Zero Carbon Australia Presents

Zero Carbon Industry Plan

Rethinking Cement

beyond ZERO emissions

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In memory of Jennifer Bates

Jennifer Bates, a treasured BZE volunteer and coordinator of BZE Team Newcastle, was killed in a tragic accident in December 2016. Jen's family encouraged her many friends and admirers to donate to BZE's Zero Carbon Industry research. These donations have helped this report become a reality. As a trained architect Jen would have been delighted to see a BZE plan for reducing the embodied emissions of buildings.

Jen was passionate about the environment, and believed Australia could lead the world in tackling climate change. Her energy and enthusiasm helped BZE Team Newcastle become one of our most active national teams, and she organised successful BZE launches of both the Renewable Energy Superpower plan and the Electric Vehicles Report.

Jen was a highly-respected senior project manager for NSW Public Works. She used that role to reduce the government's environmental footprint, proposing and implementing emissions reduction initiatives for new buildings. Her colleagues saw her as a shining star dedicated to public service, and in 2016 she was presented with a Women in Building Recognition Award by the Master Builders Association.

Jen's passing is a huge loss to her friends and family and to the planet, and we miss her greatly at BZE.

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The Zero Carbon Australia project

Our vision is for a zero carbon Australia.

Our Zero Carbon Australia series outlines and costs a national transition to a zero emissions economy within ten years. Our research demonstrates that this vision is achievable and affordable.

Stationary Energy Plan

Launched in 2010, this plan details how a program of renewable energy construction and energy efficiency can meet the future energy needs of the Australian economy.

Building Plan

This 2013 plan outlines a practical approach to fixing Australia's buildings in a decade, showing how we can halve the energy use of our buildings, deliver energy freedom to people, and transform our homes and workplaces to provide greater comfort.

Transport Plan

Commenced in 2014, when complete this plan will show how Australia can maintain and enhance mobility without fossil fuels. The 2014 High Speed Rail study proposes a high speed rail network connecting capital cities and major regional centres along the east coast by 2030. The 2016 Electric Vehicle report shows how replacing all urban cars with electric vehicles in 10 years could be cost neutral and would have many social benefits.

Land Use: Agriculture & Forestry

The 2013 discussion paper shows how greenhouse gas emissions from land use – agriculture and forestry – can be reduced to zero net emissions within 10 years.

Renewable Energy Superpower

Launched in 2015, this plan highlights the enormous opportunities Australia has to leverage its natural advantages in solar and wind resources.

Zero Carbon Industry Plan

A plan for producing industrial materials such as cement, metals, plastics and chemicals without the emissions. Rethinking Cement is the first part of this plan, with further installments due in 2018.

About Beyond Zero Emissions

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Zero Carbon Industry

Nearly every national government in the world has committed to limiting climate change to well below 2°C and to aim for no more than 1.5°C. This means we must rapidly reduce our greenhouse gas emissions to zero.

To achieve this we have to develop 100% renewable energy systems, and make our buildings and transport systems zero carbon.[1] These sectors have received the vast majority of attention from policy-makers. In comparison the industrial sector has been all but ignored. Yet the production of everyday materials like steel, chemicals, plastics and cement is the source of 30% of global emissions. Without decarbonising industry, we stand little chance of achieving the Paris goals.

In Australia industry accounts for 21% of national emissions (Figure 1.1). That's without taking into account the emissions associated with goods we import, which are not factored into national emissions inventories.

Moving to 100% renewable energy will solve only a small part of this problem. Less than a third of Australia's industrial emissions are related to electricity use. A bigger part of the problem is industry's huge demand for heat, which it meets by burning fossil fuels. A further 22% of industrial emissions come from chemical reactions during processing. Cement-making alone causes 8% of global emissions, mostly due to chemical processes and heat requirements.

BZE's Zero Carbon Industry Plan

Clearly industry is a sector in need of zero carbon solutions. BZE's Zero Carbon Industry ground-breaking research aims to describe some of them, focusing on four areas:

- **Renewable heat –** how heat for industrial processes can be produced from zero emission sources
- **Steel –** how steel can be made without coal
- **Cement –** how we can make zero carbon and even carbon-negative cements
- **Using less –** how we can reduce waste and be smarter about the way we use materials in a zero-carbon world.

The starting point of our research is the pressing need to get to zero emissions. This differs from most work in this area which focuses on improving energy efficiency. The problem with this approach is that as long as processes are fossil fuel-based, making them more efficient won't get us even half-way to zero. In fact many existing processes such as steel-making are already very efficient and future gains will only be marginal.

Our research shows that zero carbon industry is entirely possible. We can get a long way using a range of technologies that are already commercialised, but not yet mainstream. But to reach zero carbon across all industries will require further development of some maturing but not yet commercialised technologies.

Setting a goal of zero carbon industry is not only essential for maintaining a safe climate, but will help to create the Australian industries of the future. BZE's influential *Renewable Energy Superpower report (2015)* showed how Australia has a huge natural advantage in a zero carbon world thanks to our abundant sources of solar and wind energy. One way of capitalising on this abundance is to produce energy-intensive materials here for the domestic and export markets, attracting manufacturers with cheap energy just as Iceland has done using its abundant geothermal power.

In Australia we have a once in a lifetime opportunity for an industrial renaissance – and to reap the rewards of economic growth and job creation.

The timing could not be better.

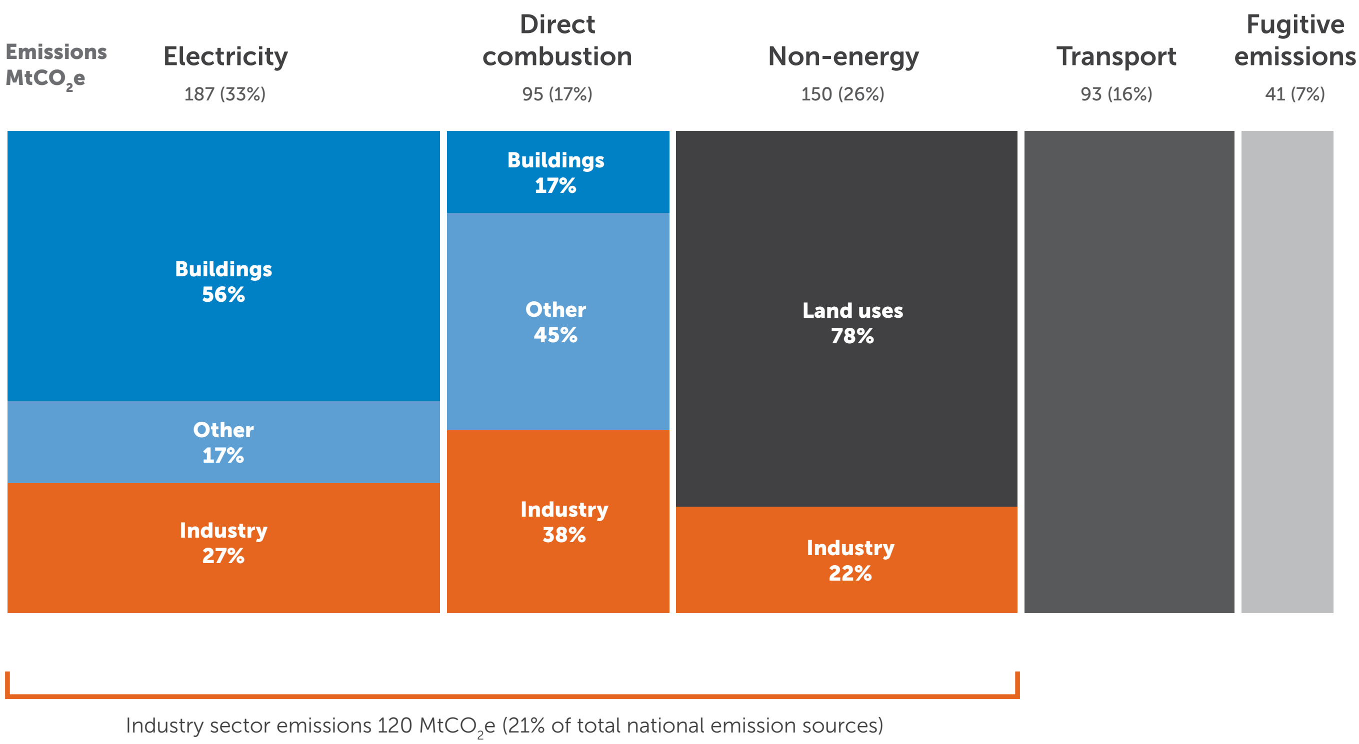


Figure 1.1: Australia's annual emissions by sector and the contribution of industry (2015)

Table of Contents

Executive summary

This report is the first part of Beyond Zero Emissions' Zero Carbon Industry Plan. It focuses on cement production, which is the single biggest industrial producer of emissions. Cement production causes 8% of global emissions – more than the global car fleet.[2] The report outlines how Australia can move to a zero carbon cement industry in 10 years.

Background

Cement is the key ingredient of concrete, the material we make more of than anything else. Around the world in 2015, we made 4 billion tonnes of cement. Concrete is everywhere – so commonplace as to be all but invisible – and is used to make large buildings, bridges, dams, tunnels and stadiums.

Despite its mundane reputation, concrete has been a vital part of celebrated structures for millennia, from the Egyptian pyramids and the Roman Colosseum to the Panama Canal and the Sydney Opera House, and people will continue to use cement in huge quantities in the decades ahead. But to enable rapid action on climate change, we must quickly change the way we make it.

The Problem

Since the 19th century, the industry standard cement type has been Portland cement, for which the raw material is limestone. The first stage of cement making is to transform limestone (calcium carbonate - $CaCO_3$) into lime (CaO), thus releasing carbon dioxide (CO_2) as a waste product. This single process accounts for about half of the carbon emissions associated with cement making, and therefore around 4% of the world's total emissions. The rest comes from the heat required to drive the production processes and the energy to grind and transport material.

When cement emissions are mentioned at all in public debate, it is typically to note that little can be done about them. However, this is true only if we continue to assume cement is limestone-derived Portland cement. In fact, there are existing alternatives with far lower carbon emissions, at similar cost, and with no loss of performance.

We can't continue to use limestone to make cement any more than we can keep burning coal.

The Solution

This report describes a pathway for tackling cement emissions, involving five strategies. Strategies 1 to 3 deliver a zero carbon Australian cement industry in just 10 years by changing the way cement is made. Strategies 4 and 5 would enable us in the longer term, to go beyond zero emissions, by changing the way we build and turning our built environment into a carbon sink.

- **Strategy 1 – Supplying 50% of cement demand with geopolymer cement.** The reactions involved in making geopolymer cements do not generate greenhouse gases, and therefore zero emission geopolymer cements are possible. Geopolymer cements made from fly ash (a by-product of coal-fired power stations) and ground-granulated blast-furnace slag (a by-product of steelmaking) are already made and used in Australia and overseas. It is also possible to make geopolymer cements from clay (metakaolin).

  Over a century of coal-burning has left Australia with more than 400 million tonnes of stockpiled fly ash. These stockpiles, which currently present an environmental problem, should be valued as one of our most readily available mineral resources. Once all coal-fired power stations in Australia are closed down, there are sufficient stockpiles of suitable fly ash to supply an estimated 20 years or more of domestic cement production.

  Geopolymer cement production does not require a kiln and therefore the set up cost of a new plant is relatively low, at less than 10% of a Portland cement plant. New plants can be established at or close to sources of stockpiled fly ash, potentially forming part of transition planning for local communities impacted by the closure of coal-fired power stations. A shift to metakaolin-based cements will be required prior to running out of fly ash stockpiles.

- **Strategy 2 – Supplying 50% of cement demand with high-blend cements.** Portland cement can be blended with other materials, reducing its carbon intensity. This strategy proposes increasing the proportion of replacement material to 70%, using fly ash, slag, clay and ground limestone. The use of high-blend cements will facilitate the transition to using alternative cements, with high-blend cements able to be manufactured largely using existing cement manufacturing equipment.

- **Strategy 3 – Mineral carbonation.** This strategy employs a new technology, mineral carbonation, to capture the emissions from the remaining production of Portland cement. With mineral carbonation, waste carbon dioxide is captured and chemically sealed within rock. Unlike conventional carbon capture and storage, there is no risk of leaking or need for monitoring post-storage. The process is applied in situ, and can produce substances with commercial value such as magnesium carbonate and silica.

- **Strategy 4 – Using less cement.** By designing structures to use concrete more efficiently, utilising high strength cement, and replacing concrete with timber, overall cement consumption could be reduced by around 15% in 10 years.

- **Strategy 5 – Carbon negative cements.** There is the long-term potential to develop magnesium-based cements which absorb carbon dioxide, and would therefore have a negative emissions profile.

Making It Happen

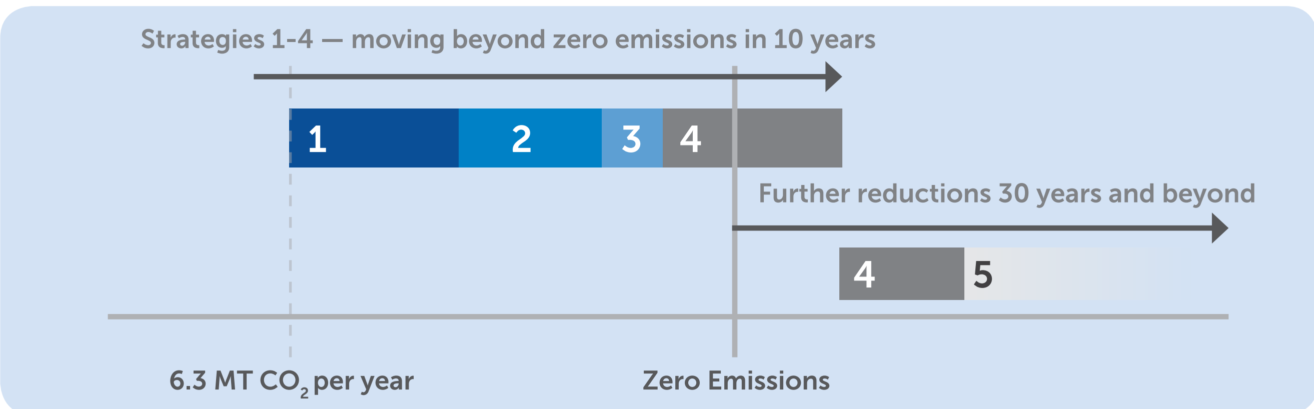
Governments and industry can support a rapid shift to a zero carbon cement industry.

One powerful stimulus to all the technologies presented in this report would be a national policy which puts a price on cement carbon emissions, including imported cement. The Australian Government could back up such a policy with a national target to reduce the carbon intensity of cement, which becomes progressively more stringent. This target could be supported by public investment into research and deployment of low-carbon cements, similar to the support for renewable energy provided by the Clean Energy Finance Corporation and the Australian Renewable Energy Agency.

We suggest that the Australian cement industry should be lobbying for policies of this type with the aim of becoming world leaders in this field. Governments and the construction sector could provide a huge boost by prioritising the procurement of low carbon cement, and mandating their use for non-structural purposes. Such changes to procurement would be facilitated by increasing the incentives to use low-carbon cements in sustainability rating tools such as Green Star and IS (Infrastructure Sustainability) Rating Scheme.

Finally governments should introduce new regulations or incentives to encourage the use in cement production of stockpiled fly ash and other waste materials such as waste glass, red mud and bagasse ash.

Figure 1.2: Overview of pathway to zero emissions cement.



