et al.*, 2013).

The most widespread view is that NaOH as a source of OH^- possesses a greater capacity to liberate SiO_2 and Al_2O_3 monomers than KOH (Van Jaarsveld and Van Deventer, 1999; Xu and Van Deventer, 2003; Duxson *et al*., 2005, 2007c). This is likely to be because of the ion size difference between K^+ and Na^+ – Na^+ is smaller than K^+ and therefore more able to migrate through the moist gel network. It could also possibly be because of the higher charge density of NA^+; therefore, Na^+ has better zeolitisation capabilities in geopolymer-forming systems (Fernández-Jiménez *et al*., 2006; Duxson *et al*., 2007c).

In general, the higher the concentration of activator, the greater the mechanical strength of the geopolymer. However, depending in part on the activator used, there may be certain threshold values above which the strength of the geopolymer does not rise significantly, or may even fall (Živica *et al*., 2014). Moreover, these high doses of alkalis may have adverse effects, increasing efflorescence and brittleness (Živica *et al*., 2014). At concentrations above 10M, the increase in mechanical strength is not significant. For economic reasons it is not convenient to use a molarity of greater than 10 for the NaOH solution (Kupaei *et al*., 2013; Hwang and Huynh, 2015).

Increases in temperature and curing time enhance mechanical strength, particularly early age strength, improve durability and limit product fluctuations and efflorescence (Živica *et al*., 2014). Geopolymers based on ashes could be cured at room temperature. However, in the reported studies cementitious materials were processed between 22°C and 40°C (see Table 2.7). Calcination at high temperature is used for metakaolin-based cementitious material production, with kaolinitic clay transformed to an amorphous phase at temperatures ranging from 650°C to 800°C. In the study by Waijarean *et al*. (2014), the water treatment residue was pre-treated by calcining the residue in an electric furnace at temperatures of 600°C, 800°C or 900°C for 1 hour. They found that calcining the water treatment residue at a temperature of 800°C for 1 hour was optimal; under this condition, dehydroxylation and destruction of the 1:1 layer–lattice aluminosilicate structure occur. This reaction enhances the geopolymerisation reactions between the water treatment residue and NaOH.

Standardised leaching tests investigate the chemical leaching or immobilisation of metals in cementitious materials. Commonly used tests are the EN 12457-4 compliance test (distilled water leaching), the EN 7345 tank leaching test (HNO_3 leaching), the toxicity characteristics leaching procedure (TCLP; acetic acid extraction) and the synthetic precipitation leaching procedure (SPLP; H_2SO_4/HNO_3 extraction) (Ogundiran *et al*., 2013). For instance, the results of the compliance leaching test for granular materials, EN 12457-4, were used to investigate the reactions that likely occurred during geopolymerisation (Ogundiran *et al*., 2013). The authors concluded that the main factor controlling leaching of Al and Si from the synthesised products was the nature of the activator.

2.2.2 State-of-the-art use of bauxite residue in alternative cementitious materials

Several research studies showed that bauxite residue is suitable as a potential raw material in the geopolymerisation process because of its high Si and Al content (Table 2.8). Bauxite residue can partially replace alkali hydroxide, one of the most expensive raw materials used in alternative binder synthesis (Zhang *et al*., 2016). In most cases, it has been used in combination with other aluminosilicate minerals such as metakaolin and fly ash (He and Zhang, 2011; He *et al*., 2012; Hajjaji *et al*., 2013; Kumar and Kumar, 2013; Mucsi *et al*., 2015; Kaya and Soyer-Uzun, 2016; Nie *et al*., 2016; Zhang *et al*., 2016).

According to Mucsi *et al*. (2015), bauxite residue can be used in cement by substituting bauxite residue up to 15% by mass for the dry mass of fly ash. If this amount of bauxite residue is exceeded, the mechanical properties are decreased because of the reduction of the amorphous content in the alternative binder.

Badanoiu *et al*. (2015) developed a foamed geopolymer using bauxite residue and waste glass cullet. In their study, the specimens were subjected to thermal treatment (calcination) after curing, at temperatures of 800°C for 1 hour. Foaming was noticed at higher temperatures.

In the study by Ye *et al*. (2016), the bauxite residue was pre-treated through an alkali–thermal activation process to obtain one-part alkali-activated precursor. The bauxite residue was mixed with NaOH pellets and then calcined at 800°C for 1 hour to decompose the

Table 2.8. Summary of techniques for use of bauxite residue (BR) in alternative cementitious materials

Chemicals and raw materials used in the process				Process steps		Properties of the product		Reference
Raw materials	Origin of BR	Amount of BR used	Other additives	Thermal treatment (calcination)	Curing or hardening	Compressive strength	Metal leaching/ immobilisation[a]	
Bayer liquor (BL) + fly ash (class F)	Australia	60–100%	–	–	70°C, 24 hours	41 MPa (60% BL), 43 MPa (80% BL), 43 MPa (100% BL) at 28 days	–	Van Riessen *et al.* (2013)
BR + municipal solid waste incineration fly ash (MSWI)	China	40–60%; optimal: 50%	NaOH	800°C, 1 hour	20°C, 24 hours	2–2.5 MPa at 3–28 days (50% BR)	–	Ye *et al.* (2016)
BR + metakaolin	Unknown	8.3–25%; optimal: 8.3% and 10%	Na_2SiO_3, H_2O	–	50°C, 24 hours	4.5 MPa at 28 days (10% BR), 13 MPa at 28 days (8.3% BR)	Na leaching test (EN 12457-2 standard): 100 ppm	Hajjaji *et al.* (2013)
BR + fly ash (class F)	Australia	0–40%; optimal: 10%	NaOH, $Na_2SiO_39H_2O$	–	27°C, 3.5–5.2 hours	28 MPa at 28 days (10% BR)	Al, Ag, As, Ba, Cd, Cr, Fe, Hg, Pb and Se leaching test (EPA 1311): lower limit value	Kumar and Kumar (2013)
BR + fly ash (class F)	USA	25%	NaOH, $Na_2SiO_39H_2O$	–	23°C	7 MPa at 28 days	Al, As, Cd, Cr, Cu, Fe and Pb leaching test (US EPA): lower limit value	Zhang *et al.* (2016)
BR + metakaolin	Unknown	10–40%	Na_2SiO_3, H_2O	800°C, 1 hour (metakaolin)	60°C, 24 hours	13.4 MPa (10% BR), 14.2 MPa (20% BR), 10.6 MPa (30% BR)	–	Kaya and Soyer-Uzun (2016)
BR + fly ash (class C)	USA	10–80%	$Na_2O.3SiO_2$	–	–	3–13 MPa at 28 days	–	He and Zhang (2011)
BR + fly ash	Hungary	5–30%; optimal: 15%	NaOH	–	90°C, 6 hours	5.5 MPa (15% BR) at 28 days	–	Mucsi *et al.* (2015)
BR + waste glass (cullet)	Unknown	25%	NaOH	600–800°C, 1 hour	60°C, 24 hours	5.5 MPa at 28 days	–	Badanoiu *et al.* (2015)
BR + fly ash (class C)	China	50%	NaOH	–	20°C, 24 hours	15.2 MPa at 28 days	–	Nie *et al.* (2016)
BR + rice husk ash (RHA)	USA	30–60%	–	–	22°C	3.2–20.5 MPa	–	He *et al.* (2013)
BR + fly ash (class C)	USA	50%	$Na_2O.3SiO_2$	–	22°C	13 MPa at 21 days	–	He *et al.* (2012)
BR	Greece	100%	C (graphite powder), SiO_2, K_2SiO_3	1100°C, 1 hour	60°C, 72 hours	40 MPa at 28 days	–	Hertel *et al.* (2016)

[a]NEN 12457–4: characterisation of waste: leaching – compliance test for leaching of granular waste materials and sludges.

original silicate and aluminosilicate phases present in the bauxite residue.