Introduction

Cement is not a material we spend much time thinking about. But just as much as electricity or telecommunications, cement makes the modern world. This is because cement is the vital ingredient of concrete, a material so common as to be all but invisible, and which we use to make buildings, footpaths, bridges, dams, tunnels and stadiums. The commonplace nature of the material means that it has long been overlooked as a huge source of carbon emissions, even as the world finally begins to take climate change seriously.

Concrete and cement are modern materials with old origins. The ancient Egyptians, Phoenicians, Greeks and Chinese all knew how to make concrete. The Romans were the first to really exploit its possibilities, building structures such as temples, harbours and aqueducts, many of which are still intact 2,000 years later. By mixing lime and volcanic ash they made a cement that was not only strong and durable but had the ability to set under water.

These hydraulic cements fell into disuse after the fall of the Roman Empire. During the Middle Ages, Europe and the Islamic world lacked structural concrete, relying instead on bricks and stone bound with lime-based mortar. This technology was a step backwards, as it sets slowly and is eroded by rain.

In the 18th and 19th centuries British and French engineers began to rediscover hydraulic cements, driven by the need to build lighthouses on coastal rocks. This led to the invention of Portland cement, which has since become the basis for nearly all modern concrete. By the mid-20th century concrete had become the most important construction material, aided by improvements in cement technology and the introduction of steel reinforcement.

Since the beginning of the 21st century cement use has boomed further, driven by economic development and urbanisation in the developing world. Between 2011 and 2014 China produced more cement than the United States made in the entire 20th century.[3]

Globally in 2015, we made 4 billion tonnes of cement[4] and more than 20 billion tonnes of concrete.[5] The world will continue to need cement in huge quantities for decades to come, as rapidly developing countries like India, Indonesia and Brazil continue to urbanise.

This high level of cement use is set to continue for several decades, but it comes at a cost: **cement production is the source of 8% of global greenhouse gas emissions**[6] - more than all the world's cars put together. As a proportion of our emissions, cement is expected to rise significantly as we tackle other sources of emissions such as electricity generation (Figure 2.4). Despite this, cement-related emissions rarely feature in public debate about climate change, and so far no one has set out how we can continue to meet cement demand while maintaining a safe climate.

BZE has produced this report to highlight the extent of the problem with cement,[7] and to demonstrate that zero carbon cements are entirely possible. We believe that Australia is ideally placed to lead the world in their development and adoption.

Cement and greenhouse gas emissions

What is cement, and why is it so useful?

Cement is the binding agent that makes concrete possible. It is a grey powder consisting of a carefully controlled blend of minerals, most importantly calcium silicates (Ca_3SiO_5 and Ca_2SiO_4). When cement is mixed with water the calcium silicates react to form hardened calcium-silicate-hydrates, which bind the aggregates (sand and gravel) to make concrete. Cement can also be mixed with water, lime and sand to make mortar, the paste used to bind bricks and stones.[8]

We use so much concrete because it is strong, durable and impermeable. In previous centuries we relied on stone and brick to provide these properties, but concrete has two major advantages over those materials. Firstly we can add steel reinforcement to give the material flexural strength, meaning it can withstand a large bending force without cracking, whereas stone would break.

The second big advantage of concrete is that when freshly mixed, it can be easily moulded into any shape, either in a factory or at a construction site. This attribute accounts for the enormous variety of concrete applications in buildings and infrastructure. It also means concrete structures can be built far more quickly, and with less labour, than those made with stone. If we didn't have cement, most major construction projects would be more technically challenging, and some would probably be impossible. In fact the biggest difference in a world without cement would be the armies of workers required to make and lay bricks and stone.

Why Portland cement is the universal cement

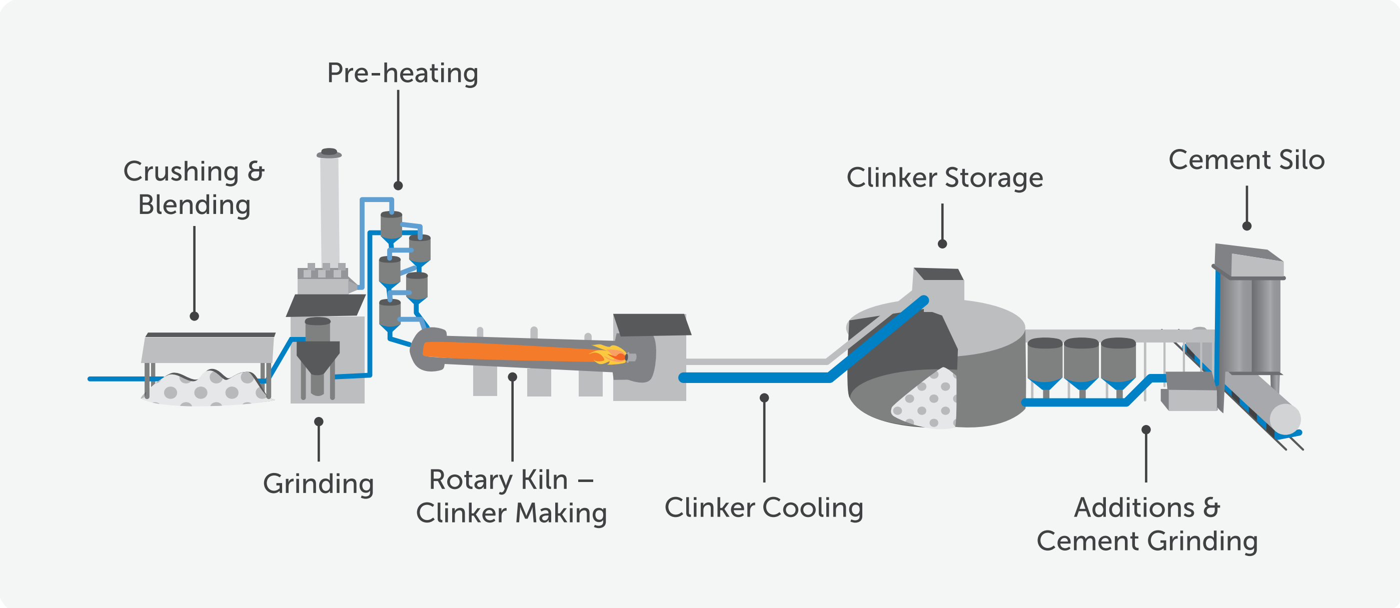
By far the most common cement is Portland cement – accounting for 98% of world production.[9] Portland cement produces high quality concrete, but there are other reasons for its central role. Firstly, it is easy to use even by untrained workers because it is a predictable product that does not demand a high level of rigour in mixing and application. Secondly, the raw materials for Portland cement (principally limestone) are abundant in most regions of the world. And thirdly, after nearly two hundred years of experience, engineers have confidence in its performance and long-term durability.

How Portland cement is made

The main raw material in Portland cement is usually limestone, a sedimentary rock formed from the shells and skeletons of marine organisms over hundreds of millions of years. After being mined and crushed, limestone is combined with ground clay and fed into a rotary kiln. The high temperatures within the kiln (up to 1,450°C) are achieved by burning fossil fuels, usually coal, coke or methane. At this temperature the raw materials fuse into various calcium silicates - called 'clinker'.

The clinker is then ground up with other materials, mainly gypsum (calcium sulphate), and sometimes additional materials, such as blast-furnace slag, coal fly ash, or ground limestone. This produces a homogeneous powder (Portland cement) which is stored in silos before being dispatched in bulk or bagged. Figure 2.1 shows the steps involved in cement manufacture.

Figure 2.1: The process of manufacturing cement



Cement manufacturing in Australia

Cement manufacture is a significant national industry. In 2014-15 Australia's three cement manufacturers (Adelaide Brighton, Boral and Cement Australia) produced 9.1 million tonnes of cement, all for domestic consumption.[10] This was supplemented with 2.76 million tonnes of imported clinker and cement, mostly from Japan and China.[11] The industry had a turnover of A$2.4 billion in 2014-15 and employed over 1,500 people.[12]

Cement plants are major manufacturing sites, often capable of producing more than one million tonnes of cement per year. These plants are major investments, costing hundreds of millions of dollars to set up and tens of millions more to maintain and upgrade. These high costs mean cement-making tends to be a centralised industry.

In Australia there are just five integrated cement plants (combining clinker manufacture and cement grinding) and five stand-alone cement mills (Table A3.1 - Appendix 3).

Australia's national production of cement is well below one percent of the global production, and future growth is likely to be modest. In recent years more than half of global production has occurred in just one country – China. For the foreseeable future the majority of cement production will be in China and other developing countries such as India, Indonesia and Brazil.

How cement-making produces greenhouse gas emissions

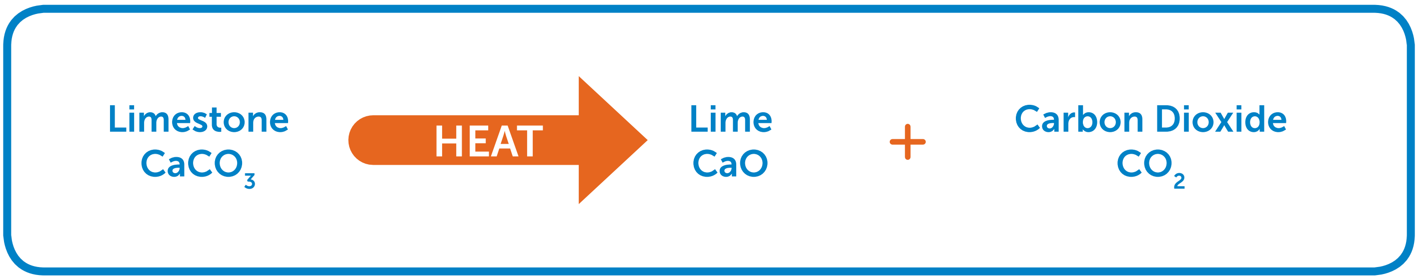
The manufacture of one tonne of cement causes about 0.87 tonnes of carbon dioxide emissions (global average).[13] The average emissions of Australian cement manufacturers are about 0.82 tonnes of carbon dioxide.[14] This is slightly better than the global average but not as good as the world's best performance of around 0.7 tonnes.

More than half (55%) of the emissions from cement making are a result of heating limestone. When a cement rotary kiln reaches about 900°C the limestone (calcium carbonate - $CaCO_3$) begins to decompose into lime (CaO)[15], and releases carbon dioxide (CO_2) as a waste product. This is known as limestone calcination[16] and this single chemical process accounts for around 4% of the world's total emissions. These emissions are unavoidable as long as we produce limestone-based cement. Figure 2.2 shows the key chemical process.

A further 32% of cement-related emissions come from burning fossil fuels (coal, coke or natural gas) to generate the heat required to make clinker in the rotary kiln. The remaining 13% of emissions relate to the electricity used to grind and transport material. Producing one tonne of cement requires between 3,000 and 6,000 megajoules of energy depending on the process efficiency and raw materials used.[17] The average level has been reduced in recent years to around 4,000 megajoules. Even so cement-making uses more energy than any other industry, accounting for 10-15% of the world's total industrial energy consumption.[18]

Globally, the manufacture of cement produces more greenhouse gas emissions than any other single product – about 3 billion tonnes per year, or 8% of the world total. In Australia, production of Portland cement is responsible for 7.4 million tonnes of emissions, about 1.3% of national emissions. If we include the contribution of imported cements this rises to 9.7 million tonnes.

Figure 2.2: The transformation of limestone into lime, producing carbon dioxide



There are additional cement-related emissions that Figure 2.3 does not take into account, including mining and transport of limestone and other raw materials. These emissions represent only a small fraction (<5%) of the total and are excluded from our analysis. They could be eliminated through electrification, and all-electric mining operations already exist.[20]

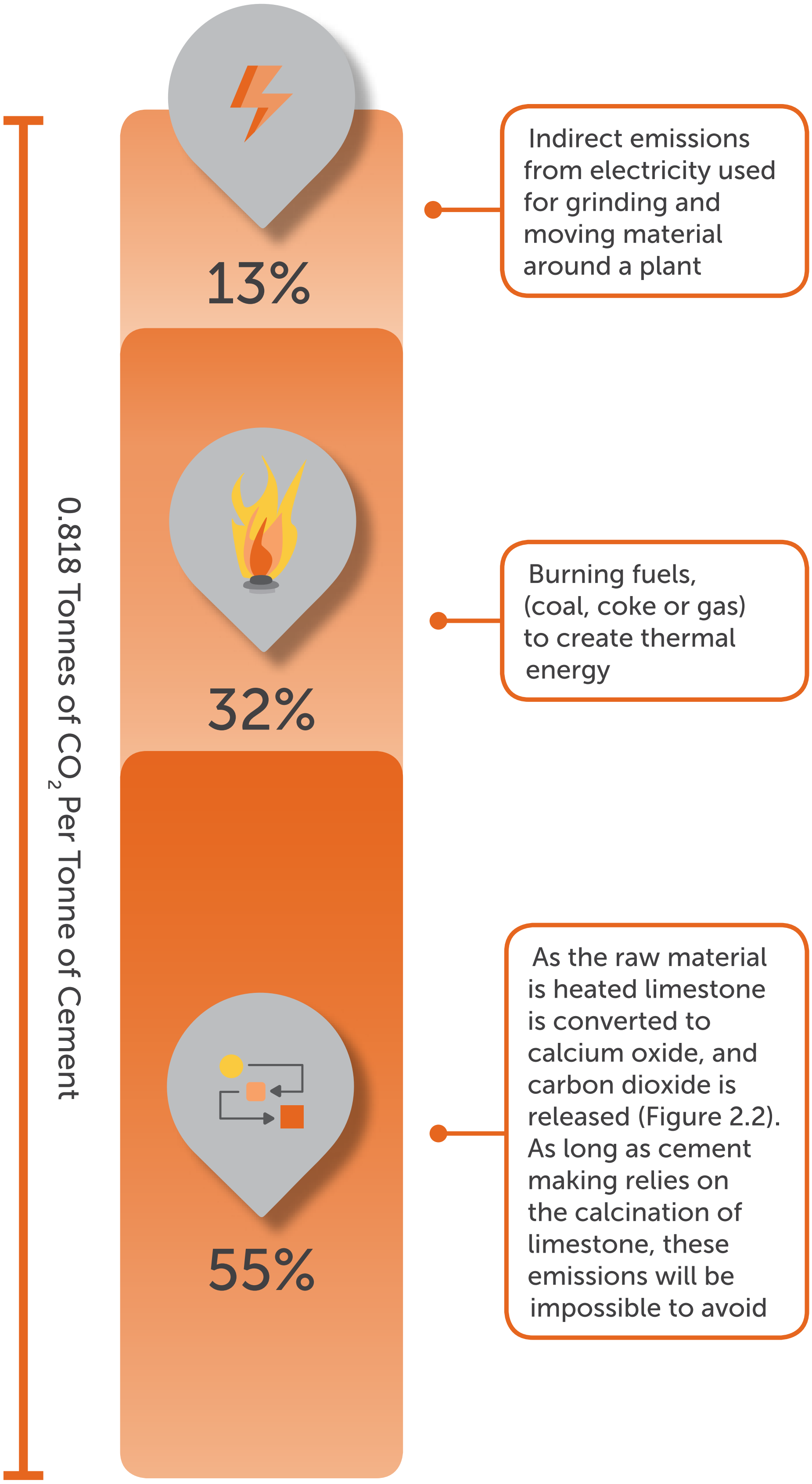


Figure 2.3: Source of greenhouse gas emissions in a cement plant [19]

What is the likely level of cement-related emissions in 2050?

Global demand for cement is likely to remain high for several decades as more countries develop and rural populations continue to migrate to cities. Forecasts of demand in 2050 range from 3.7–5.5 billion tonnes.[21] If this cement were produced using today's best available technology, it would result in the emission of 2.6–3.9 billion tonnes of carbon dioxide. This should be seen in a context where, to have even a 50% chance of limiting warming to 2°C, net global emissions by 2050 must be no more than 14.9 billion tonnes.[22]

Cement industry efforts to reduce emissions

By extending the downward trend of recent decades the Portland cement industry could reduce emissions by 2050. Industry efforts to improve the emissions-intensity of its product have focused on three areas:

- **improving efficiency** – modernising cement kilns so they use less energy
- **alternative fuels –** replacing a proportion of fossil fuels with alternatives such as wood wastes, used tyres and fuels derived from refuse
- **clinker substitution –** increasing the level of clinker substitutes (known as supplementary cementitious materials) such as fly ash - the main waste product of coal-fired power stations. This substitution reduces the amount of limestone that needs to be calcined, without reducing the quality of the cement (See Strategy 2, p41).

Since 1990 through a combination of these measures the cement industry in Australia has reduced emissions – but only by about 10%.[23] Cement production is already one of the most efficient industrial thermal processes, hence further reductions due to efficiency improvements may be limited to about 3%.[24]

Further small reductions – the industry has estimated around 8% – are possible from greater use of alternative wastes and bio-based fuels. However, in a low carbon world there will be many demands on such resources, and there is no reason to think they will be reserved for the cement industry. The cement industry also foresees only small reductions in emissions from the substitution of greater proportions of clinker with supplementary cementitious materials. As will be described in Strategy 2, BZE believes far greater improvement in this area is possible.

Several studies have quantified the long-term potential to continue emissions reductions through determined effort in these three areas. For example, in 2015 the UK Government found that by 2050, with maximum technological effort, emissions related to production of a tonne of cement could be reduced by 25%.[25] A 2009 roadmap issued by the Cement Sustainability Initiative,[26] which involved many of the world's leading cement producers, estimated the industry could achieve an "ambitious" 18% reduction by 2050.[27]

We cannot rely on carbon capture and storage

Unfortunately such levels of reduction are not enough even to offset potential growth in cement production, and far below what is needed for a safe climate. This has led both the UK study and the Cement Sustainability Initiative to explore the use of a fourth measure to reduce cement emissions – carbon capture and storage (CCS).

This involves capturing the emissions from a cement plant and then securing the carbon dioxide component underground. The appeal of CCS is that it deals with emissions from the calcination of limestone, unlike the current approaches to emissions reduction. The Cement Sustainability Initiative found that by 2050 CCS could reduce the sector's emissions by a further 20%, contributing to overall reduction of about a third.

As detailed in an earlier BZE report on carbon capture and storage, this is not a viable strategy.[28] For years CCS has been touted as a solution to emissions from fossil fuel-fired power stations, but has rarely been implemented. The main obstacle is the huge cost. If coal-fired power stations, with their even higher emissions, have failed to embrace CCS, it is hard to see how it would be viable for cement companies. Adding CCS to a new cement plant would double both capital and operating costs,[29] and no company in the world is seriously considering it. Another huge barrier to the implementation of CCS is that it requires the presence of a local geological formation suitable for locking away carbon dioxide. Even if a cement plant happens to be near such a formation, the long-term behaviour and security of the stored carbon dioxide is not well understood.

A related technology with more promise is mineral carbonation, where carbon dioxide is reacted with a chemical to form a stable carbonate rock. Mineral carbonation is more practical and likely to become more cost-effective than CCS, and is explored in more detail in Strategy 3.

Limestone – the new coal?

If asked to name the major contributors to climate change, many people would list coal, oil and gas, but few would mention limestone. This needs to change. As we aim for a safe, liveable climate we need to recognise the similarities between limestone and coal. Both materials were formed over eons through the compression of countless organisms. Both underpin the modern era, with billions of tonnes dug up each year. And, crucially, our use of both limestone and coal leads inescapably to the release of ancient carbon, and the acceleration of dangerous climate change.

We can't continue our use of limestone for cement any more than we can keep burning coal.

We must urgently find a better way of making cement

With current methods of production cement emissions are on course to consume 26% of the world's carbon budget by 2050 (Figure 2.4). Even if we assume the global cement industry achieves its own reduction targets, cement-related emissions in 2050 will account for an alarming 20% of the world's remaining carbon budget. (This refers to the carbon budget for a 50% chance of limiting warming to 2°C. It would be as much as 40% of the 1.5°C global carbon budget.[30])

As it stands cement manufacturing is incompatible with global climate commitments. To prevent catastrophic climate change, developed countries like Australia must be carbon neutral by 2050, as most state and territory governments acknowledge. ACT, NSW, South Australia, Queensland and Victoria all have targets or policies for zero emissions by 2050.

If we don't rethink cement this essential material could be a major factor in blowing the planet's carbon budget – the maximum amount of greenhouse gas we can emit to have a reasonable chance of preventing disastrous climate change. The key technical challenge here is the calcination of limestone – a process which leads unavoidably to large scale carbon dioxide emissions. In the fight against climate change calcining limestone should be seen as problematic as burning coal. But unlike coal-fired power generation this is not a problem that can be addressed by switching to renewable energy.

What we need is radical change in cement production. Slow, incremental improvements advocated by industry will not achieve deep enough cuts. We urgently need to find ways of making emission-free cements that perform as well as, or better than, Portland cement. **The only sustainable trajectory for cement manufacture is one that leads to zero emissions.**

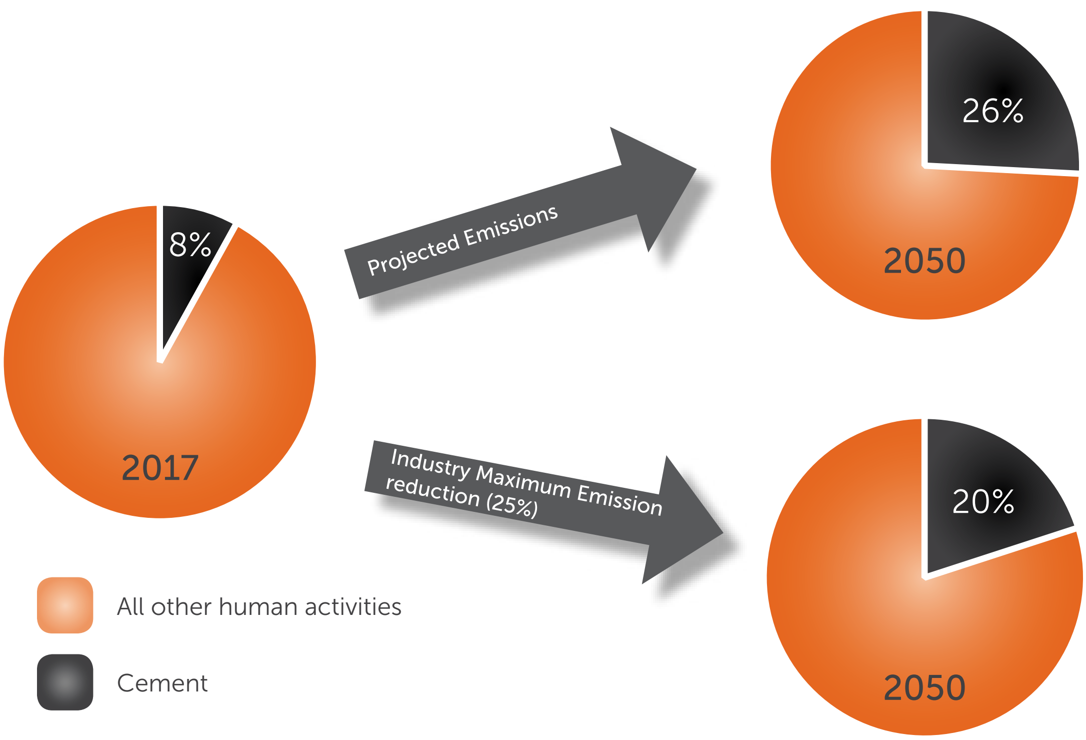


Figure 2.4: Projected CO_2 emissions associated with cement production compared to all other human activities (high demand scenario - 5.5 billion tonnes per year) [31]

Absorption of carbon dioxide by Portland cement

As it ages Portland cement concrete slowly carbonates, reabsorbing carbon dioxide. Attempts have been made to quantify the amount, with one recent well publicised study claiming that 43% (16.5 billion tonnes CO_2e) of emissions due to calcining limestone between 1930 and 2013 have been reabsorbed.[32] The study did not include the emissions from using fossil fuels in cement manufacture. When we include these emissions the percentage of carbon dioxide reabsorbed would be a little over 20%.

Contrary to recent reporting of this research, the carbonation of Portland cement concrete does not reduce the urgency of finding a replacement. Carbonation is a slow process. The carbon dioxide released during cement-making is only absorbed over years, during which time it has a global warming effect. Furthermore, carbonation actually harms reinforced concrete as it leads to steel corrosion, and ultimately the demolition of buildings and the manufacture of more concrete. It is important to consider the carbonation of concrete when quantifying global sources and sinks of carbon, but it does not lessen the need to develop lower carbon ways of making cement.

Moving to zero carbon cement

As we have shown, the cement industry is responsible for a remarkably large and growing proportion of greenhouse gas emissions. Neither industry nor governments have a plan for limiting these emissions to a level compatible with a safe climate. In this report BZE proposes a 10-year pathway for an Australian cement industry with zero emissions - the only sustainable level.

BZE believes this is the world's first detailed plan to eliminate cement-related emissions. If we follow this plan, our cement industry would make a major contribution to Australia's obligations to tackle global climate change. Implementing this plan would have the additional benefits of creating an international market for Australian technology and expertise in zero carbon cement, and consuming large amounts of waste material such as fly ash.

We do not suggest this is the only viable pathway to zero carbon cement – there are likely to be others. But we hope this report will inspire policy-makers and the cement industry to be more ambitious, and start planning for emissions reduction on the scale now urgently required.

Five strategies for zero carbon cement

Our 10-year plan to decarbonise cement consists of four achievable and affordable strategies (Figure 3.1).

These strategies are a complementary package, which when implemented together, can reach our target of zero-emission cement within a decade. The strategies include a diversity of approaches, enabling flexibility to respond to differing rates of technological development and cost reduction. This makes the overall pathway to zero emissions more robust. If one strategy proves less economic or scalable, others can be ramped up. An apt comparison is with the switch to 100% renewable electricity, which will rely on a range of technologies deployed in combination.

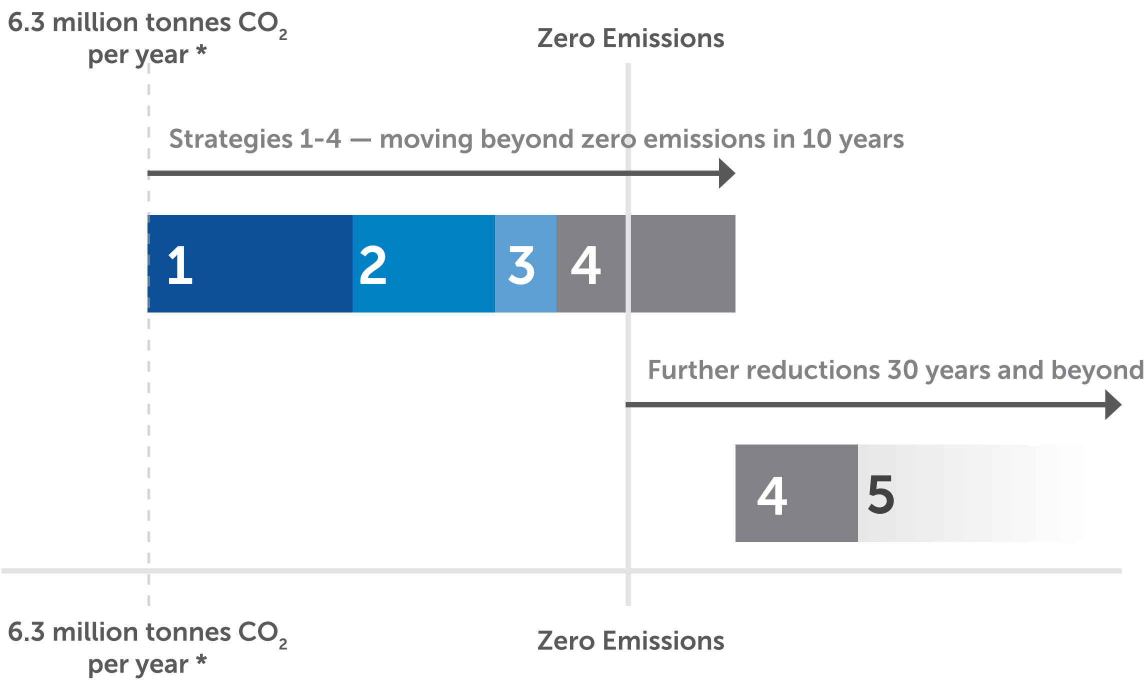
Strategies 1 and 2 involve alternative cements that are fit-for-purpose and made from raw materials available in sufficient quantities in Australia. **Strategy 1** relies on cements that could be zero carbon, whereas **Strategy 2** has some residual emissions. **Strategy 3** demonstrates a method for removing these residual emissions by capturing carbon dioxide and using it to create useful materials. **Strategy 4** focuses on reducing our use of cement, simplifying the task of transitioning to alternatives. The use of timber in **Strategy 4** means that our overall pathway could actually be carbon negative (Figure 3.1).

Beyond the 10-year timeframe, we suggest a **fifth strategy** based on carbon negative cements. We have included this strategy due to the potential of a genuinely carbon negative cement to make a significant contribution to the fight against climate change. While these cements are promising, they are not yet ready to be commercialised and require further research.

In describing this transition we acknowledge the considerable advantages of Portland cement, such as its versatility and easiness to work with. We believe replacing Portland cement will be a challenge, but one that Australia and the world can and must step up to. **As the world nears dangerous levels of warming, business-as-usual is no longer an option.**

beyond ZERO emissions

Figure 3.1: Overview of pathway to zero emissions cement.



			Emissions reduction (CO_2)	
		Target	10 years	30+ years
Strategy 1	Using geopolymer cements that contain no Portland cement	replacing 50% of cement market	2.7 MT	
Strategy 2	Using high-blend cements with a low volume of Portland cement	replacing 50% of cement market	1.9 MT	
Strategy 3	Carbon mineralisation	reducing remaining Portland cement emissions to nearly zero	0.8 MT	
Strategy 4	Minimising the use of cement	reducing cement use by 15%	0.9 MT¤ 1.4 MT×	3 MT
Strategy 5	Carbon negative magnesium-based cements.	developing commercial carbon negative cements	–	2-3 MTˇ

** Estimated process emissions from Australian cement production in 2027 (business as-usual)*
¤ Avoided emissions from reducing cement use
× Carbon sequestered in structural timber
ˇ Carbon sequestered in concrete (uncertain)

Objectives, principles and assumptions

In developing this pathway we have been guided by the objectives, principles and assumptions set out in Table 3.1. Figure 3.2 shows how the report deals with different types of cement-related emissions.