Bayer liquor (sodium aluminate slurry), a stream from alumina production, has been used to produce alkali-activated binders and geopolymer foams (Van Riessen *et al.*, 2013). In this study, using Bayer liquor instead of NaOH showed a negligible loss in mechanical properties. At the same time, the contaminants inside the liquor did not have an impact on the geopolymerisation process.

Hertel *et al.* (2016) have suggested using 100% bauxite residue to produce ready-made mortar, transforming the process into a zero-waste process. However, this was achieved by firing bauxite residue at 1100°C, which supports the formation of a liquid phase and results in a semivitreous material after subsequent fast cooling (Hertel *et al.*, 2016).

Toniolo and Boccaccini (2017) concluded that the SiO_2/Al_2O_3 molar ratio and the amorphous phase of the bauxite residue are too low to achieve an alternative binder using just this waste as the only aluminosilicate source. To resolve this drawback, bauxite residue is usually used in combination with fly ash.

Figure 2.2 shows typical compositions of fly ash and bauxite residue (Sathanandam *et al*., 2017, Cusack *et al*., 2018). The Si/Al ratio in fly ash is 1.8, whereas it is 0.7 in bauxite residue. According to Table 2.6 (see section 2.2), an ideal Si/Al ratio of 2 would be sustainable in low CO_2 cements and concretes. Therefore, bauxite residue can be mixed potentially with fly ash to increase the Si/Al ratio. In this case the high-temperature thermal treatment (calcination) is also avoidable because there is no need to apply metakaolinite in the geopolymerisation process.

Typical fly ash								
SiO_2 (wt%)	Al_2O_3 (wt%)	Fe_2O_3 (wt%)	CaO (wt%)	MgO (wt%)	Na_2O (wt%)	K_2O (wt%)	P_2O_5 (wt%)	TiO_2 (wt%)
50.0	28.3	13.5	1.8	0.9	0.3	0.5	1.0	1.5

Si/Al ratio = 1.8

Bauxite residue from Ireland						
SiO_2 (wt%)	Al_2O_3 (wt%)	Fe_2O_3 (wt%)	CaO (wt%)	MgO (wt%)	P_2O_5 (wt%)	TiO_2 (wt%)
8.6	12.7	43.9	5.9	3.6	0.6	2.4

Si/Al ratio = 0.7

Figure 2.2. Typical composition of fly ash and bauxite residue. Source: Cusack *et al.* (2018) and Sathanandam *et al.* (2017).

3 Survey of Stakeholders within the Market

A survey was developed for relevant stakeholders to gain an understanding of the state of the art practised within the market regarding the use of wastes within geopolymers and the extent of their market penetration. Four sets of questions were developed for four different stakeholder groups: (1) researchers and academics in the geopolymer field, (2) the alumina industry (regarding the use of bauxite residue in geopolymer applications), (3) cement producers and (4) geopolymer manufacturers and producers. A copy of the questionnaires is available in Appendix 1. Tables 3.1–3.4 aggregate the responses of the stakeholders within each of the categories.

The knowledge gained from the survey of the above stakeholders was used to develop a state of knowledge map, as presented in the following section.

Table 3.1. Geopolymer researchers and academics: aggregated responses

No.	Question	Aggregated responses from academic/research institutions (*n* = 5) from different countries
1	Are you aware of industry or pilot-level industrial wastes or by-products (e.g. bauxite residue, mine tailing, recycled glass, fly ash) applied in geopolymer production in Europe or elsewhere? If yes, where, what organisation and what type of process is used?	• India: “Pilot scale application of (a) bauxite residue and fly ash combination, (b) fly ash and slag combination for the production of paving blocks in India” • Europe: “Mainly primary-based geopolymer producers (fly ash, waste)” • India: “Pilot and industrial-scale plant in India (Tata Steel, Jamshedpur) and Australia (Zeobond Ltd) where secondary raw materials are used, mainly fly ash and granulated blast furnace slag” • Mexico: “Start-up company called Sialato S.A. de C.V., Morelia (www.sialato.mx) . . . uses recycled glass, fly ash and industrial by-products. The process is a wet process and is still at laboratory/pilot plant scale” • Sweden: “Geopolymers or alkali-activated materials have no practical application. There are some research efforts from different universities, but the construction industry is not very open to this type of material”
2	Regarding geopolymer technology, what do you believe would be the key influencing factors that would affect the usage of geopolymers as a construction material?	• “Cost and availability of raw materials: transportation cost of waste materials is prohibitive – should be available < 50 km from plant. The alkali costs vary seasonally, which influences the use of geopolymers” • “Absence of codes and standards for geopolymer production affect it adversely. It is often judged on specification of similar products, and loses its advantage of energy and environmental superiority” • “Need of trained manpower, cement-based process/products are easy to handle but geopolymers require trained personal” • “Effect of temperature variation on processing and product properties. In plant conditions, in winter it takes longer time to set, whereas in summer it sets very fast” • “Key influencing factor is durability, freeze–thaw resistance and unreacted Na leaching” • “Reducing of CO2 gases and energy . . . and . . . recycling potential” • “The main restrictions for a more common usage in Sweden are the lack of a track record for gp/aam (geopolymers/alakaline-activated materials) (even though, e.g. super-sulfated slag cements, one type of activated material, were used for a long time). Concrete producers, entrepreneurs and property owners simply do not know about the short- or long-term performance of constructions with gp/aam concretes under different environmental conditions. To them it is not clear how the gp/aam binder can be safely handled in the concrete or precast plant, how it can be transported and casted on site in a safe and efficient way. 40 years of research on gp/aam has failed to produce this track record and the necessary criteria and standardisation for ensuring a constant quality. Another hinder is that gp/aam consist of the same main pozzolana and latent hydraulic products (SCM) the cement and concrete industry is already using and familiar with. In Sweden, they know how to use them in concrete and cement and all the legislation and standards are in place”

Table 3.1. Continued

No.	Question	Aggregated responses from academic/research institutions (*n* = 5) from different countries
3	Are you aware of any concrete or cement products from waste-based geopolymers that are available for purchase on the market?	• "In India . . . following materials are available in market: a. Paving blocks meeting BIS 15658 specification, b. quick road-repairing material. Apart from this, few other companies are marketing precast products, all use fly ash" • "Pilot and industrial-scale plants in India (Tata Steel, Jamshedpur) and Australia (Zeobond Ltd) where secondary raw materials are used, mainly fly ash and GGBS" • "Yes, in different parts of the world like Australia, South Africa and Mexico (starting)" • "Some smaller companies in Europe produce geopolymer precast elements, which are more on a pilot scale or within larger R&D projects"
4	Who are the main producers of geopolymer cements that you are aware of?	• "I am not aware of producers of geopolymer cement; however, there are many producers of geopolymer-based precast products such as Millikens, Rocla, etc." • "Beside India and Australia, recently Chinese companies are coming up" • "For geopolymer concretes, I think it is Zeobond in Australia and there is another small company in South Africa. Our company in Mexico is at starting stage. Mainly for not structural applications" • "There are none in Sweden that we are aware of"
5	What technical standards are used to produce and assess geopolymer cements that you are aware of?	• India: geopolymer "cements are assessed on the properties of OPC or Pozzolanic Portland cements" • Hungary/Europe: "there is still not an accepted standard for geopolymers (since the name of it is critical, e.g. geopolymer or alkali-activated cement)" • Mexico: "one standard proposal, but is still under research" • "There are no Swedish standards, guidelines or recommendations about gp/aam available, at the moment. To our knowledge in Europe, there is only the state-of-the-art report produced by the RILEM committee on alkali-activated materials (RILEM TC 224-AAM), which can be a sort of a guidance document"
6	Are you aware of any particular legislation or requirements that affect the use of waste-based geopolymer cements in your country?	• India: "There is no such legislation in India. However, as per Ministry of Env. and Forests, Thermal Power Plant has to ensure 100% use of fly ash they are generation, thus use of fly ash for various applications including geopolymers are of interest. We are making efforts for similar type of notification for red mud also" • Hungary: None • Mexico: "For structural applications only can be use ordinary Portland cement in Mexico, for non-structural, there are not problem to use other binders like geopolymers" • Sweden: "At the moment, the legislation and standardisation in Sweden concerning concrete is streamlined for Portland cement-based binders, so it is in the rest of Europe. It took around 5 to 10 years to implement SCM (fly ash, slag, silica fume) to a larger extent into the Swedish concrete standard (SS 137003). For a binder system not yet implemented in any buildings or demonstrator in Sweden, the standardisation and legislation process would possibly take 15 to 30 years. A shortcut could be the European Technical Approval process, at least to initiate the standardisation procedure, to foster the use of gp/aam binders and build up a track record"
7	In your opinion, what are the main technical and/or scale-up challenges for the use of industrial wastes such as biomass ash, bauxite residue, recycled glass and mine tailings for geopolymer production?	• India: - "a. To get the consistent quality of waste throughout the operations. Any change in amorphous content changes the quality of the product - b. Seasonal variation of temperature and humidity also affects the properties - c. Selection and use of right type of plasticiser is essential, as the geopolymer paste becomes very sticky and pouring is difficult - d. Curing and storage condition is important or carbonation occurs" • Hungary: "Technical challenge summarised in no. 2. are solvable by scientists and engineers, but social acceptance is much harder issue in my view" • Mexico: "Construction industry in Mexico is very traditional and they still do not know other commercial inorganic binders like geopolymers, so the price is higher than traditional OPC and OPCs-based binders"