Figure 3.2: Treatment of cement-related emissions in this report and the overall Zero Carbon Industry Plan

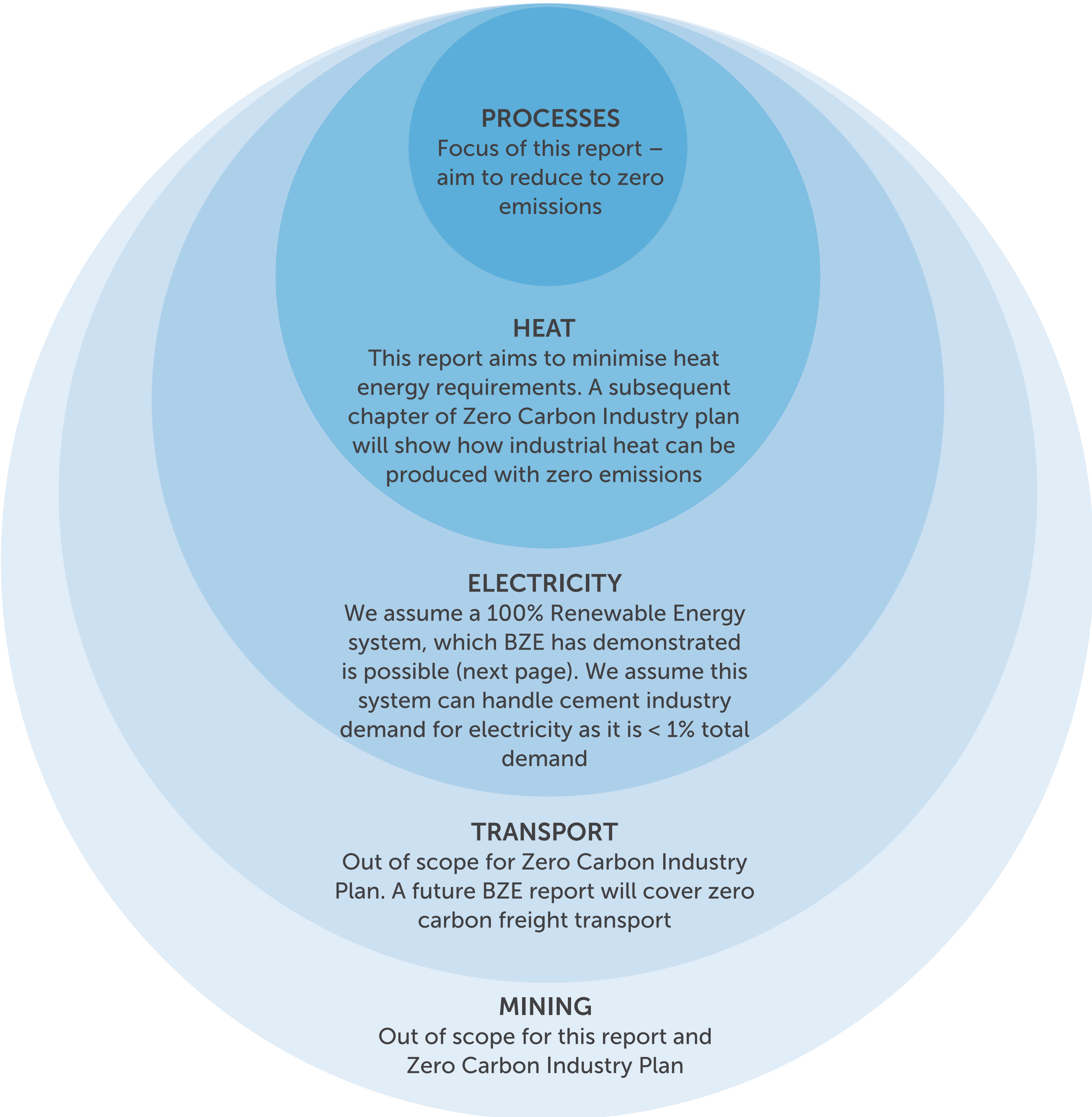


Table 3.1: Objectives, principles and assumptions in this report

Overall objective	To reduce cement-related emissions to zero
Additional objectives	• To develop a viable zero carbon cement industry that Australia can export to the world, including cement products and intellectual property. • To reduce the use of Portland cement clinker to the bare minimum, given the extreme difficulty of reducing emissions from this product.
Principles	• Replacement cements must be fit-for-purpose and ready to be commercialised. • Solutions must be applicable to Australia, in particular the raw materials must be available domestically in sufficient quantities. • Where we identify solutions as applicable outside Australia, we must demonstrate the availability of raw materials overseas. • We define a zero carbon cement as one with no process emissions (ie those from calcining limestone). Such a cement would have no associated emissions in an economy where sectors such as electricity, freight transport and industrial heat supply are decarbonised (Figure 3.2).[33] • If there are cement-related emissions we can't avoid we will consider how these could be captured and secured.
Assumptions	• One tonne of alternative cement can replace one tonne of Portland cement. • The pathway assumes a domestic cement demand of 14 million tonnes in 2027. This is based on current annual consumption of 12 million tonnes and a 1.5% annual growth rate.[34] • The process emissions of 14 million tonnes of cement would be 6.3 million tonnes. This is the figure we aim to reduce to zero. • We consider four broad categories of cement use: precast concrete; pre-mixed concrete (<40 MPa); high-performance pre-mixed concrete (>40 MPa) and bagged cement (Figure 3.3).

100% renewable electricity system for Australia

In this report we assume that Australia sources 100% of its electricity from renewable sources. Beyond Zero Emissions' Stationary Energy Plan, launched in 2010, showed how this could be done within ten years.

The plan proposed 40% wind generation, with concentrated solar thermal (CST) plants providing almost 60% of capacity and the storage needed to give reliable 24-hour power, 365 days a year. In CST plants, solar power is used to melt salt and keep it at high temperatures. This stored heat can later be used to produce steam that drives turbines. Twelve of these CST plants around the country would suffice. A small role for hydro and biomass was also envisaged as backup.

Since 2010, studies by the Australian Energy Market Operator, Australian National University and others have confirmed that Australia is able to move to a 100% renewable system. In the intervening seven years the shift has become a lot more straightforward as renewable power generation costs have plunged below coal, gas or nuclear. We have more than enough solar and wind resources to generate electricity for all our industrial needs.

BZE's study shows that a transition to 100% renewables would not only reduce carbon emissions, it would be less hazardous to health, consume less water than coal-fired power plants and provide at least as many jobs as fossil-fuel enterprises.

Australia's current cement market

The switch to zero carbon cement must take account of the existing Australian cement market. To succeed alternative cements must be useful for the same purposes, and capable of providing the same level of performance for key attributes of cement and concrete listed in Table 3.2.

How is cement and concrete sold to the market?

There are three types of concrete and cement product sold to the public: pre-mixed concrete; manufactured precast concrete products and dry bagged cement (Figure 3.3).

Pre-mixed concrete

The largest market (70%) is for pre-mixed concrete made in a central plant and delivered to a work site in semi-liquid form by transit mixer. The cement is pre-mixed with water, sand and gravel in precise quantities, meaning quality can be more carefully controlled than if the concrete was mixed on site.

Most pre-mixed concrete is a standard strength concrete for residential and light commercial and industrial applications such as driveways, low-rise buildings, footpaths and house foundations. It typically achieves a compressive strength of around 20-30 megapascals (MPa). Standard pre-mixed concrete accounts for more than half of cement demand in Australia.

Large building foundations and major infrastructure tend to require a stronger concrete. Pre-mixed concrete above 40 MPa accounts for about 15% of the domestic market. The rest of the pre-mixed industry is geared towards decorative concrete and specialised concrete, tailor-made to a client's specifications, for atypical uses such as highly-corrosive or marine environments.

To progressively replace high-emission pre-mixed concrete we need a product that can be mixed in a central plant and remains semi-liquid during the time taken to transport and work it on-site. It also needs to set within a reasonable length of time at ambient temperature in the same way as Portland cement concrete.

Precast concrete

About 20% of cement is used to make concrete products such as panels, pipes, bricks, blocks, tiles and beams. This proportion has been increasing in recent years as precast products allow faster and more precise construction compared to using pre-mixed concrete.

Precast concrete products are made in a factory under controlled conditions, meaning manufacturers are able to use cements that might pose challenges on a construction site. Attributes such as lower workability, longer setting time or toxicity can all be managed in a regulated factory environment, and any necessary training can be provided to workers.

Dry bagged cement

The final 10% of cement is sold in its dry powered form, often in 20 kilogram bags. There is no data on how this cement is used, but we can assume it is largely for small scale applications such as landscape gardening and small-scale renovations. Dry cement is also mixed with sand and hydrated lime to make mortar for laying bricks and masonry blocks. In many developing countries bagged cement accounts for the majority of the cement market.[35]

Dry bagged cement must be easy to mix on-site into concrete and mortar, preferably following simple instructions so someone without training can work with it. It also needs to set within hours at ambient temperature.

Figure 3.3: Australia's cement use: baseline for pathway to zero emissions[36] (Australian demand in 2027 in million tonnes)

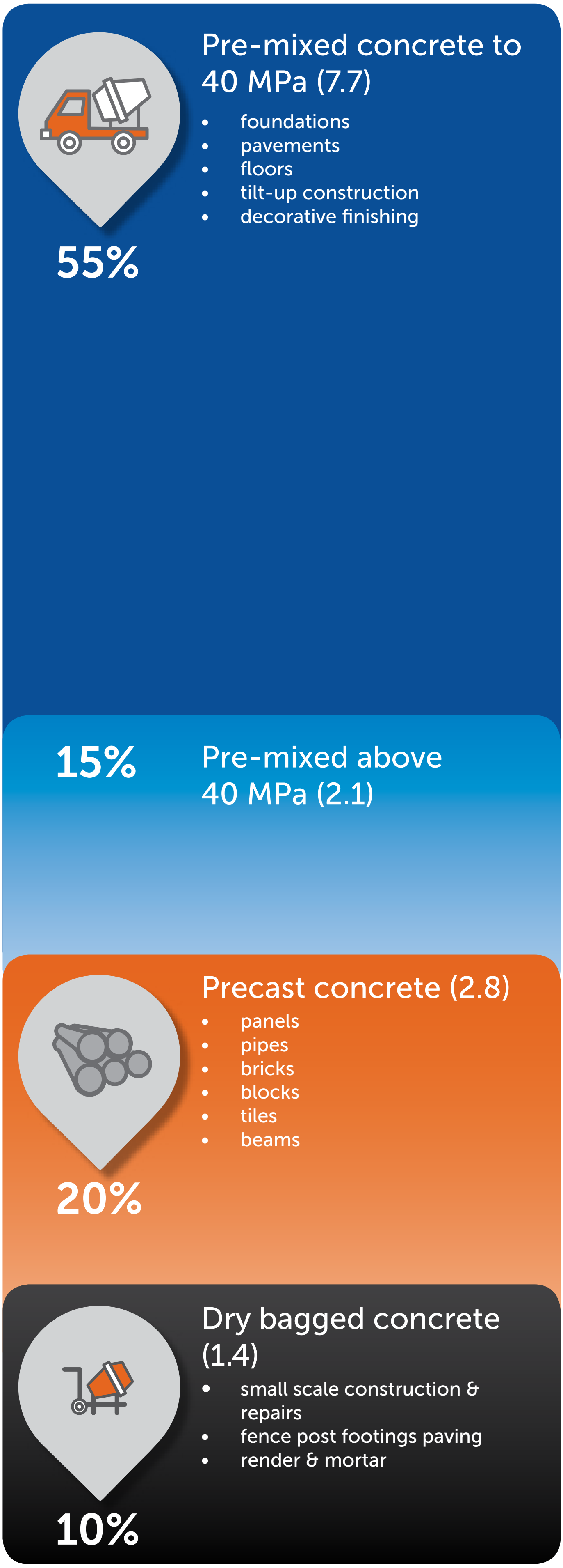


Table 3.2: Key properties of concrete which are influenced by cement

Compressive strength	Often considered the most important property of concrete, measured in megapascals (MPa). 40 MPa concrete can withstand the equivalent of 800 African elephants (4,000 tonnes) per square metre before failure.
Flexural strength	Ability to withstand bending, measured in megapascals (MPa). Typically around 10% of the compressive strength.
Durability	Long term performance, including resistance to chlorides, sulphates and acids.
Workability/Slump	The ease with which concrete can be poured, moulded, compacted and finished.
Setting and hardening time	Cement should ideally set within a few hours – giving enough time to work the concrete but not so long that construction is delayed. It will continue to harden to reach its target compressive strengths – as measured after 7 and 28 days.
Fire resistance	Concrete can often be used without additional fire resistance because it does not burn and conducts heat very slowly.
Drying shrinkage	As concrete hardens it dries leading to some contraction. This can lead to unsightly cracks in the concrete which can reduce its service life.
Safety for workers	Cement and fresh concrete are strongly alkaline (pH13) and can irritate or even burn skin. Traditional cement and concrete are however considered safe enough for handling by unskilled workers.

Strategy 1 – Geopolymer cement

Strategy 1 at a glance

- Geopolymer cement accounts for 50% of the market in 10 years – 6 million tonnes of cement.
- The uptake of geopolymer cement starts where it has an advantage over traditional cement, e.g.:
  - Hostile environments such as sewers
  - Applications requiring a high level of fire-resistance such as road tunnels
  - Precast products where the lower cost of fly ash can be maximised.
- The strategy has materials requirements of:
  - Fly ash (3.8 million tonnes)
  - Ground granulated blast-furnace slag (0.63 MT)
  - Metakaolin (0.57 MT)
  - Ground limestone (0.6 MT)
  - Alkali-activator (0.39 MT)
- The required fly ash will be sourced entirely from stockpiles from 2024.
- Geopolymer manufacturing will be decentralised, often based at the site of closed coal-fired power stations for easy access to stockpiled fly ash.

What is geopolymer cement?

Geopolymer cements are a well-established class of cements that can be produced with much lower greenhouse gas emissions (potentially zero).[37] They provide the same functions as Portland cement but with a different underlying chemistry. Geopolymer cement is made by reacting a solid aluminosilicate material with an alkaline solution – known as the alkali activator.

Currently most commercially available geopolymer cement is based on two materials: fly ash (waste ash produced in coal-fired power stations) and ground granulated blast-furnace slag (GGBS, a by-product of iron blast-furnaces). However geopolymers can be made with almost any material with a high enough content of aluminosilicates (silica - SiO_2 and aluminium oxide - Al_2O_3).[38] Silicon and aluminium are the second and third most abundant elements in the earth's crust, and so abundant natural sources exist in Australia and overseas.

Significant research demonstrates the potential to make geopolymer cement with certain types of clay and volcanic ash, as well as a variety of waste products. The key is to design a cement composition in which the raw materials and activator complement each other, tailoring the cement to suit its application.
Viable geopolymer mixes include:

- fly ash + GGBS + activator
- fly ash + activator
- fly ash + waste glass + activator
- clay (metakaolin) + activator
- clay (metakaolin) + red mud + activator.

Geopolymer cement

A polymer is a large molecule consisting of chains of repeating subunits. We are most familiar with organic polymers such as plastics and DNA. A geopolymer is an inorganic mineral-based polymer. The term was coined by Joseph Davidovits in 1978 to describe the type of mineral binders that make geopolymer cement.

Carbon benefits of geopolymer cement

In terms of energy and emissions geopolymers have two huge advantages over Portland cement. The most important advantage is that there is no need to calcine limestone. In fact the reactions involved in making geopolymer cement do not generate any carbon dioxide or other greenhouse gases. This removes more than 50% of cement-related emissions at a stroke.

The second energy-related advantage of geopolymer cements is that their manufacture is a low temperature process. The principal reactions take place at room temperature, thus avoiding the need to burn large quantities of fossil fuels required in Portland cement manufacture.

Due to these advantages, geopolymer cement made in Australia today produces at least 80% fewer emissions than Portland cement. This is based on independent life-cycle analyses of current products such as Zeobond's E-Crete and Wagners Earth Friendly Concrete.[39] However, with zero carbon sources of energy, a 100% reduction could be achieved.[40]

Many of the emissions from geopolymer cement result from the production of the alkali activator – usually sodium silicate. There are two methods for making sodium silicate and both have high emissions (see Appendix 2). The first method has inherent process emissions (from the carbonation of sodium carbonate), and the second requires a large amount of electricity to drive electrolysis of salt (the chlor-alkali process). In this report we will focus on the potential of the second method, as with 100% renewable electricity we could remove most of the emissions related to sodium silicate manufacture.

Use of fly ash and other wastes to manufacture geopolymer cement

Another major environmental advantage of geopolymer cements is their potential to consume waste products that are otherwise difficult to dispose of. Strategy 1 advocates using fresh fly ash only while coal-fired power stations operate in Australia, and switching to our huge stockpiles once they close. The principal material in our geopolymer strategy is fly ash that has been landfilled or dumped in ash dams next to coal-fired power stations. This fly ash requires long-term management and presents a risk to health and the environment. The residents of Port Augusta experienced this early in 2017 when extreme weather broke the seals on the ash dam at the town's closed power station, and fly ash blew through the town.[41]

There is also potential to use a wider range of wastes in Strategy 1. Research has shown that several waste products that are currently hard to deal with could be used to make geopolymer cement. This includes broken glass, sugar cane bagasse ash, waste clay at mines and red mud (a toxic waste from alumina production). The section 'Availability of raw materials for 10-year pathway' has more detail on using wastes in geopolymers.

The performance of geopolymer cement

Concrete made with geopolymer cement matches the performance of Portland cement concrete, and meets the requirements of Australian standards.[42] It has been tried and tested in a wide range of applications including major infrastructure and multi-storey buildings. Geopolymer concrete hardens in the same time as traditional concrete, and provides equivalent durability and strength.[43]

In several key areas geopolymers can be designed to outperform traditional concrete:

- Flexural strength - geopolymers have greater ability to be bent without cracking
- Resistance to chlorides, acids and salts
- Fire-resistance
- Shrinkage – geopolymers shrink less as they dry.

Given these performance advantages geopolymers are already a better option for certain applications and should be used instead of Portland cement. These applications include:

- Concrete piping exposed to high sulphate or acidic solutions, such as sewer pipes
- Structural foundations in acidic or high chloride soils
- Marine environments, such as ports
- Structures where higher fire-resistance is required, such as road and rail tunnels.

Experience of geopolymer cement

Historical use of geopolymer cement

Geopolymer cement is not a new invention. In fact, the Romans developed a type of cement which shared some characteristics with today's geopolymers. They used volcanic ash naturally high in aluminosilicates, which reacts with lime and water to create an extremely strong and durable cement. We now call materials with this property pozzolans because the Romans sourced this ash from Pozzuoli near Mount Vesuvius. Celebrated Roman buildings made with this cement, such as the Pantheon and the Colosseum, are still standing after 2,000 years.[44]

The first genuine geopolymer cements were based on slags – by-products of the iron and steel industry. Much of the early research application of slag-based cements took place in the 1950s and 1960s in the Soviet Union where they were used to make sewer pipes, railway sleepers, road pavements and multi-storey buildings (Figure 4.1).[45] Slag-based geopolymers were also used to construct several buildings in Belgium in the 1950s (Figure 4.2).[46] These early geopolymer buildings, now over 50 years old, are still in use and analysis has shown their durability to be as good as Portland cement buildings.[47] Further advances in slag-based geopolymers were made in China, driven by an incentive to make use of the large quantities of slag produced by the Chinese steel industry.

Research continued in the 1970s, 80s and 90s in countries including France, UK, Spain and Australia. This research revealed more about the chemistry underlying geopolymer cements, and demonstrated that, in addition to slag, they could be made from naturally occurring rocks and clays.

Since 2000 investigation and testing of geopolymer cements has increased dramatically in academia and industry, driven by the need to reduce greenhouse gas emissions. This recent research has led to a greater understanding of the manufacture and performance of geopolymer cements, including the suitability of coal fly ash as a raw material. Australian researchers and companies such as Zeobond and Wagners have been at the forefront of these developments.

21st century use of geopolymers

In the last 10 years geopolymer cement has come of age, as cements with a range of mix designs and activators have seen use in many major projects across the world (case studies pp29-35).

Some clients have selected geopolymers for their superior performance in hostile environments. Rocla promotes its geopolymer pipes for durability in the highly corrosive sewer environment (See the Rocla case study p33). Ceratech had great success marketing to clients requiring concrete trenches that could withstand prolonged exposure to hot sulphuric acid. The US military also took advantage of the high-heat resistance of Ceratech's products in building jet engine test pits (case study p34).

Increasingly geopolymer cement is moving away from its history as a niche product. Recent projects have shown it can be used for any type of construction:

- Australia's first new airport for decades, Brisbane West Wellcamp Airport, used 50,000 cubic metres of geopolymer concrete, including heavy-duty surfaces for taxiing aircraft (case study p32).
- Part of an upgrade to the world's largest inland port, Johannesburg's City Deep Container Terminal (case study p35)
- Precast panels for multi-storey buildings (case studies pp30-31)
- Precast geopolymer products for infrastructure applications such as sewer pipes, kerbsides, pavements and railway sleepers (Table 4.1).

The wide variety of projects demonstrates the ability of geopolymer cement to rapidly replace a large proportion of demand for Portland cement in the next 10 years. More examples are provided in the case studies on the following pages. Table 4.1 lists some of the companies currently producing geopolymer cement, including five Australian manufacturers: Wagners, Zeobond, Rocla, Reinforced Concrete Pipes Australia and Nu-Rock. These companies have proven the suitability of geopolymers, and could be set to do for cement what Tesla has done for cars by shaking up the industry.

Despite the fact that they are still an emerging technology, geopolymers are already cost-competitive, or close to it, even without a carbon price. Wagners' Earth Friendly Concrete (EFC) is around 10-15% more expensive than traditional concrete but when a specification requires higher acid resistance or an off-white colour, EFC is a cost-effective choice as it already has these properties.

Murray and Roberts have found that geopolymer cement is actually cheaper than Portland cement in South Africa, partly because of a plentiful supply of fly ash and slag.[49] Australia has less slag than South Africa, but we do have an abundance of fly ash and other raw materials to enable cheap manufacture of geopolymers. Rocla considers that if their geopolymer pipes were produced on the same scale as their traditional products, they would be less expensive. With further development and commercialisation geopolymers are likely to become the cheapest type of cement due to their use of waste materials and lower energy input.

Figure 4.1: (left) 20-storey residential geopolymer concrete building. Lipetsk, Russian Federation, 1987–1989; (right) 9-storey geopolymer residential buildings, Mariupol, Ukraine, 1960 [48]

Figure 4.2: Les ateliers Delle in Ukkel, Belgium built using a geopolymer called Purdocement in 1957

Table 4.1: Current manufacturers of geopolymer cements

Company (product name)	Location	Geopolymer precursors*	Applications	Projects
Zeobond, E-Crete	Victoria, Australia	Fly ash (up to 80%) GGBS (up to 90%)	Pre-mixed and precast	50+ projects including Melton Library and Swan Street Bridge Retaining Wall
Wagners, Earth Friendly Concrete	Queensland, Australia	GGBS (70%+) Fly ash	Pre-mixed and precast	Brisbane Wellcamp Airport, UQ Climate Institute Building
Rocla	Victoria, Australia	Fly ash (75%+) GGBS	Precast	Sewer line – Toowoomba, Burial crypts - Sydney
Nu-Rock	NSW, Australia	Fly ash (95%)	Precast concrete blocks and bricks	Manufacturing plant at Mt Piper power station, NSW
Reinforced Concrete Pipes Australia eCP	Victoria, Australia	Fly ash GGBS	Precast	Pipes
Banah, BanahCEM	UK	Metakaolin (60%)	Precast	Large-scale production to start late 2017
Ceratech Inc Ekkomaxx	USA	Fly ash (95%)	Pre-mixed and precast	Acid and heat resistant products for chemicals industry.
Milliken Geopolymers	USA	Fly ash Metakaolin	Mortar	Concrete pipe repair works
Murray & Roberts	South Africa	Slag (56%) Fly ash (38%)	Pre-mixed	City Deep Container Terminal, Johannesburg
National Metallurgical Laboratory	India	Fly ash Slag	Precast	Preparing for commercialisation

** Precursors listed in order of importance, percentage included where known.*

Geopolymer producers and case studies

Zeobond

Zeobond, based in Victoria, can rightly claim to be one of the most important innovators in geopolymer technology. The company's geopolymer cement, E-Crete, is used to make both precast concrete products and in-situ pre-mixed concrete.

E-Crete is possibly the world's most widely employed geopolymer cement, having been used in more than 50 construction projects. Figure 4.3 below shows examples of E-Crete projects in Melbourne by Zeobond licensee Aurora Construction Materials. Precast E-Crete products including pipes, panels and pits have been used in both infrastructure and building projects. Pre-mixed E-Crete has been used for house slabs, footpaths, driveways and retaining walls. Zeobond is now branching out overseas, particularly in the Middle-East and India.

VicRoads used E-Crete for a section of footpath on Salmon St Bridge, Port Melbourne (Figure 4.4). VicRoads required the precast sections to meet their highest specifications for structural grade concrete.

VicRoads also used E-Crete for the retaining wall at Swan St Bridge, Melbourne (Figure 4.5). This was a pre-mixed concrete application for which VicRoads specified 40 MPa.

Whittlesea City Council used E-Crete for the pavement works at Thomastown Recreation and Aquatic Centre (Figure 4.6).

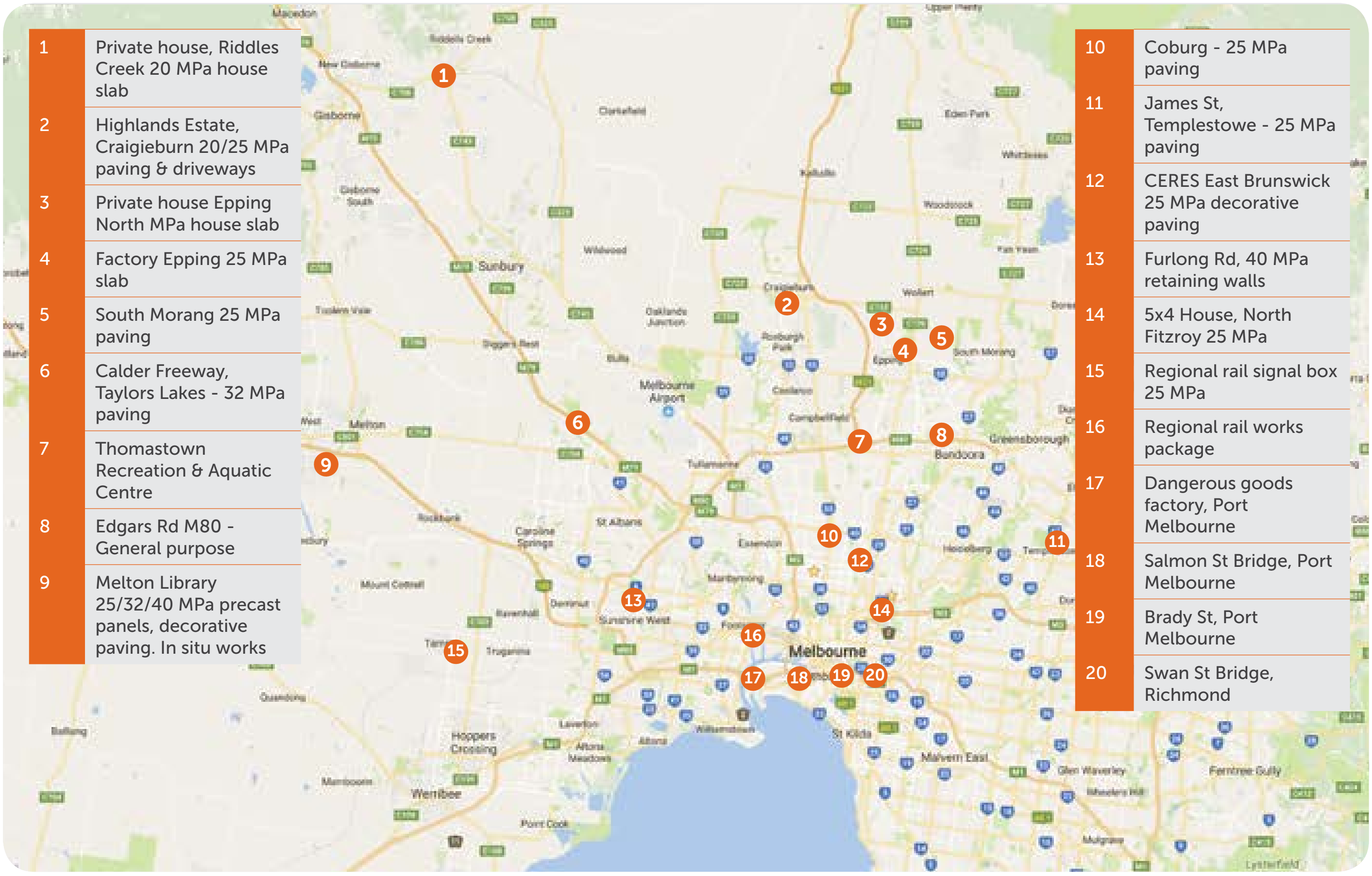


Figure 4.3: Zeobond licensee Aurora Construction materials has used E-Crete in many projects around Melbourne.

Figure 4.4: Precast footpath sections made from Zeobond's E-Crete at Salmon St Bridge, Port Melbourne

Figure 4.5: Retaining walls made from Zeobond's E-Crete at Swan St Bridge, Melbourne

Figure 4.6: Pavement made from Zeobond's E-Crete at Thomastown Recreation and Aquatic Centre.

Figure 4.7: E-Crete precast panels at Melton Library

Case study: Geopolymer concrete helps win national award

The use of geopolymer concrete in precast panels helped get a Melbourne library a five star Green Star rating in 2014. It was the first time that geopolymer precast panels used in a structural setting have ever been awarded innovation points towards a Green Star rating in Australia.

Zeobond's E-Crete product was used in precast panels, footpaths and in-situ works in the Melton Library and Learning Hub, in Melbourne's north-west.

More than 30 precast 40 MPa E-Crete panels make up the exterior of the building.

The building won multiple awards in 2014, including the Master Builders Australia National Environment and Energy Efficiency Commercial Building Award.

Wagners

Wagners is a large construction materials firm based in Toowoomba, Queensland. Over the last decade Wagners has developed a geopolymer product, Earth Friendly Concrete, made from slag and fly ash.

Wagners considers its product to out-perform Portland cement-based concrete in several ways - improved durability, lower shrinkage, higher flexural tensile strength and increased fire resistance. Independent assessment has shown the proprietary geopolymer binder used in Earth Friendly Concrete to reduce the carbon emissions associated with Portland cement by 80 to 90%.

Wagners' commercialisation of Earth Friendly Concrete has gone a long way to demonstrating the potential of geopolymer cement in large-scale projects. As described below, Earth Friendly Concrete has been used to build an entire airport, as well as the world's first building made from precast geopolymer concrete units.

Wagners is now taking their technology overseas. The company has combined with JSW Group, an Indian conglomerate, to produce Earth Friendly Concrete for use in construction in India. They are also exploring opportunities in the Middle East where soils high in sulphates and chlorides favour the use of geopolymer cement that is more resistant in these conditions.

Figure 4.8: Global Change Institute, University of Queensland made from Wagners' Earth Friendly Concrete

World first structural geopolymer concrete use in Queensland

In 2013, Wagners built the world's first structure made from precast geopolymer concrete. The 4 storey Global Change Institute at the University of Queensland is constructed with 33 reinforced geopolymer floor beams (Figure 4.8).

Until this project many industry experts had thought that significant structural use of geopolymer concrete was still many years away. The building achieved Green Star level 6 and won many awards, among them the 2013 BPN Sustainability award for the suspended geopolymer panels.