Table 3.1. Continued

No.	Question	Aggregated responses from academic/research institutions (*n* = 5) from different countries
		• Sweden: "From our point of view there are three major points, which are challenging for the cement and concrete industry: - Quality and quality control: There is a lack of quality criteria for such industrial wastes others than class-F fly ash (EN 450), blast furnace slag (EN 15167) and silica fume (EN 13263). The materials are often highly variable in quality depending of the source (e.g. bio ashes, mine tailings). Without clear quality criteria and standardisation for these materials no concrete would be produced and accepted for the safe and reliable use for the 50 to 150 years of service life of a structure - Logistics: Concrete is a large quantity commodity. Cement and concrete producer need to rely on the availability of such materials any time in sufficient amounts and quality. At the moment, tools are lacking which can link the availability of a rest material from different sources, if one source is not sufficient. This is also a problem for the use of CDW materials in concrete - Save handling of the material: When mixing gp/aam the material is strongly alkaline (even more than Portland cement). For a larger scale, first safety routines need to be developed in order to use it in the plants by relatively unskilled workers. This entails also that the concrete technology for concretes with gp/aam: At the moment there are no more advanced application for gp/aam concretes other than relatively low quality concretes (e.g. no slump concretes). This is due to the lack of compatible concrete admixtures, which sustain the high pH during mixing and which greatly improve the quality, workability and long term durability of a concrete"
8	Are there any industry reports or documents that review the state of the art that you would recommend?	• "There are multiple informations, but no one touches the practical aspects of upscaling" • "Unfortunately I do not know industry reports regarding this topic, but scientifical papers . . ." • "Yes, there is a market research study about 'geopolymers markets' but it is too expensive for emergent countries like Mexico" • "We mentioned already the RILEM report on alkali-activated materials: https://www.springer.com/gp/book/9789400776715"
9	Can you recommend geopolymer/waste example(s) that we could use as a case study? We are hosting an international workshop and are seeking a case study to present and invited speakers. Can you make any recommendations?	• "Recently CSIR developed geopolymer paving blocks meeting IS 15658 specification using red mud and fly ash combination" • "Sialato have done some products using fly-ash, cullet glass and other industrial by-products" • "Case studies on gp/amm as named in the above-mentioned RILEM report. The authors of said report could also be potential invited speakers"

Table 3.2. Alumina industry: aggregated responses

No.	Question	Aggregated responses from industry/associations (*n* = 4)
1 and 2	Are you aware of industry- or pilot-level bauxite residue applications for geopolymer production in Europe or elsewhere? If yes, where, what organisation and what type of process is used?	• "Blue Planet (USA) has the intent to test bauxite residue for such a use, not sure if any pilot has been started yet" • "European Commission-funded EIT project called RECOVER is currently building a pilot plant to demonstrate technology. Pilot scheduled for 2020" • "EC-funded project called RemovAl under Horizon 2020 will carry out pilot-scale project with various bauxite residue to demonstrate applications, planned in 2019. There is an element of work on geopolymers in the RemovAl project. For anyone not familiar with RemovAl, it has just received €10.5 million funding from EU for a series of research programmes on bauxite residues"[1] • "Aluminium of Greece alumina refinery are currently re-using 110,000 t of bauxite residue to local cement industry (3 companies). This is for normal strength type concrete but they are looking at cementitious binders with BR"

1 The University of Limerick is a partner in the RemovAl Horizon 2020 project.

Table 3.2. Continued

No.	Question	Aggregated responses from industry/associations (*n* = 4)
		• “Quite a lot of work has been done on this topic under the Horizon 2020 ETN REDMUD project; in particular at the KU Leuven” • “Various others have done related work including Waugh at University of the West Indies (Jamaica) in the 1980s” • “CERAM Research (now called Lucidean) in UK did some work and it is frequently raised as a fruitful research area as it employs alkaline silicates which could readily be provided by a Bayer plant”
3	Are you aware of any commercial-level uses of residue-based geopolymer cements?	• Not to the collective knowledge of the participants
4	Do you see any barriers to using bauxite residue in geopolymer cements?	• “Public acceptance, economics of the production” • “No international standard product specification developed for geopolymer cements” • “Classification of bauxite residue should be done at EU level and implemented by national Member States (e.g. Ireland)” • “Economical and environmentally robust technology to produce cementitious binders using bauxite residue” • “Feasibility study approved by EC: technical, economical, legislation, market, environment” • “Legislation at European level to support and incentivise re-use of bauxite residue locally” • “Iron oxide decreases strength. To activate the bauxite residue, it is necessary to melt and quench the material to get a vitreous slag; this is costly and materials are in competition with other metallurgical slags that are already vitreous (lead production slag, etc.)” • “Potential barriers: - concrete quality requirements/industry standards - possibly legislations on radioactivity and trace elements - customer perception (lack of market acceptance) e.g. colour and radioactivity”
5	Are you aware of any particular legislation or requirements that affect the use of bauxite residue-based geopolymer cements in your country or countries where your company operates?	• “No international standard product specification developed for geopolymer cements” • “Radioactivity in bauxite residue” • “Leaching behaviour of the end product” • “Bauxite residue source far from cement market” • “Concrete quality/standards – geopolymers are not defined as cements. Would probably need performance-based documentation” • “Bauxite residue is classified as a waste and cannot be used in valorisation product unless its classification is changed. Bauxite residue cannot be both a by-product and a waste according to current legislation. This poses a significant roadblock given it is not envisaged that all bauxite residue produced by a refinery will be used in the cement industry and that bauxite residue already produced is disposed of in a way which does not allow removal and hence will remain as a waste” • In Europe: “CEM I is not accessible. CEM II neither as there is a closed list of possible raw materials that can be included under specifications”

Table 3.3. Cement producers: aggregated responses

No.	Question	Aggregated responses from cement producers (*n* = 6)
1	In which country or countries do you operate?	• Irish cement companies (CMI members): sell primarily on island of Ireland, some export to UK, minor quantities to Europe • Banah UK currently manufactures product in Northern Ireland and sells to the rest of the UK and Ireland • Australia (Boral): sells in Australia only
2	How many years has your company been in the cement production business?	• Oldest company 90 years, ranging down to 80, 30, 18, 16 and 10 years in business