Figure 4.9: Brisbane West Wellcamp Airport

Case study: The world's largest geopolymer concrete project

In 2014 Brisbane West Wellcamp Airport was built using more than 50,000 cubic metres of Wagners' geopolymer concrete, Earth Friendly Concrete (EFC). This was Australia's first new public airport in almost 50 years and is the world's largest geopolymer concrete project.

Taxiways, aprons, building foundations and civil works were all built out of EFC, which is more durable and resistant to corrosion than ordinary concrete. The heavy duty geopolymer pavements met or exceeded every requirement, achieving flexural strength of 6 MPa - the equivalent of 50 MPa compressive strength.

Aircraft pavements in Australia are traditionally constructed using side forms and vibrating beams to ensure sufficient compaction. EFC achieved the needed high level of compaction using a slip form road paver machine, allowing a 30% faster schedule. The regional airport now has international flights, including heavy 747 cargo planes flying to Hong Kong.

Rocla

Rocla is an Australian manufacturer of precast concrete, and one of the global pioneers in commercial geopolymer precast concrete. Their geopolymer cement contains over 75% fly ash, and the concrete is heat cured with steam.

Rocla's products include pipes, railway sleepers and wall panels made using geopolymer cement. Sewer pipes were tested according to the South Australian water testing protocol and were found to be more durable in the acidic sewer environment. This superior performance influenced Toowoomba Regional Council to install Rocla's geopolymer pipes in the upgrade of a sewer line. Eight years after installation these pipes show no sign of wear, and Rocla estimate they will last at least 100 years.

Figure 4.10 below shows the long-term performance of Rocla's concrete in a corrosive setting compared to a traditional concrete.

Nu-Rock

Nu-Rock makes geopolymer precast bricks, blocks and pavers made from 95% fly ash and 5% activator. Nu-Rock is collaborating with Energy Australia to use both fresh and stockpiled fly ash from Mount Piper power station. Company testing has demonstrated their products can be made from fly ash from many other Australian power stations, including Port Augusta, Gladstone, Tarong, Stanwell, Eraring and Bayswater.

Nu-Rock began commercial operation in June 2017 with a plant capable of processing 30,000 tonnes of fly ash per year. The company plans a larger plant at Mount Piper which would use 250,000 tonnes of fly ash each year, employing 36 people at the site, and an additional 95 for product distribution.

Nu-Rock's bricks and blocks cost less than half of the typical industry price, and have been used in building projects in Sydney and South Africa. Nu-Rock USA is currently planning a new manufacturing facility at a power station in Illinois owned by Dynegy. The plant is expected to more than off-set the loss of 64 jobs at the power plant in October 2016.

After 1 year: Left - Rocla geopolymer, Right - Portland cement concrete

After 2 years 6 months: Left - Rocla geopolymer, Right - Portland cement concrete

Figure 4.10: Acid resistance of geopolymer and PC concrete pipe sections after immersion in a sewerage tank

Ceratech

US company Ceratech makes several geopolymer cements, all of which are composed of 95% fly ash and 5% activator. Ceratech's cements used a high-calcium fly ash produced from burning brown coal. They are cost-competitive with Portland cement and suitable for any concrete application, using regular methods of mixing and application.

The company claimed their products were carbon neutral, used 50% less water and hardened more quickly than Portland cements. Ceratech produced three geopolymer cements, all of which met US standards and were certified by the US Green Building Council:

- ekkomaxx™ – standard cement with high resistance to fire, acid and sulphates
- kemrock™ – adjusted for even higher resistance to acids and sulphates
- firerock™ – adjusted for even higher fire resistance, withstanding sustained temperatures of 300°C and intermittent temperatures of 1,000°C.

These cements have been used in a number of applications, including road surfaces, building foundations and precast materials.[50] The Port of Savannah, Georgia replaced parts of their mobile crane runways using cement. The superior strength of ekkomaxx enabled the port to save time and money by dispensing with steel reinforcement.

Ceratech has had particular success in toxic or high-stress environments. For example, the United States Marine Corps used firerock for their jet engine test pits in North Carolina due to its ability to withstand high temperature (>500°C) jet thrusts of military aircraft. After several years in operation the concrete shows no visible signs of degradation.

More than 10 petroleum and chemical processing companies have chosen kemrock for its durability in high-sulphate and acid environments. Chemical processing company Gulf Sulphur Services in Texas used kemrock to replace concrete trenches that hold hot molten sulphur. Manager Tony Worthen said the company had never found anything that worked as well. The trenches usually show clear signs of deterioration after a few months, but after several years Worthen said "the kemrock concrete looked like the day we poured it" (Figure 4.11).[51]

Figure 4.11: Corroded sulphur trench of Portland cement concrete at a petrochemical facility (left), and similar trench made with Ceratech's kemrock™ cement (right) after 2 years of service, showing sulphur build-up but no deterioration.[52]

Banah

Banah is the first company in the world to produce a clay-based geopolymer cement. Banah's product, called BanahCEM, is made from calcined clay, or metakaolin. Clay-based cements are likely to play a crucial role in a zero carbon world because suitable clays are available in sufficient quantities to satisfy the entire global demand for cement.

BanahCEM can achieve impressive strength of up to 130 MPa, which it gains rapidly — 50% of its 28 day strength in just 9 hours. Its other advantageous properties are resistance to fire, sulphates and acid, as well as an attractive terracotta colour which distinguishes it from other cements.

Later in 2017 Banah will open a factory capable of producing 200,000 tonnes of cement per year. The company's initial focus will be the precast market, particularly precast products used in harsh environments such as seawater. In future Banah may expand into the wider market as tests have shown that BanahCEM is suitable for pre-mixed concrete. BanahCEM has been independently assessed to achieve an emissions reduction of 80% compared to Portland cement. The remaining emissions could be eliminated if sources of zero carbon electricity and heat were available.

Figure 4.12: BanahCEM has two ingredients: calcined clay and a proprietary activator.

Murray and Roberts

In 2015 Murray and Roberts completed an upgrade of the world's largest inland port in Johannesburg. Some of the cement was geopolymer: 56% slag; 38% fly ash; 6% activator.

The geopolymer concrete exceeded the target strength of 40 MPa, achieving 51 MPa after 28 days and 70 MPa after one year. A key reason for choosing geopolymer cement is its greater durability in a salt-water environment as well as its superior resistance to abrasion.

A notable feature of this geopolymer cement was the low concentration of activator. This significantly increased the safety of the cement as its pH was less than 12, lower than regular cement. The low level of activator also reduced the cost. This factor, coupled with plentiful local supply of slag and fly ash, meant the cement cost 30% less than Portland cement.

The 10-year geopolymer strategy for Australia

Strategy 1 is a plan for large-scale uptake of geopolymer cements so they meet 50% of Australian demand in ten years. This target is not the maximum that could be achieved but we have selected this goal based on the availability of materials and realistic uptake.

This assumed rate of adoption is similar to recent innovations such as the internet and mobile phones, and not far ahead of the take-up of solar PV in the last 10 years. The advantage of geopolymer cements over such technologies is that they are already well-developed and cost-competitive. A 50% target for geopolymers provides a balanced approach when combined with the other strategies in our pathway.

The strategy uses five raw materials: fly ash, ground granulated blast-furnace slag, metakaolin, ground limestone and alkali-activator. The required quantity of these materials is shown in Table 4.2, and their availability is discussed in Section 9 and Appendix 2. The strategy makes best use of the properties and strengths of geopolymer cement as described below.

Reaching the 50% target for geopolymer cement

Geopolymer cement should always be used where it has a performance advantage

Geopolymer cements perform better than traditional cement in certain situations, including some hostile environments. For such applications geopolymer cement should replace Portland cement very quickly, as they are superior even before emissions are considered. These applications include sewers, chemical tanks, marine harbours, foundations in acidic or high-chloride soils and structures where exceptional fire-resistance is required, such as road and rail tunnels.

Geopolymer cement can immediately become the default option for non-structural cement

Public sector bodies such as councils and roads authorities should start using geopolymer cement for non-structural purposes. This will help to broaden experience of using geopolymer cement, and expand the number of providers.

All precast concrete could be made with geopolymer cement

All precast concrete could be made from geopolymer cement, and Strategy 1 assumes that geopolymers account for 90% of the market by 2027. This focus on precast products allows us to design geopolymers with a very high proportion of fly ash, and no slag. Such mix designs require the concrete to be heat cured at around 60°C. This is a straightforward industrial process, and many precast concrete products are heated to accelerate setting and strength gain.

We have assumed that on average precast geopolymer products will contain 75% fly ash. With the right type of fly ash this proportion could be higher in some applications. Both Ceratech's commercial cement mixes and Nu-Rock's concrete products contain 95% fly ash. The use of a high proportion of fly ash has key advantages. It consumes a waste material which is abundant in Australia and available at about half the cost of Portland cement. When precast geopolymer products are made at large scale they are likely to be cheaper than those made with traditional cement.

We have also assumed the use of some metakaolin as well as ground limestone as a filler. The proportion of alkali activator can be minimised to 5% due to the use of accelerated heat curing.

Pre-mixed concrete

Pre-mixed concrete must be able to cure at ambient temperature. Using current geopolymer technology this will normally require the addition of some slag (GGBS). For a concrete strength up to 40 MPa we propose a mix containing 15% slag and 7% activator.[53] For higher strengths (>40 MPa) higher proportions of slag (25%) and activator (10%) are likely to be required.[54]

Dry bagged cement

Strategy 1 assumes no dry bagged cement is replaced by geopolymer cement. We took this decision due to the greater precision required in mixing geopolymer concrete, and the potential safety risks from higher alkalinity. These factors make geopolymers less suitable for bagged cement that is sold to the public, and used in an uncontrolled way by unskilled workers. However, in the long term dry bagged geopolymer cement is likely to be feasible — with dry activator pre-mixed in the bag and water added later in the same way as regular cement.

Selection of materials for geopolymer strategy

The selection of materials and their proportion has been based on demonstrated geopolymer technology as well as the availability of materials. After 10 years Strategy 1 has an annual requirement for the following five materials: 3.8 million tonnes of fly ash; 0.63 million tonnes of slag; 0.57 million tonnes of metakaolin; 0.6 million tonnes of ground limestone and 0.39 million tonnes of activator solution. The availability of these materials is discussed in Section 9.

The basis for the material selection is explained below.

Fly ash (3.8 million tonnes) – In selecting the proportions of cement materials we have maximised the amount of fly ash. Fly ash provides 63% of the raw material for Strategy 1. Table 4.1 shows that some commercialised geopolymer cements contain as much as 95% fly ash. We have favoured fly ash due to its availability in Australia in sufficient quantity and quality. In the short-term (to 2024) we assume fresh fly ash will be available from coal-fired power stations. We also assume the cement industry will progressively move to use stockpiled fly ash, so that from 2025 all the fly ash required for geopolymer cement will be sourced from our huge domestic stockpiles of at least 400 million tonnes.

Ground granulated blast-furnace slag (GGBS – 0.63MT) – GGBS is an extremely effective raw material for geopolymer cement, and it will play an important role in the transition to zero carbon cement. However, there is currently high global demand for all GGBS and Australia imports more than half the slag consumed domestically. For this reason its importance as a cement material in the long term is likely to decline, and we have restricted its use for our 10-year strategy

Activator (0.39 MT) – Geopolymer cements must be activated, usually by an alkaline solution. In the last 30 years the amount of alkali activator required to make geopolymer cement has reduced significantly from around 40% to 5-15%, and further reductions are likely to be possible.[55] Manufacturing the most common activator, sodium silicate, requires a high energy input and produces large amounts of chlorine as a by-product. We have based our strategy on the latest geopolymer cement mixes which contain a lower proportion of activator than earlier geopolymers.

Metakaolin (0.57 MT) – Geopolymers can be made from specific clays. These clays, principally kaolinite clay, must first be calcined (heat treated) to produce calcined clay or metakaolin. Metakaolin-based geopolymers are in the early stages of commercialisation but in 10 years have the potential to account for a significant proportion of the geopolymer market. This is important for the long term as kaolinite clay is abundant in Australia and many developing countries, and could play an important long-term role in zero carbon cements.

Limestone (0.6 MT) – Ground limestone can be added as a filler in geopolymer cement. This use of limestone as a filler is discussed in more detail in Strategy 2. The Australian cement industry currently sources more than 10 million tonnes of limestone, and as our strategy would lead to a substantial fall in demand, we can safely assume that this quantity of limestone is also readily-available.

Table 4.2: Material requirements for 6 million tonnes geopolymer cement in 2027

Type of cement/ concrete	Australian demand ('000 tonnes)	Target geopolymer replacement ('000 tonnes)	Cement materials - average proportions				
			Fly ash	Slag	Metakaolin	Limestone	Activator*
Precast	2,400	2,160 (90%)	75%	0%	10%	10%	5%
Pre-mixed to 40 MPa	6,600	3,300 (50%)	58%	15%	10%	10%	7%
Pre-mixed above 40 MPa	1,800	540 (17%)	50%	25%	5%	10%	10%
Dry-bagged	1,200	0 (0%)	*Not using geopolymer cements for dry-bagged product*				
Total	12,000	6,000					

** Alkaline activator used is sodium silicate solution with 48% solid content.*

Areas for further testing and development of geopolymer cement

Demonstrating the durability of geopolymer cement

One obstacle to the wider uptake of geopolymer cement is a perceived lack of experience in using it as a construction material. Portland cement has more than a century of implementation in a wide variety of projects and environments. This gives structural engineers confidence in the performance and long-term durability of Portland cement.

However, as we have shown, geopolymer cement has been tried and tested in many construction projects stretching back to the 1950s. There is now a substantial and growing body of evidence supporting the performance of geopolymer cement – far greater than we typically have for an emerging technology. In fact because geopolymer cements tend to shrink less than Portland cement they may even be more durable in the long term.[56] As geopolymer cement starts to be employed more frequently, engineers will gain further confidence in its performance and long-term durability.

Steel protection

There is some evidence that geopolymer concrete can carbonate more quickly than Portland cement concrete. This is a problem for steel reinforced concrete as carbonation eventually leads to steel corrosion. The extent of this problem and how it could be fixed is an area of active research.[57] But the best long-term solution to this problem is to stop using steel to reinforce concrete. A future part of BZE's Zero Carbon Industry plan will focus on steel, presenting more sustainable options for reinforcing concrete, such as glass or basalt fibre reinforced polymers. Not only do these alternatives have the potential to be zero emissions, they could also endure for centuries whereas steel corrodes in a few decades despite our best attempts to protect it.

Annual material requirement for target replacement ('000 tonnes)

Fly ash	Slag	Metakaolin	Limestone	Activator
1,620	0	216	216	108
1,914	495	330	330	231
270	135	27	54	54
n/a	n/a	n/a	n/a	n/a
3,804	630	573	600	393

Table 4.2 shows further details of this target: the percentage replacement of different types of product, the geopolymer mix designs and the quantities of material we will require. The percentages of material are averages, and individual cement mix designs will vary from this average.

Setting and strength gain

An important property of Portland cement is that it sets in a few hours at ambient temperature then gains strength in a few days. However, geopolymer cements based on fly ash tend to set more slowly. (For example, at an ambient temperature of 25°C the setting time might be 7 hours compared to 4 hours for Portland cement. At lower ambient temperatures the difference will be greater.)

This is not a problem for precast concrete made in factories, where setting can be accelerated through heat treatment. But for pre-mixed concrete on work sites it can delay construction, pushing up costs. To tackle this issue, methods are now being developed to adjust the chemistry of fly ash-based geopolymers so they harden more rapidly. Geopolymer cements made with GGBS or metakaolin set and harden sufficiently quickly at ambient temperatures.

Safety risk from high alkalinity

Most geopolymer cements require a highly alkaline activator to speed up the necessary reactions. Strong alkalis pose a safety risk to workers as they can corrode human tissue. With regards to the alkaline solution itself this seems to be a manageable problem, as it need only be handled in controlled factory environments. Procedures can be implemented to manage the risk, just as with many other hazardous industrial materials.

A construction site environment is harder to control. Some fresh geopolymer concrete has a pH of 14 compared with a pH of 13 for traditional wet concrete.[58] (A solution of pH 14 is ten times more alkaline than one of pH13.) This too can be managed through appropriate handling and safety procedures. A more satisfactory long-term solution will be to lower the pH of the product, as some companies have already achieved. Murray and Roberts has developed a geopolymer cement with a pH of less than 12, and Banah's use an activator which, despite having a pH of 13.5 is only classed as an irritant according to European standards (similar to Portland cement).

The need for further research

Cement chemistry is highly complex and there is much we do not understand even about Portland cement. The properties of geopolymer cements are sensitive to many factors including the physical characteristics and chemical composition of the precursor materials, the activator type and content, curing regimes and mixing procedures. Developing geopolymer cements for new applications and from new source materials (e.g. a fly ash from a different power station) requires more research and experimentation.

So far the level of investment and research into geopolymer cement has been small compared to the effort directed into Portland cement and many other materials on which our well-being relies. Despite this geopolymer researchers and companies have been able to prove their value, commercialising geopolymer cement in the face of a powerful incumbent industry. This suggests that with a solid research effort by academia and industry we can anticipate rapid progress in geopolymer cement technology, enabling it to become a mass-market replacement for Portland cement.

Geopolymers in standards

A historical barrier to the adoption of geopolymer cements in Australia is the absence of national standards covering their use. Current concrete standards do not explicitly exclude geopolymer cement but implicitly assume that concrete is Portland cement-based. This has made it difficult for engineers to get approval for better alternatives. Standards Australia are now addressing this barrier, and are working with the Cooperative Research Centre for Low Carbon Living (CRCLCL) to develop a Geopolymer Concrete Handbook, building on the Concrete Institute of Australia's 2011 *Geopolymer Recommended Practice Handbook*. It is expected that this will lead to a *Standard Specification for Construction with Alkali-Activated and Geopolymer Concrete*, although that might not be for several years. The handbook and standard for geopolymers will make it easier for engineers to specify geopolymer concrete.[59]

Despite the current absence of a general standard, several organisations have approved geopolymers for use in their own standards. VicRoads led the way in 2010, making clear that geopolymer cement and Portland cement are "equivalent products" for specific uses such as reinforced concrete pipes, drainage pits, footpaths and kerbs. (up to 32 MPa).[60] VicRoads have since applied geopolymer concrete in several projects (p30 for two case studies involving bridges in Melbourne). The governments of Tasmania[61] and South Australia[62] have changed their standards to allow the use of geopolymer cement in situations similar to VicRoads. VicTrack has also approved geopolymer concrete for rail projects in Victoria, and requires it to be "prioritised where possible to take advantage of its ... low embodied carbon".[63]

Strategy 2 – Developing high-blend cements with reduced clinker content

Strategy 2 at a glance

- Develop a new generation of high-blend cements containing on average only 30% Portland cement clinker.
- High-blend cements account for 50% of market in 10 years (6 million tonnes of cement).
- The strategy has materials requirements of: fly ash (1.6 million tonnes); slag (0.5 MT); metakaolin (0.9 MT) and ground limestone (1.1 MT).
- The required fly ash will be sourced entirely from stockpiles from 2024.
- High-blend cements can be manufactured largely using existing cement industry equipment.

Overview of clinker substitution

Traditional Portland cement consists of at least 90% lime-based clinker. In recent years however the industry has begun to add increasing amounts of clinker substitutes, known as fillers and supplementary cementitious materials. Supplementary cementitious materials react with clinker, playing a role in the strength development of concrete, whereas fillers are only slightly reactive. This report will refer to both as fillers and supplementary cementitious materials as 'clinker substitutes', and to Portland cement with a high proportion (>50%) of clinker substitutes as 'high-blend cement'.

Portland cement now includes an average of 20-30% of clinker substitutes, mostly limestone (a filler), coal fly ash and ground granulated blast-furnace slag (supplementary cementitious materials).[64] Strategy 2 explores the potential for using much higher levels of those three substitutes, plus a fourth – metakaolin.

How can high-blend cements reduce emissions?

In our existing high-carbon economy, for every 10% of clinker substitute in Portland cement we achieve an immediate 6% reduction in emissions.[65] So for a 50% substitution we would get a 30% reduction, and for a 70% substitution we would get a 42% reduction in emissions. In the economy of the future, with zero carbon energy and transport, the carbon reduction will equate to the percentage of substitution.

When compared to traditional Portland cement production, the increased use of clinker substitutes is already resulting in a global saving of approximately 500 million tonnes of CO_2 per annum.[66] However, clinker substitution offers far greater potential for emissions reductions.

Experience with high-blend cements

Strategy 2 focuses on the use of four materials familiar from Strategy 1: GGBS, fly ash, metakaolin and limestone. Experience of cements using high levels of each clinker substitute is outlined below.

Slag as a clinker substitute

Ground granulated blast-furnace slag (GGBS) is an effective supplementary cementitious material already used by the cement industry. In mass market cement GGBS generally replaces no more than 15% of Portland cement clinker, but much higher replacement rates have been demonstrated satisfactorily.[67]

The cement used in the Portside building in Cape Town had 65% of its Portland cement replaced with slag.[68] Built in 2011, Portside, is a 30-storey building incorporating concrete with strengths up to 60 MPa. More recently, in 2016, a cement comprising 72.5% GGBS was used in part of the new concrete roof at Paddington Station in London.[69] This roof is part of the Crossrail project – a new 100-kilometre railway across London. Crossrail's concrete specification requires an average of 50% Portland cement replacement, though higher rates have been achieved in several instances.

Several Australian cement makers have developed high-slag cements. For example, Boral markets Envisia, a cement which can include up to 80% clinker substitution, comprised mostly GGBS but with some fly ash. Envisia handles and performs in exactly the same way as Portland cement. Boral has used an Envisia mix with 50% clinker replacement at the Barangaroo South development in Sydney. Boral was also involved in the development of Pixelcrete which achieved 60% clinker replacement with fly ash and slag.

Case study: Pixelcrete

The Pixel building is an award-winning four-storey office block in Melbourne built by Grocon. The piles, groundworks, slabs and columns of the Pixel building were made with Pixelcrete, a low clinker cement. Grocon worked with Boral to develop Pixelcrete, in which 60% of the Portland cement is replaced by supplementary cementitious materials. This was the first recorded commercial use in Australia of a high-blend cement with more than 50% replacement of Portland cement.

Pixelcrete has a compressive strength of 40 MPa after 56 days. A patent application by Grocon shows several mix designs which achieve 60% replacement of Portland cement with fly ash and slag, and one design which achieves 64% replacement through the addition of 4% of silica fume (which improves workability).[70] Across the different mix designs the fly ash proportions varied from 24-46% and the slag proportions from 15-37%.

Pixelcrete and Envisia are the most prominent Australian examples of cements with a high content (>50%) of clinker substitutes.[71] To differing extents they both rely on GGBS, and implementing Strategy 2 requires around half a million tonnes of slag. However, there are constraints on the supply of GGBS, so we will consider three other clinker substitutes which are available in larger quantities, namely: fly ash, clay and ground limestone.

Figure 5.1: Loeriesfontein Wind Farm – turbine foundation

Case study: Loeriesfontein Wind Farm, South Africa

Loeriesfontein Wind Farm is the world's first windfarm made from ultra-low volume Portland cement concrete. The cement used in the wind farm foundations contained on average 89% slag and only 11% Portland cement.

Compressive strength after 28 days was 55 MPa, with an expected final strength of 100 MPa after 56 days. The installation's 61 wind turbines are due to begin generating at the end of 2017.

South Africa has a large and growing slag and ash waste problem, meaning that these by-products are often cheaper than the limestone needed for Portland cement.

High volume fly ash cement

In high volume fly ash cements, fly ash replaces more than 50% of Portland cement clinker. The viability of such cements was first demonstrated in the 1980s in Canada, where cement containing 55% fly ash was used to build a hotel/office complex in 1988 and a wharf development in 1990.[72] In 2001 York University in Toronto built the Computer Science Building using a 50% fly ash cement – with the concrete achieving a strength of over 50 MPa after 28 days.

Since 2000 a number of projects in the United States have used cements with at least 50% fly ash, including the foundation slab of the BAPS Hindu temple and cultural complex in Chicago which used 65% fly ash cement.[73] This was the highest rate of fly ash in a high-blend cement until the upgrade to the City Deep Container Terminal described in the case study below.

Figure 5.2: BAPS Shri Swaminarayan Mandir, Chicago. Foundation slab made with 65% fly ash cement.

These structures and others have proven durable, as we would expect in line with the evidence base showing that high volume fly ash concrete is less prone to cracking and sulphate attack.[74] Adding large amounts of fly ash also improves the workability of concrete, and can reduce the required amount of water.

One advantage high volume fly ash cements possess over fly ash geopolymer cement is that they do not require heat curing. However, they do have a tendency to develop strength more slowly. This may not be an issue for some projects, but for most it may drive up costs by delaying construction. Recent research has shown that there are several options for addressing the problem of slow strength development in high volume fly ash cements, such as using:

- ultra-fine fly ash
- lime water (hydrated lime)[75]
- chemical accelerators[76]
- fine ground limestone.[77]

These materials all increase the reactivity of the cement, leading to earlier hardening. A recent study at RMIT in Melbourne used lime water with fine fly ash from power stations in Queensland to produce high performance cement containing 80% fly ash.[78] This cement gained a compressive strength of 40 MPa after 28 days and 60 MPa after 56 days.

Case study: City Deep Container Terminal, Johannesburg

In 2015 Murray and Roberts completed an upgrade to Johannesburg's City Deep Container Terminal, the world's largest inland port. The cements used in the project contained a very high volume of fly ash – up to 68% of cement content. The slower strength gain of the high volume fly ash cement was an advantage in this case as it gave the builders more time to work and cut the concrete.

The high volume fly ash concrete exceeded the target strength of 40 MPa, achieving 55 MPa after 28 days and a massive 125 MPa after one year. The material had numerous advantages over traditional concrete including enhanced durability in a marine environment, reduced water consumption, improved workability and minimal cracking.

Calcined clay as a clinker substitute

Calcined clays with high alumina content have excellent potential as a clinker substitute.[79] We already have considerable experience of substituting calcined clay for clinker. In Brazil this technique has been successfully used in the construction of large dams, like the 1962 Jupia Dam built with more than 200,000 tonnes of metakaolin.[80] An advantage of calcined clay is the abundance of suitable clay deposits in Australia and overseas (Section 9).

The amount of clinker that could be replaced with calcined clay depends in part on the application of the cement, in particular whether the concrete is required to gain strength quickly. It is certainly possible for calcined clay to constitute 50% of the Portland cement product for most applications.

Ground limestone as a clinker substitute

A third widely-available clinker substitute is limestone, which can be added to Portland cement in powder form. When limestone is used in this way it does not release its carbon dioxide, meaning that it is a very low emissions replacement for high-emissions clinker.

Limestone is usually known as a filler rather than a supplementary cementitious material as it is only slightly reactive. The first recorded uses of high-volume cement fillers was in the construction of the Arrowrock and Elephant Butte Dams in the US, still in use after 100 years.[81] The cement for these dams included 50% filler comprised of local granite and sandstone.

As with calcined clay we have significant experience using limestone as a cement filler and it is now routinely added as a filler in Portland cement. Most national standards allow this, and European cement standards allow limestone to comprise up to 35%.[82] Australian standards limit limestone content to 7.5% in general purpose cement, and 20% in general purpose limestone cement.

In practice, limestone does not usually replace more than 10% of clinker as above that level it can affect the strength of the concrete. However, with good mix design and control of limestone particle size, a much higher proportion can be used. A commercial cement with 20% limestone replacement was manufactured by Heidelberg Cement as long ago as 1965.[83] Adding 20% limestone has even been shown to increase the strength of cement with a high proportion (40-50%) of fly ash.[84] As discussed in the next section, recent developments in cement technology have shown it is possible to substitute limestone for as much as 50% of clinker without affecting strength.[85]

Increasing clinker substitution by using less water

One way to achieve a high level of clinker substitution is to reduce the ratio of water to cement in a concrete mix. It is well known in the industry that a given concrete strength can be achieved with less cement simply by reducing the water content. The limitation of this approach is that a lower water/cement ratio makes fresh concrete harder to work with. We can readily overcome this limitation by using water-reducing admixtures known as plasticisers. Adding small amounts of plasticisers can allow a reduction in clinker of 20% or more.[86]

An effective complementary strategy is to increase the packing density of the particles within the cement and concrete. Through carefully combining the ingredients of cement and concrete, smaller particles fill the voids between larger particles, and the cement mixture becomes denser and stronger.[87] Studies of particle packing reveal the important role of fine filler material such as ground limestone (Figure 5.3). With appropriate mix design, and the inclusion of some fly ash or GGBS, finely-ground limestone can be increased to more than 50% of the binder proportion without any loss of strength.[88]

Managing packing density is a complex process influenced by the density, shape, size and physical stability of particles. It requires all ingredients of the cement and concrete to be well matched. For instance, when rounded sand is combined with coarse aggregates, particle packing and distribution will differ from a mixture of angular sand and more rounded aggregates. Engineers are still experimenting with methods of improving packing without affecting other key attributes of concrete such as workability. Further research will also be required to produce cost-effective methods for optimising the distribution of particles in cement. It is likely that improved computer models of cement design will be of use here, as will new grinding technology, in which high-blend cement materials are ground separately, to allow the optimisation of particle sizes.

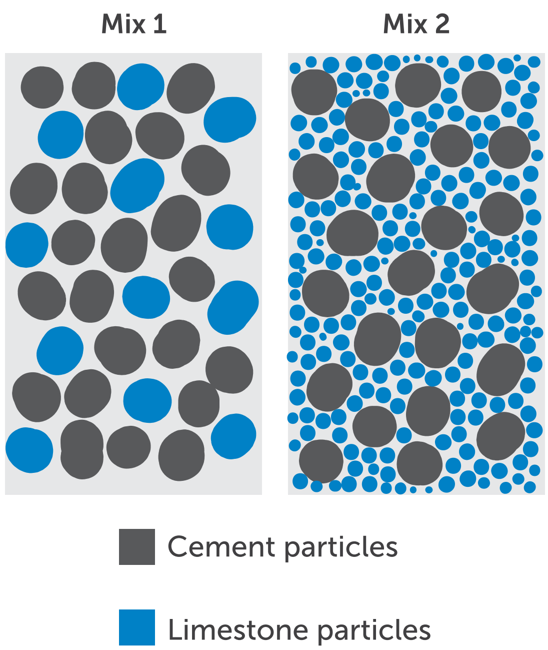


Figure 5.3: Two cement mixes with limestone filler. The limestone in Mix 1 has the same fineness as the cement particles, while Mix 2 has much finer particles of limestone. Mix 2 is more tightly packed, allowing a significantly lower proportion of both cement and water for the same outcome in terms of concrete strength.

70% clinker substitution in 10 years

Strategy 2 outlines our plan for a rapid increase in the proportion of clinker substitutes in Portland cement. The strategy anticipates that by 2027 high-blend cements containing an average of 70% clinker substitutes will meet half of Australian demand (Table 5.1). Seventy per cent substitution is ambitious but achievable, as real-world examples described above have already employed as much as 68% fly ash, and more than 80% slag. The transition will be assisted by advanced use of plasticisers, computer-assisted mix design, new grinding technology and improved particle packing.