Table 3.3. Continued

No.	Question	Aggregated responses from cement producers (*n* = 6)
3	Except for standard OPC, do you produce cements with additives such as waste or by-products? If so, please state which additives you use	• CEM I (OPC): Composed of > 95% clinker but now < 20% of market – sets quickly (RAPID) – favoured by pre-casters and pavement layers • CEM II: “normal” and ready-mix cements. CEM II allows replacement of clinker with other materials/ingredients, but there are limits under EU standards; additives max. 6–20% - limestone fines – added at CEM production or can be added at kiln end of process - pulverised fly ash (PFA) - chemistry is critical to maintain strict standards - consistency and strength are key for clients - progress in reducing emissions: CEM II more eco-efficicent, with lower CO_2 emissions (20% reduction since 2006), but lags behind transport and heating in this regard • “Use overburden and asphalt dust residue from asphalt manufacturing operations, and low-grade bauxite. In the past we have also used alum sludge, and waste aluminium-derived material and waste iron oxide” • “Produce CEM I and CEM II. The CEM II contains limestone fines as an addition, and both cements contain a minor % of flue dust Portland cement (FDPC) which is a by-product of our own cement manufacturing process” • “PFA has been used in the past. Now locally sourced limestone chips (CEM II/A–L) • “We do not produce OPC – produce a calcined clay pozzolan from locally available kaolinitic clay. We also manufacture novel cement systems known as geopolymers” • Australia: “Produce cements with 40% slag and 60% slag. Produce a product which is milled slag with 4% gypsum. Produce a slag product with an additive which acts as an activator”
4	How much OPC (in metric tons) does your company produce per year? If your company is using industrial waste additives, how much of this type of cement does your company produce per year?	• “3.6 Mt pa (Central Statistics Office data for CEM I and CEM II) produced on island of Ireland” • “Produces c.650,000 t pa. All cements are made from the same clinker which inherently has the same components contributing to its composition” • “Currently produce ~1 million tonnes of cement annually, containing up to 10 thousand tonnes of FDPC” • “Plant is a 1.4 million tonne cement plant. Production levels vary according to market demand. Company manufactures CEM I and CEM II/A–L. (Refer to EN 197-1:2000 standard for table reference.)” • “We do not produce OPC” • “Company produces c.2.5 Mt per annum. Of this only about 250,000 tons has slag content. 125,000 tons of this will be blended downstream with cement during concrete batching. Fly ash is used as an additive in Australia but most of the addition of fly ash takes place in concrete plants, not the cement plants”
5	What is the final destination of the cement produced by your company? If international, please state which country or countries your company exports cement to	• Ireland: “60% on island (varies among each individual company)” • UK: “Northern Ireland, GB” • EU: “some to continent” • “The ability to export was vital during the financial downturn” • “Demand in UK is currently strong but the industry is keeping a watching brief on Brexit and its impacts” • “Currently our calcined clay pozzolana is sold in the UK only” • “100% of our production is consumed in Australia”
6	If geopolymer, a new-generation construction material formed by using industrial waste or by-products, was available, would it affect your business model or value chain?	• “There is currently low availability of geopolymer suitable materials in Ireland – unlikely to change in the near term and even in the longer term - Chemistry is critical – concerns about quality assurance of diverse source materials - There are limited end-use applications - Feedstock tend to be industrial by-products e.g. bauxite residues, PFA, mine residues – all of which are in limited supply here. Ireland does not have the heavy manufacturing base to guarantee supply, while decarbonation of energy generation means that the current supplies of PFA will likely reduce

Table 3.3. Continued

No.	Question	Aggregated responses from cement producers (*n* = 6)
		- Would depend on volumes and wastes used ultimately, most likely not significantly - If geopolymers were to replace clinker, this would likely affect our annual production (negatively) • "Geopolymers are available – Banah UK Ltd market three versions of a geopolymer based on calcined clay: banahCEM FIRE; banahCEM ACID; banahCEM THERMAL" • "Difficult to answer as I do not know the cost per ton of geopolymer cement or geopolymer concrete. Construction materials used are very price sensitive. Our company supplies 60% of its cement to company-owned concrete plants so the supply chain is largely in-house. Company has commenced using waste to substitute some coal in the pyro-process of producing clinker – this is reducing both costs and CO2 emissions"
7	Are you aware of any concrete or cement products based on waste geopolymers that are available for purchase on the market?	• "Aware of research in the Netherlands – using small amounts of geopolymers to produce cement without clinker" • "Not at this point, at least not domestically" • "Banah CEM in UK currently produce a geopolymer cement (see Q6 response)" • "Fly ash and blast furnace slag are used primarily"
8	In your opinion, what are the main technical and/or scale-up challenges for the use of industrial wastes such as biomass ash, bauxite residue, recycled glass and mine tailings for cement production?	• "Change of policy needed to promote the circular economy" • "Standards/technical certification associated with using waste materials required; acceptance and incorporation" • "Waste classification: red tape, difficulty in getting materials out of waste classification. Also they are wastes and as such are going to be highly variable in composition. This will require frequent re-formulation to maintain performance or will result in a highly variable product" • Australia: "The government and EPA have been extremely slow in approving use of waste in the manufacture of cement; very bureaucratic and frustrating. Our company started burning waste in the cement kiln in August of this year after about 5 years of preparation, legal work, community interaction, etc. Technically the process is now well established and understood" • "Material consistency and supply availability; by-products – and thus scalability - Chemistry and quality control of inputs, in line with requirements and critical (Ca-Si-Al-Fe) balance - Local climatic requirements – temperature, humidity/moisture content must be consistent to quality assure products" • "Sustainability of supply will become an issue – fly ash supplies are currently experiencing this problem and GGBS will follow suit. Alternative materials resources need to have many years of supply available" • "Market acceptance - Displacement of existing excellent materials will be difficult to achieve: replacing materials that work, are tried and tested, reliable and acceptable to market - Capex requirement for incorporating into manufacturing processes, as well as plant/process upgrades must provide significant cost-effective alternative to overcome existing market competition from existing proven material - Manufacturer reluctance for change – would take time to 'make its mark' in performance - New health and safety challenges in manufacturing processes" • "R&D on strengths and applications and on product mix" • "Robustness of proving suitability of ranging wastes for ranging applications; added costs; traceability" • "There will be no 'silver bullet' replacement of existing products"

Table 3.4. Geopolymer manufacturers: aggregated responses

No.	Question	Aggregated responses from geopolymer producers (*n* = 3)
1	Which raw materials/ waste materials does your company use for geopolymer products?	• "Fly-ash type F, GGBS, microsilica, metakaolin, soluble silicates, potassium and sodium hydroxides (waste)" • "GGBFS, coal fly ash, biofuel ash, oil shale ash, wood industry chemicals etc."
2	Are you aware of any concrete or cement products based on waste geopolymers that are available for purchase on the market?	• Renca Rus: "produce geopolymer binders for various applications, including 3D geopolymer, geopolymer foams, paints, plasters, repair mortar, fire protective coating, ordinary construction binder"
3	Who are the main producers of cements with industrial waste and by-product additives that you are aware of?	• Russia: "produces geopolymer cements based on wastes and by-products" • Australia: "Wagners company produces geopolymer concrete for its own use" • India: "there is a company Kiran global that also produces geopolymer cement" • Finland: "many cement producers, such as Finnsementti"
4	How much (in metric tons) industrial waste or by-product materials does your company utilise per year?	• Russia: "niche application . . . use about 1000 tons of wastes and by-products per year" • Finland: "in partnership 50,000 to 100,000 tons and growing"
5	How much (in metric tons) cement or other products, such as bricks and paint, does your company produce per year?	• "We produce about 1000 metric tons of products" • "Partners produce, we develop and get commission"
6	What is the final destination of the geopolymer products made by your company? If international, please state which country or countries your company exports to	• "We usually supply geopolymers inside Russia, to Italy, and sometimes to other parts of the world, including Singapore, Hong Kong, Norway" • "All kinds of construction in Scandinavia, eventually Nigeria"
7	Does your company use any pre-treatment of raw materials such as carbonation or calcination? If yes, please state which material treatments you use	• "No, we don't. We take ready-to-use materials" • "In partnership, calcination modification of wood industry and mining industry waste"
8	In your opinion, what are the main technical and/ or scale-up challenges for the use of industrial wastes such as biomass ash, bauxite residue, recycled glass and mine tailings for cement production?	• "The main challenge is constant composition and properties. As this is regarded as waste by the producing company they do not control the properties" • "Consistency, quality control" • "New types of pre-treatment/mixing methods" • "Optimisation of thermal treatment cycle, complex equilibrium analyses and phase identification resulting from impure ingredients"

3.1 State of Knowledge Map

Figure 3.1 shows the geopolymer knowledge map developed from the information revealed through the survey of stakeholders. A list of key geopolymer producers is detailed, spanning a wide variety of regions including Europe, the USA, Russia and Australia. Some of these companies are large multinationals that have a geopolymer offering within their product portfolio whereas others are start-ups or small and medium-sized enterprises developing novel geopolymers for niche applications.

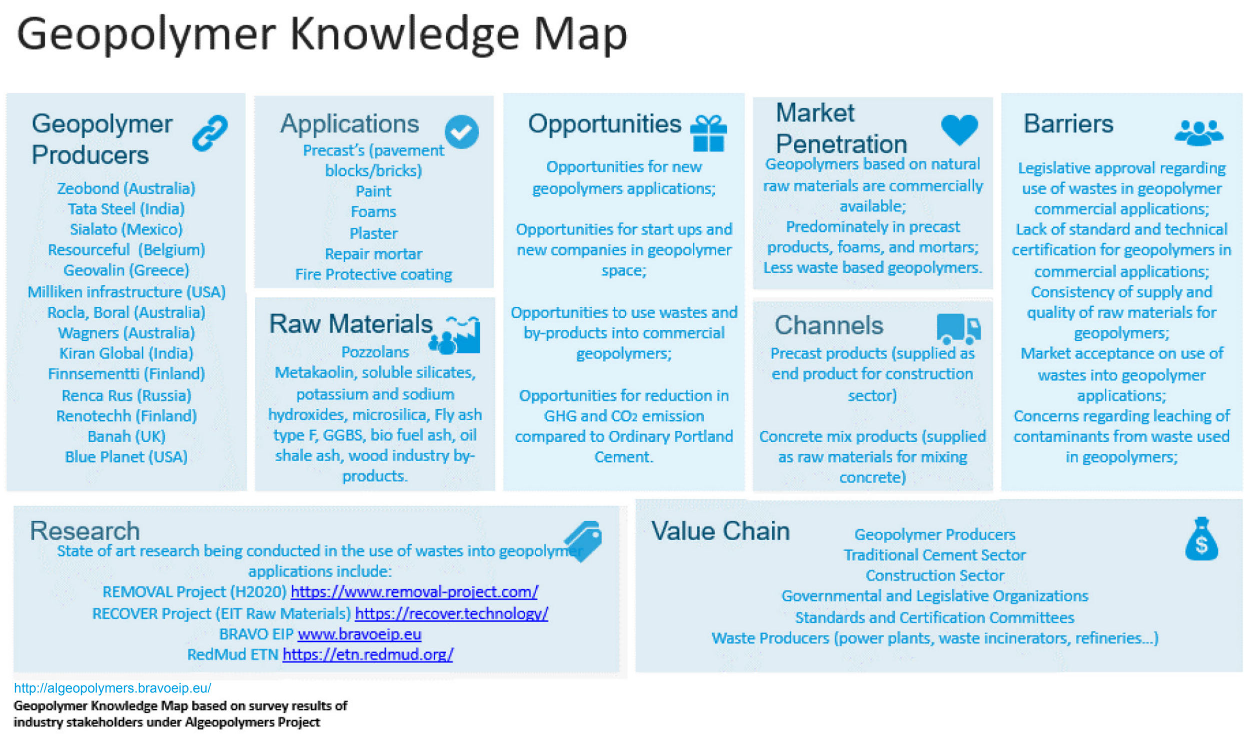

Figure 3.1. The geopolymer knowledge map.

The current commercial application areas for geopolymer materials are predominantly focused on precast products, foams, paints and mortars, with the raw materials being natural aluminosilicates, including pozzolans, metakaolin and soluble silicates, with some waste materials or by-products, such as those accepted for blending in traditional cement, also being included (fly ash, GGBS).

The opportunities in Figure 3.1 highlight the potential for growing geopolymer applications, as well as the potential for new and existing companies within the space to develop novel waste-based geopolymers and the associated positive environmental impact of reduced GHG and CO_2 emissions compared with traditional cements. The barriers to market for new products include market acceptance and lack of standards, among others.

The survey highlighted that significant research was being undertaken regarding the potential for increased incorporation of waste into geopolymer applications, including the projects listed in Figure 3.1, with new technologies and treatments being developed for this purpose. However, the major market barriers did not point to a lack of technology but to a lack of legislation acceptance and standards. This highlights the potential for research activities to directly address these barriers with a more market-oriented approach. A list of the key market players within the value chain for commercial geopolymer applications stresses the disruptive nature of geopolymers within a traditional OPC-based market. The challenges regarding geopolymers are twofold: (1) increasing the number of applications as alternative products within a traditional and extremely regulated market and (2) acceptance of the incorporation of waste materials into geopolymer applications.

4 National Stakeholder Workshop and Roadmap

The potential for Irish wastes to be used in geopolymer and cement applications was investigated through a national stakeholder workshop. Relevant stakeholders from different sectors were divided into groups, with a representative from each sector per group. Groups were asked to challenge and explore synergies using an approach called the “Six Thinking Hats” technique. The Six Thinking Hats technique, published in 1985, was created by Edward de Bono and involves assessing a topic from six perceptions labelled with colours as follows: white – facts, data, figures; red – emotions, hunches, feelings, instincts; black – critic, analyst; yellow – positive, logical; green – creative, growth, ideas; and blue – agenda, decision, global, overview (De Bono, 2016) (Figure 4.1). The successful solution or outcome can be reached from a rational, positive viewpoint, but it can also pay to consider a problem from other angles, e.g. an emotional, an intuitive, a creative or a risk management viewpoint.

The national stakeholder workshop, entitled the “Use of Residue and By-products in Geopolymer Cement Applications”, was held on 19 September 2018 at Covanta Waste to Energy Facility in Dublin. The workshop was attended by participants representing the cement, alumina, power plant and waste-to-energy sectors, as well as government and policy stakeholders (Figure 4.2). The event involved a

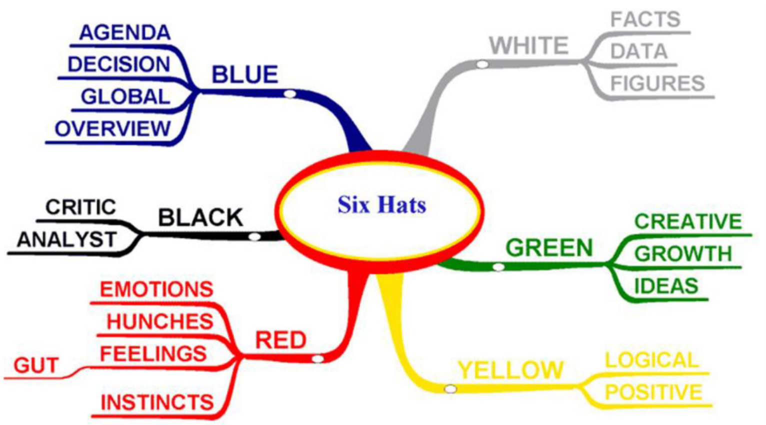

Figure 4.1. The Six Thinking Hats technique.

Figure 4.2. Organisations that participated in the national stakeholder workshop.

review of the key results from the Algeopolymers project, as well as international speakers from companies including Geovalin (Greece) and Resourceful (Belgium), which are start-up companies incorporating wastes into geopolymer applications. This was followed by the workshop element to explore opportunities within the Irish context.

4.1 Setting the Scene: The Irish Context

Currently, SCMs used in Ireland in blended OPCs include coal power plant fly ash (CEM II/V/W), GGBS (CEM III/A) and limestone (CEM II/A-L) (see Table 4.1). These are approved blended cements based on the EN 197-1:2000 standard and represent

Table 4.1. Potential SCMs identified in Ireland

Potential standard code	Type of waste	Type of facility producing	Location of facility producing	Waste disposal site	Annual production of waste (t)	Reference
CEM II/V	Biomass bottom ash	Biomass power plant	Killala	Off-site, transported to appropriate sites (landspreading)	≈2400	Mayo Renewable Power (2018)
CEM II/V	Biomass fly ash	Biomass power plant	Killala	Off-site, North County Dublin	≈3600	Mayo Renewable Power (2018)
CEM II/V	Bottom ash	Waste-to-energy plant	Dublin	On-site	50,000–80,000	Dublin Waste to Energy Project (2001)
CEM II/V	Air pollution control residue (mixture of fly ash and residues from treatment of flue)	Waste-to-energy plant	Dublin	Off-site, abroad	5000–20,000 (dry), 3750–16,000 (semi-dry), 2750–13,200 (wet)	Dublin Waste to Energy Project (2001)
CEM II/V	Fly ash	Waste-to-energy plant	Dublin	Off-site, abroad	2500–12,000	Dublin Waste to Energy Project (2001)
CEM II/V	Fly ash	Waste-to-energy plant	Duleek	Off-site, abroad	≈2000	Indaver Ireland Limited (2013)
CEM II/V	Bottom ash	Waste-to-energy plant	Duleek	Off-site, Knockharley Landfill	≈8000	Indaver Ireland Limited (2013)
CEM II/V	Peat bottom ash	Power plant, peat resources	Edenderry	Off-site, Clonbullogue ash facility	≈6000	Bord na Móna Energy (2008)
CEM II/V	Peat fly ash	Power plant, peat resources	Edenderry	Off-site, Clonbullogue ash facility	≈28,000	Bord na Móna Energy (2008)
CEM II/V	Peat fly and bottom ash	Lough Ree Power Plant, peat resources	Lanesborough	On-site	≈35,000	Bord na Móna Energy (2014)
CEM II/V	Peat bottom ash	West Offaly Power Plant, peat resources	Shannonbridge	On-site	≈6000	ESB (2012)
CEM II/V	Peat fly ash	West Offaly Power Plant, peat resources	Shannonbridge	On-site	≈35,000	ESB (2012)
CEM II/V	Coal fly ash	Coal power plant	Carrowdotia South	On-site	≈100,037	ESB International (2014)
CEM II/V	Coal bottom ash	Coal power plant	Carrowdotia South	On-site	≈17,276	ESB International (2014)
–	Bauxite residue	Alumina plant	Aughinish	On-site	≈1,370,000	McMahon (2017)
–	Mine tailings	Zinc/lead mine	Navan	On-site	≈1,200,000	Boliden Tara Mines (2017)

the state of the art or best available techniques in terms of a reduced environmental impact of the cement sector. Fly ash is one of the most used and suitable wastes for construction materials because of its mainly amorphous SiO_2 and Al_2O_3 composition and favourable particle shape and size (Barough *et al*., 2012; Feng *et al*., 2015).

Table 4.1 summaries the relevant wastes and residues within Ireland that have potential for use in geopolymer and construction sector applications. In Ireland, in addition to traditional energy-generating plants (coal power plants), the biomass-based energy-generating industry is growing (SEAI, 2015). Currently, ≈3.5% of Irish energy is produced from biomass. Under current practices there is *c*.1.7 million metric tons of biomass available in excess of livestock requirements (McEniry *et al*., 2013); hence, it is estimated that, by 2035, ≈30% of Irish energy will be based on biomass (SEAI, 2015). According to 2013 analysis, ≈2400 metric tons of biomass fly ash is produced per year in Ireland (Mayo Renewable Power, 2018), which is historically sent to landfill, but the scenario is changing with the European Union (EU) Landfill Directive (1999/31/EC). With the increasing biomass fly ash volume and regulations to avoid landfilling, there may be the potential to blend this fly ash into cement and geopolymer applications.

Bauxite residue, also known as red mud, is a by-product generated during the Bayer alumina production process. Approximately 1.51 million metric tons of bauxite residue was produced in Ireland in 2017, which is stored in a bauxite residue disposal area of 183 ha (McMahon, 2017). Bauxite residue is a potential candidate raw material for geopolymers as a result of the significant quantities of Al_2O_3, SiO_2 and caustic soda it contains (Toniolo and Boccaccini, 2017).

In addition, waste-to-energy facilities in Ireland produce a minimum of 6063 metric tons of fly ash and 2205 metric tons of bottom ash per annum, and also represent a significant source of aluminosilicates with potential for geopolymer applications.

There are a number of benefits that can arise from using untapped SCMs such as these in the Irish construction sector. Besides the reduction of CO_2 emissions compared with OPC, an additional benefit is the valorisation of natural resources, by-products or waste materials that are not currently used in an economic way. Nevertheless, the key driver for the wider adoption of alternative cementitious materials over recent years is the reduction of CO_2 emissions compared with OPC (Provis and Van Deventer, 2014). Life-cycle analysis studies of alternative binder systems have resulted in calculations of CO_2 emission reductions of between 40% and 80% compared with an OPC baseline (Provis, 2017, and references therein).

Performance improvement is also an important benefit as the service life of concrete structures mainly depends on the durability of the concrete (Nath *et al*., 2018). Concrete made of OPC is considered to be a durable material for the non-aggressive environment; however, concrete is susceptible to degradation in aggressive exposures such as in the marine environment, underground and on exposure to chemicals (PCA, 2018). The use of SCMs such as fly ash with OPC can improve the durability of concrete because of its pozzolanic reaction and particle-packing effects (Poon *et al*., 2000).

The production of eco-efficient cements using by-products or waste materials can be a basis for synergies between industries such as cement producers, alternative binder producers and waste disposal facilities.

4.2 Workshop Key Findings

As Ireland has limited commercial geopolymer activities, external geopolymer producers were invited to participate in the workshop (Figure 4.3). In addition, to make the event relevant to the Irish cement sector, a two-pronged approach was taken:

1. long-term approach: residue and by-product use in geopolymer applications (disruptive technology within the market);
2. short-term approach: residue and by-product use in blended cement applications (complementary to the existing Irish market).

The basis for the synergies among the sectors represented at the workshop are represented in Figure 4.4, where it can be seen that different sectors have different objectives. Waste producers are looking for sustainable and environmentally friendly applications to turn the waste into a potential resource, whereas the cement sector is seeking opportunities

Figure 4.3. Photographs from the national stakeholder workshop.

Figure 4.4. Summary of the basis for synergies among the sectors represented at the stakeholder workshop. SME, small and medium-sized enterprises.

to reduce the high carbon footprint associated with cement manufacture. In addition, the opportunity to monitor and assess the potential for geopolymers to be disruptive within the cement sector was an important aspect, as technologies continue to develop and geopolymer producers pursue broader markets in the future.

The Irish industrial perspective regarding the potential for waste to be used in geopolymer applications is shown in Figure 4.5. It can be seen under the "facts hat" review that assessment of data from the different industry players regarding wastes and detailed compositions of wastes over time would be informative to an assessment of its use in both geopolymers and blended cement applications. Understanding the potential replacement for the currently used coal fly ash with alternative fly ashes produced from different sectors, including the waste-to-energy and biomass sectors, may illuminate future paths for blended cements. On the other hand, understanding the allowable tolerances in compositional variation for infeed raw materials within the cement sector would assist in finding a potential operation window regarding

Figure 4.5. Irish industry perception of the use of waste in geopolymer applications.

a process for blending wastes and raw material feedstock. Clarification regarding the end-of-waste status of particular wastes such as bauxite residue was emphasised, when it would not be possible to reuse all of the residue in such applications and hence a split classification scenario may occur regarding landfill and reuse.

Under the "critic hat" review, it can be seen that from the cement sector's perspective the risk associated with the use of new geopolymers in structural applications is high ("no history of use") and the gain is low, as there is no incentive in the cement sector to adopt new materials. In addition, unreliable sources of wastes and residues for large-scale cement production was also highlighted, and product and social acceptance was deemed to be one of the largest challenges.

On the other hand, the "positive hat" review highlights the circular economy (waste to resource) and reduced CO_2 emissions as key benefits and drivers. In particular, the cement sector has potential in the short term to secure alternative low CO_2 blending materials, in addition to coal-powered plant fly ash, which may be limited in supply in the future for the production of CEM II cements. The benefits of the clean-up of legacy issues (legacy sites and landfills) and future-proofing regarding the environmental impact were stressed.

Additional benefits regarding the development of research and development capacity within Ireland and the potential for spin-outs and economic growth in the space of green technologies were included. Under the "emotions hat" review, it can be seen that participants felt that the potential use of wastes in these applications was worth investigating, while the challenges ahead were seen as significant.

The results of the workshop combined with the information and knowledge generated from the review and survey were used to generate a roadmap of steps for the use of wastes in both blended cements and potential geopolymer applications in Ireland.

4.3 Irish Geopolymer Roadmap

Figure 4.6 displays a proposed direction for the exploration of wastes for use in geopolymer applications in the Irish context. This roadmap proposes a level 2 workshop with national stakeholders and industry where non-disclosure agreements (NDAs) are put in place to allow the different sectors to share data regarding the composition of wastes and raw materials for cements. The sharing of details such as composition, physical characterisations, processing parameters, process tolerances and historical variation in these would allow

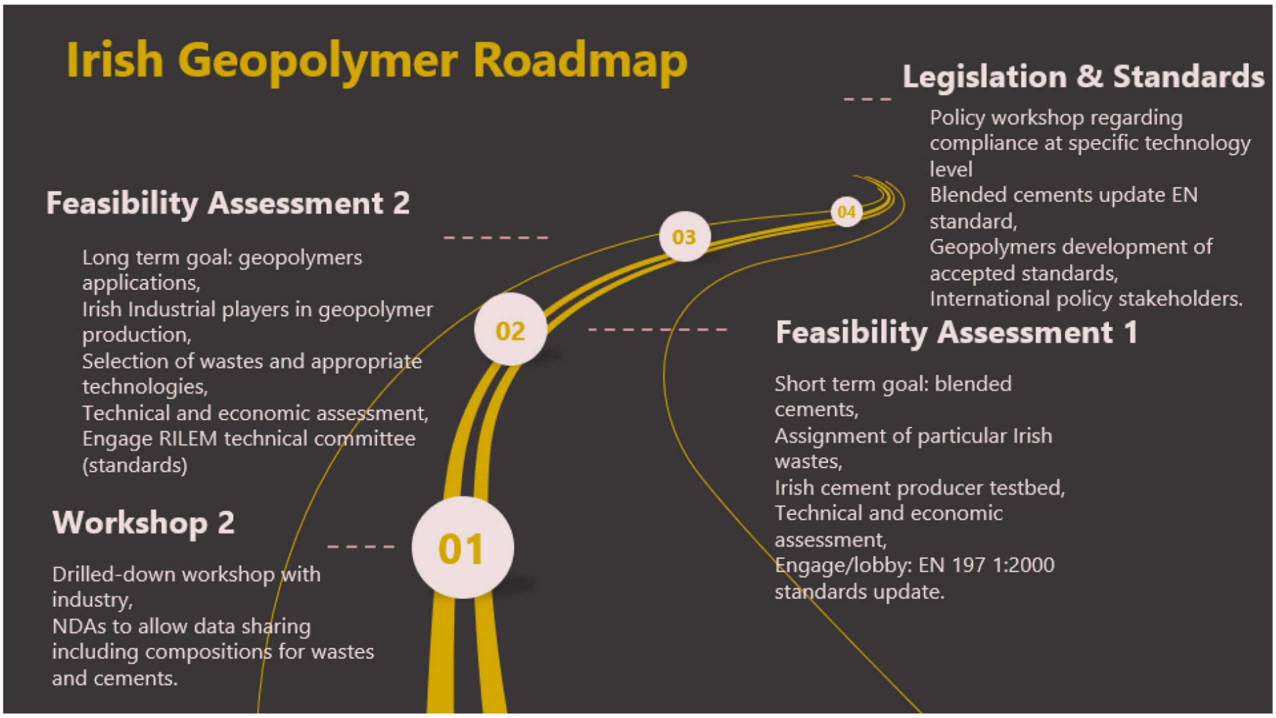

Figure 4.6. Irish geopolymer roadmap.

a detailed assessment of what industrial wastes or potential combined wastes could be used as blending materials or raw materials. A phased approach to the incorporation of Irish wastes into cements has been considered, with feasibility assessment 1 focusing on the acceptance of various Irish wastes as blending materials for traditional cements. This would require the selection of relevant wastes (facilitated by the preceding workshop) and the participation of the Irish cement sector to test blending compositions and tolerances. The results would then be available to provide a case for updating the EN 197-1:2000 standard for the inclusion of these waste materials in the CEM I–V categories.

Feasibility assessment 2 focuses on geopolymers and the industry within Ireland interested in pursuing geopolymer applications (which may or may not include the traditional cement sector). This would require selection of Irish wastes and relevant processing technologies to be tested to develop cement/concrete products for the market. Engagement with the RILEM technical committee regarding the development of standards for geopolymers is proposed. The incorporation of waste materials into the initial drafting of a geopolymer standard would be key and it would be of benefit to Ireland to ensure that drafts contained references to wastes that are prevalent within Irish industry where applicable (bauxite residue, biomass residues and waste-to-energy residues).

Legislation and acceptance (product and public) are the biggest challenges facing these materials and it is perceived that appropriate legislation and standards would go a long way towards public and product-level acceptance of new materials. An international policy workshop and early engagement with relevant associations regarding the development of standards is central to progressing geopolymers and/or new blended cements for the sector.

4.4 Concluding Remarks

According to the RILEM technical committee, there are several reasons why alternative cementitious materials have not received the same traction in the marketplace as OPC to date (Provis and Van Deventer, 2014). It highlighted six reasons as follows: (1) limestone is available everywhere so OPC can be produced in close proximity to markets, (2) advanced admixtures are not yet available for alternative cementitious materials, (3) OPC has an extensive track record of more than 150 years, (4) there are existing standards for OPC, (5) durability tests are linked with the standards regime for OPC and (6) the existing engineered design codes for OPC are based on a set of implicit assumptions relating microstructure to macro behaviour of the concrete under different environmental conditions and these assumptions may not be valid for alternative cementitious materials (Provis and Van Deventer, 2014).

Duxson and Provis (2008) reported that the main impediment facing the uptake of new construction materials is the existing standards regime, with prescriptive standards specifying particular mix designs for concrete rather than allowing any material that meets given performance standards to be utilised.

Perera (2007) found that conservatism of the end-user, lack of historical and long-term durability data, lack of investment in alternative cementitious material plants, improved scientific knowledge, and variability and use of ambiguous terminology are barriers to the use of alternative cementitious materials.

Greater acceptance and commercialisation of new materials require a bridge between research and routine field use (Heidrich *et al*., 2015). Maine *et al*. (2005) predicted that a 20-year period is needed for the widespread acceptance and substitution of new materials. They presented a methodology for a viability analysis of new materials that includes a technical feasibility study, production cost modelling, a value analysis and a market assessment. According to Maine *et al*. (2005), market assessment of new materials can follow two broad strategies: a search for new markets or applications created by the new material or exploration of substitution into existing markets. The substitution steps for new materials include identifying potential markets by comparing the properties of new materials with those of existing materials and noting the most promising property combinations of the new material, identifying the size of potential markets, prioritising potential markets according to size and type of substitution, assessing the utility of different markets and/or applications for performance–cost attributes, using logistics curves to estimate the time of market penetration and choosing a toe-hold market for roll-out (Maine *et al*., 2005; Heidrich *et al*., 2015).

The Modern Product Association (MPA, 2015) has stated that economic and regulatory changes, together with an increasing commitment from all stakeholders to sustainable development, are all drivers for change with regard to the cement process, composition and performance.

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Abbreviations

BS	British Standard
EU	European Union
GGBS	Ground granulated blast furnace slag
GHG	Greenhouse gas
NDA	Non-disclosure agreement
OPC	Ordinary Portland cement
SCM	Supplementary cementitious material

Appendix 1 Questions for the Survey of Stakeholders within the Market

A1.1 Questions for Geopolymer Institute and Academic Researchers

1. Are you aware of industry or pilot-level industrial wastes or by-products (e.g. bauxite residue, mine tailing, recycled glass, fly ash) applied in geopolymer production in Europe or elsewhere? If yes, where, what organisation and what type of process is used?
2. Regarding geopolymer technology, what do you believe would be the key influencing factors that would affect the usage of geopolymers as a construction material?
3. Are you aware of any concrete or cement products based on waste-based geopolymers that are available for purchase on the market?
4. Who are the main producers of geopolymer cements that you are aware of?
5. What technical standards are used to produce and assess geopolymer cements that you are aware of?
6. Are you aware of any particular legislation or requirements that affect the use of waste-based geopolymer cements in your country?
7. In your opinion, what are the main technical and/or scale-up challenges for the use of industrial wastes such as biomass ash, bauxite residue, recycled glass and mine tailings for geopolymer production?
8. Are there any industry reports or documents that review the state of the art that you would recommend?
9. Can you recommend geopolymer/waste example(s) that we could use as a case study? We are hosting an international workshop and are seeking a case study to present and invited speakers. Can you make any recommendations?

A1.2 Questions for the Alumina Industry and Associations

1. Are you aware of industry- or pilot-level bauxite residue applications for geopolymer production in Europe or elsewhere?
2. If yes, where, what organisation and what type of process is used?
3. Are you aware of any commercial-level uses of residue-based geopolymer cements?
4. Do you see any barriers to using bauxite residue in geopolymer cements?
5. Are you aware of any particular legislation or requirements that affect the use of bauxite residue-based geopolymer cements in your country or countries where your company operates?

A1.3 Questions for Cement Producers

1. In which country or countries do you operate?
2. How many years has your company been in the cement production business?
3. Except for standard OPC, do you produce cements with additives, such as waste or by-products, bauxite residue or other waste materials? If so, please state which additives you use.
4. How much OPC (in metric tons) does your company produce per year? If your company is using industrial waste additives, how much of this type of cement does your company produce per year?
5. What is the final destination of the cement produced by your company? If international, please state which country or countries your company exports cement to.
6. If geopolymer, a new-generation construction material formed by using industrial waste or

by-products, was available, would it affect your business model or value chain?

7. Are you aware of any concrete or cement products based on waste geopolymers that are available for purchase on the market?
8. In your opinion, what are the main technical and/or scale-up challenges for the use of industrial wastes such as biomass ash, bauxite residue, recycled glass and mine tailings for cement production?

A1.4 Questions for Geopolymer Cement and Precursor Producers

1. Which raw materials/waste materials does your company use for geopolymer products?
2. Are you aware of any concrete or cement products based on waste geopolymers that are available for purchase on the market?
3. Who are the main producers of cements with industrial waste and by-product additives that you are aware of?
4. How much (in metric tons) industrial waste or by-product materials does your company utilise per year?
5. How much (in metric tons) cement or other products, such as bricks and paint, does your company produce per year?
6. What is the final destination of the geopolymer products made by your company? If international, please state which country or countries your company exports to.
7. Does your company use any pre-treatment of raw materials such as carbonation or calcination? If yes, please state which material treatments you use.
8. In your opinion, what are the main technical and/or scale-up challenges for the use of industrial wastes such as biomass ash, bauxite residue, recycled glass and mine tailings for cement production?
9. We are hosting a national-level workshop – would you be interested in this or in supplying a good case study and are there any speakers you could recommend?

Appendix 2 National Stakeholder Workshop on the Use of Residue and By-products in Geopolymer Cement Applications

Algeopolymers

National Stakeholder Workshop on Use of Residue and By-products in Geopolymer Cement Applications

Wednesday 19 September 2018

Covanta Waste To Energy Facility, Dublin

Preamble

The University of Limerick are undertaking an EPA-funded project called Algeopolymers. The Algeopolymers project is researching the potential for Irish wastes to be used in geopolymer cement-type applications. This national stakeholder workshop forms part of the activities of the project to explore synergies in the Irish value chain.

Agenda

10.00	Welcome by **Mr Kieran Mullins, Covanta** Round-table introductions Introduction to the Event, BRAVO EIP & Algeopolymer Project by **Dr Lisa O'Donoghue, University of Limerick**
10.30	Tour of the Dublin Waste to Energy Facility Coffee and network (in boardroom)
11.30	Modern cement manufacturing and future challenges by **Mr Brian Gilmore, Cement Manufacturers Ireland IBEC**
11.50	Algeopolymer findings State-of-art uses of waste in geopolymer application by **Dr Éva Ujaczki, University of Limerick** Summary of Irish by-products and wastes by **Dr Rama Krishna Chinnam, University of Limerick** Introduction to REMOVAL – large-scale multi-pilots action across the EU regarding valorisation of bauxite residue by **Dr Lisa O'Donoghue, University of Limerick**
12.30	Geopolymer development activities by **Dr Wouter Crijns, ResourceFull, Belgium**
12.50	Developing functional materials through innovative processes by utilising industrial wastes by **Dr Konstantinos Sakkas, Geovalin, Greece**
13.10	Internal research project at Indaver by **team member, Indaver**
13.30	Lunch and networking
14.00	Workshop element Round-table discussion on potential value chain with in Ireland regarding: • blended cement and/or geopolymer applications • policy and legislation aspects • synergies between waste streams, potential for blending wastes • logistics and synergies between industry members
15.30	Roadmap recommendations and next steps post the event
16.00	Close of event

Notes:

1. H&S aspects: for participants undertaking the tour of the facility the following requirements apply: no skirts or heeled shoes are permitted.
2. Recommended accommodation: the Gibson Hotel or Sandymount Hotel.
3. Key aspects of the event will be recorded.

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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Algeopolymers

Authors: Éva Ujaczki, Chinnam Rama Krishna and Lisa O'Donoghue

Climate - Water - Sustainability

Identifying pressures • Informing policy • Developing solutions

Identifying Pressures

Concrete is the second most widely used material in the world and is made of cement, sand and aggregates. Cement manufacture requires high temperatures and generates substantial CO2 emissions. However, a new class of materials called geopolymers has potential construction applications and generates much lower CO2 emissions. In addition to this benefit there is also the potential for the incorporation of waste materials as core ingredients in the geopolymer cement, giving further environmental benefits through the use of waste as a resource. Potential candidate Irish wastes include bauxite residue, of which Ireland produces approximately 1.9 million tonnes annually from the alumina manufacturing process, and various types of fly ash from coal power stations, peat-powered stations and waste-to-energy plants within Ireland, which are all currently stored or sent to landfill.

Informing Policy

The Algeopolymer project was directly aligned with "a resource opportunity–waste management policy in Ireland", in which maximum value was sought from wastes by researching their reuse potential as core ingredients in geopolymer cement. This desk-based study investigated the potential to reduce the amount of waste going to landfill. A state-of-the-art review of wastes used in geopolymer applications internationally was undertaken and a database was developed for comparison with Irish wastes. Primary market research and a national stakeholder workshop were carried out with the Irish cement industry and waste producers to develop a potential roadmap for geopolymers in Ireland and to inform policy. Key challenges to the development of an Irish geopolymer market based on waste materials include legislative barriers and market acceptance.

Developing Solutions

Ordinary Portland cement (OPC) exerts a substantial environmental impact: OPC releases approximately 0.95 tonnes of CO2 per tonne of product whereas geopolymer cement creates only between 0.2 and 0.5 tonnes of CO2 per tonne of product. Geopolymer cement relies on minimally processed natural materials or industrial by-products to significantly reduce its carbon footprint, while also being very resistant to many of the durability issues that can plague conventional concretes. The use of waste materials for the manufacture of geopolymer cements would consolidate its position as an environmentally sound construction material of the future.

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