As with Strategy 1 it will be important to design high-blend cements according to their purpose. Some cement used for high strength concrete applications may still need to contain 50% Portland cement clinker. But we will be able to exceed 70% replacement for other applications, such as bagged cement which is often used in cement-rich mixes and rarely for high-strength concrete.

One advantage of a strategy based on high-blend cements in the short term is that it can be adopted using existing cement manufacturing equipment, requiring only marginal investment. An additional advantage is that it complements the geopolymer strategy by using the same raw materials. Experience producing and using fly ash, GGBS, calcined clay and limestone in high-blend cements will provide valuable lessons for the geopolymer industry and vice versa.

Clinker substitutes can be used in combination

The best approach to clinker substitution may be to employ combinations of the different available materials – fly ash, slag, ground limestone and calcined clay. Swiss company, LC3, is doing precisely this, as they move to commercialise a cement in which 50% of the clinker is replaced by 30% calcined clay, 15% limestone and 5% gypsum. LC3's cement can be produced using existing cement plant equipment, and the company claims the cost will be equivalent to or even cheaper than Portland cement.[89]

Selection of materials for Strategy 2

The clinker substitutes considered here are fly ash, slag, calcined clay and limestone – materials familiar from Strategy 1. Table 5.1 shows the proposed mix designs and material requirement for 70% high-blend cements. The proportion of supplementary cementitious materials is 50% regardless of application. The proportion of limestone filler varies from 15-30% according to the strength requirement of the final product.

Strategy 2 will require 3 million tonnes of supplementary cementitious materials per year - a requirement which can be met with a combination of slag, calcined clay and fly ash. As shown in Strategy 1, we have sufficient quantities of these materials at our disposal in Australia. The strategy also requires 1.23 million tonnes of limestone. Given that the Australian cement industry currently sources more than 10 million tonnes of limestone, and that our strategy would lead to a substantial fall in demand, we can safely assume that this quantity of limestone is also readily available.

Clinker substitution in standards

Understanding of clinker substitution is growing rapidly, and some cement standards are starting to catch up. A new proposed European standard will allow up to 55% clinker substitution.[89] Dubai now requires Portland cement to contain a minimum of 36% of fly ash or GGBS, and up to a maximum of 55% fly ash or 80% GGBS.

Australian standards (AS 3972) do not limit the amount of fly ash used in high-blend cement as long as the ash meets the AS 3582.1 specification. However, some state-specific specifications restrict the amount of fly ash permitted in high-blend cement. For example, Roads and Maritime Services (NSW) limits fly ash content to 40%.[90] Another regulatory barrier in Australia is that substitutes are limited to fly ash and GGBS, thus excluding viable alternatives such as calcined clay, volcanic rock and slag from other sources.

If adopted, Strategy 2 will lead to a 35% reduction in cement-related process emissions in Australia. This means that Strategies 1 and 2 could together remove 85% of cement-related emissions – leaving us with 15% from the ongoing manufacture of Portland cement clinker. Tackling these emissions is the object of Strategy 3.

Table 5.1: Material requirements for 6 million tonnes high-blend cements in 2027

			Clinker substitutes – average proportions				Annual material requirement for target replacement ('000 tonnes)			
Type of cement/ concrete	Australian demand ('000 tonnes)	Target high-blend cement (% - '000 tonnes)	Slag	Fly ash	Metakaolin	Ground Limestone	Slag	Fly ash	Metakaolin	Limestone
Precast	2,400	240 (10%)	0%	25%	25%	20%	0	60	60	48
Pre-mixed to 40 MPa	6,600	3,300 (50%)	10%	25%	15%	20%	330	825	495	660
Pre-mixed above 40 MPa	1,800	1,260 (70%)	15%	30%	10%	15%	189	378	126	189
Dry-bagged	1,200	1,200 (100%)	0%	30%	20%	20%	0	360	240	240
Total	12,000	6,000					519	1,623	921	1,137

Strategy 3 – Mineral carbonation

Strategy 3 at a glance

- Employ mineral carbonation to capture the remaining emissions from making Portland cement.
- Capture 0.8 million tonnes of carbon dioxide per year, chemically secured as carbonate rock.
- Use serpentine rock that is abundant in Australia.
- Produce by-products with a commercial value such as magnesium carbonate and silica.

Implementing strategies 1 and 2 will dramatically reduce the need for Portland cement clinker to 15% of current demand or 1.8 million tonnes per year. Using current methods, producing this clinker will lead to carbon dioxide emissions of 1.5 million tonnes, of which 0.8 million tonnes comes from calcining limestone. Strategy 3 addresses these residual emissions from calcination, through an emerging technique called mineral carbonation.

Carbon capture and utilisation

Mineral carbonation is a member of a group of technologies known as carbon capture and utilisation (CCU). The UN has recognised CCU as "a potentially important future part of a balanced strategy for reducing greenhouse gas emissions".[91] CCU involves the beneficial use of carbon dioxide after its capture from flue gases or other industrial emission sources.

Cutting-edge companies are starting to commercialise CCU. Icelandic company Carbon Recycling International produces renewable methanol from carbon dioxide and hydrogen.[92] Materials firm Covestro is taking waste carbon dioxide from a chemical plant to manufacture polyols (the key ingredient in polyurethane foam), replacing petroleum as the primary feedstock.[93] In the future many other plastics could be manufactured in this way.

These technologies have the potential to supply certain markets but in the Australian context are unlikely to be able to capture the full 0.8 million tonnes of carbon dioxide every year. The advantage of mineral carbonation is that it has the potential to be scaled up to this level.

Mineral carbonation

Mineral carbonation (also known as carbon mineralisation) is a process in which carbon dioxide is reacted with calcium or magnesium to produce a carbonate mineral, permanently locking away the carbon dioxide in a stable solid form. It mimics a natural process in which carbon dioxide is converted to carbonate rocks over millennia. This process can be accelerated to occur in minutes through the application of heat and pressure. Mineral carbonation could prevent 95% of cement kiln emissions from escaping to the atmosphere.[94]

Most research into mineral carbonation focuses on magnesium silicates which are available in naturally abundant rocks such as olivine and serpentine. In one process the serpentine is made more reactive through crushing, grinding and calcination at 650°C.[95] The calcined magnesium silicate is then reacted with a stream of carbon dioxide at a temperature of 150°C and a pressure of 150 bar. This results in two main products – magnesium carbonate and silica – both of which have a number of commercial applications.

The most developed versions of mineral carbonation require an almost pure stream of carbon dioxide. This means carbon dioxide must first be separated from the exhaust gas by absorption in a suitable solvent, and then extracted from the mixture by heating. This capture process has a financial and energy cost. However almost half of the energy required can be supplied from heat generated by the reaction between magnesium silicate and carbon dioxide.

It may be possible to avoid the need to separate carbon dioxide. Some companies, including MCi (see below) are conducting research on mineral carbonation using untreated exhaust gases from cement kilns or conventional power generation. Another approach might be to alter the process in the cement kiln itself so that it generates a relatively pure stream of carbon dioxide. Australian company Calix has built a demonstration plant in Belgium which does precisely this using its patented Direct Separation Reactor technology.[96]

Mineral carbonation has several significant advantages over conventional carbon capture and storage. Firstly there is no risk of leaking or need for post-storage monitoring, as the carbon dioxide is chemically bonded within a stable mineral. Secondly the technology can be applied in-situ at any location without the need for a local geological formation capable of storing carbon dioxide. Thirdly the economics are more promising because mineral carbonation can produce substances with commercial value, and can avoid the costs of compressing, transporting and storing carbon dioxide.

Commercialisation of mineral carbonation

Several companies around the world are working to realise the potential of mineral carbonation, including two Australian firms, Integrated Carbon Sequestration Pty Ltd and Mineral Carbonation International (see below).

Abundance of magnesium silicates

The potential of magnesium silicate rock to absorb carbon dioxide is enormous. Olivine and serpentine are readily available at a low cost, and widely distributed around the world. It has been calculated that carbonating the olivine present in Oman alone would absorb 24 times more carbon dioxide than the total present in the atmosphere.[97]

In Australia serpentine is more common than olivine, and deposits have been mined in NSW for use in iron and steel making. It has been estimated that enough mineable serpentine exists in one part of the Great Serpentinite Belt of the New England area of NSW to absorb all the state's stationary carbon dioxide emissions for 300 years.[98]

Figure 6.1: Mineral carbonation – conversion of silicates to carbonate

$$Mg_3Si_2O_5(OH)_4 + 3CO_2 = 3MgCO_3 + 2SiO_2 + 2H_2O$$

Mineral Carbonation International (MCi)

MCi is a commercial collaboration between GreenMag Group, Orica Limited and the University of Newcastle. MCi is developing mineral carbonation processes using locally sourced serpentine. The company has built a research pilot plant to test its technology and to determine the design and cost of large scale implementation. MCi has developed alternative processes which can absorb carbon dioxide from both pure and impure sources, creating magnesium carbonate and silica products.

MCi's aim is to commercialise their process by 2022, reducing the cost of mineral carbonation to $40 per tonne of carbon dioxide. Once proven at the commercial scale MCi could increase production to capture hundreds of thousands of tonnes per year, using locally abundant serpentine. MCi intend to market magnesium carbonate as an aggregate, a fire-resistant building material or for other chemical applications. The company also envisages numerous commercial applications for silica (SiO_2), including as a binder in cement. It could also be used to produce sodium silicate for activating geopolymer cement.

Carbon8 Aggregates

UK company Carbon8 Aggregates has commercialised a process to react carbon dioxide with the calcium content in various waste streams. This produces calcium carbonate – similar to natural limestone – which is used to make aggregates for the construction industry. The process can absorb carbon dioxide from many processes, and can even work with a low concentration (10-25%) of carbon dioxide in the flue gas.

The company has two operating plants using residue from waste incineration plants, which is high in calcium oxide due to the use of lime to absorb pollutants in flue gases. (In the UK more than 25% of municipal waste is incinerated.) Their plants treat 100-200 tonnes of waste residue per day.

Carbon8 Aggregates has tested their process at a cement kiln demonstrating not only the ability to absorb carbon dioxide from the kiln, but also the added benefit of using waste cement kiln dust as the primary medium of absorption. The cement industry produces tens of millions of tonnes of cement kiln dust every year, and disposing of it safely is a challenge.[99]

The company claims that the resulting aggregate captures more carbon dioxide than is produced from the energy required for its manufacture, resulting in the world's first carbon negative aggregate. Typically the aggregate produced has a footprint of -40 kilogrammes of carbon dioxide per tonne. One plant produces around 80,000 tonnes of aggregate per year.

Table 6.1: Implementation of Strategy 3 – mineralising emissions from calcining limestone ('000 tonnes)

Portland cement manufacture	Emissions from calcination	Emissions captured (capture rate 95%)	Serpentine	(Theoretical) magnesium carbonate	(Theoretical) silica
1,800	800	760	2,800	1,600	800

Skyonic

Mineral carbonation technology has already been retrofitted to at least one cement works. Skyonic's SkyMine® process captures around 75,000 tonnes of carbon dioxide per annum from a cement factory in Texas, producing sodium bicarbonate. Skyonic captures only about 15% of the emissions from the cement plant.

Implementation of strategy

Current targets of mineral carbonation research are to absorb up to 90% of carbon dioxide emissions. For the purposes of Strategy 3 we have assumed that in 10 years the process will improve to the point where it can absorb 95% of the emissions from a cement kiln.

We have also assumed that the energy required for mineral carbonation can be obtained in a zero carbon way. Currently the process has a high energy requirement, but researchers are exploring how this can be significantly reduced.

Sequestering one tonne of carbon dioxide through mineral carbonation requires 3.5 tonnes of magnesium silicate rock. To implement Strategy 3 and capture 0.8 million tonnes of carbon dioxide yearly, we would require 2.8 million tonnes of rock (Table 6.1). This is a small quantity compared to overall mining in Australia, which extracts several hundred million tonnes of iron ore alone every year. Carbonating 2.8 million tonnes of rock should theoretically produce 1.6 million tonnes of magnesium carbonate and 0.8 million tonnes of silica. The remaining emissions will be less than 50,000 tonnes, or about 0.5% of Australia's current cement-related emissions.

Strategy 4 – Minimising the use of cement

Strategy 4 at a glance

- Reduce cement demand by at least 14% (2 million tonnes) by 2027.
- This would offset the estimated growth in demand for cement, limiting consumption to today's level of 12 million tonnes.
- Use 7% less cement by designing large structures to use concrete more efficiently and using high performance concrete for large structures.
- Use 7% less cement by using timber to build 20% of buildings.

The first three strategies in our 10-year pathway to zero carbon cement focus on the cement industry itself. In Strategy 4 we switch attention to the design of structures. The best way to reduce cement emissions is simply to avoid using cement whenever possible, and this is something that can be achieved through design. Strategy 4 explains two broad approaches to reducing demand for cement and concrete:

- Strategy 4.1 – Using less cement by design:
  - Designing structures to use concrete more efficiently, without compromising structural resilience
  - Designing structures to use less cement and concrete by using high strength concrete
- Strategy 4.2 – Making far greater use of timber construction, using the latest generation of engineered wood products.

Figure 7.1: The Chillon viaducts which connect France and Switzerland were upgraded using ultra-high strength concrete (Ductal). Photo credit: Hartmut Mühlberg

Strategy 4.1 - Using less cement by design

The cost of materials gives developers a natural incentive to minimise their use. But labour also has a cost, particularly in high-wage countries like Australia. As a result the potential savings from using less material are often outweighed by the greater expense of more complicated design or construction. One result is that many structures use much more cement and concrete than they need.

Below we propose two potential approaches to reducing cement use.

High strength concrete

High strength concrete is specially designed to achieve greater compressive strength than ordinary concrete. Some commercially-available high strength concretes are as strong as 230 MPa, making them stronger than steel.[100] These concretes achieve their superior strength through low water-cement ratios, as well as by adding materials like silica fume, plasticiser and slag. High performance concrete has been used in many large construction projects, including tunnels, high-rise buildings, bridges, sewer pipes, airport pavements and wind turbine foundations.[101]

Potential of high strength concrete to reduce cement use

High strength concretes require more cement per cubic metre than ordinary concrete. However, we need significantly less concrete overall to support a given load. As a result, using high strength concrete can lead to an overall reduction in the amount of cement required for a construction project, and additional reductions in aggregate, water and reinforcement, and the emissions associated with the production and transport of these materials. An additional advantage of high strength concrete is that because it is more durable, it extends the lifespan of a structure,[102] resulting in a net reduction in cement use in the long run.[103]

High strength concrete costs more per unit but can reduce overall costs by reducing the required quantities of cement, steel and aggregate.[104] It can also increase the marketable space in a building by allowing walls and columns to be slimmer. Long-term cost savings result from high strength concrete's lower maintenance requirements and longer service life.

Table 7.1 presents an overview of three in-depth assessments of high strength concrete compared to traditional concrete. These case studies show that for particular applications, a 20% reduction in cement use can be achieved by using high strength concrete.

Table 7.1: Examples of using less cement in high strength concrete structures

Example	Use of strength concrete	Change in cement use
Comparison of two actual highway bridges different dimensions but serve the same purpose[105]	• Bridge 1 — traditional concrete • Bridge 2 — high strength concrete at 60 and 80 MPa	20% less
Concrete columns in car park of apartment block[106]	• Reference case — traditional concrete • Actual — high strength concrete at 80 MPa	20% less
Bridge with a lattice structure in pre-stressed concrete[107]	• Reference case — traditional concrete • Actual — ultra-high strength concrete at 200 MPa	18% less

There is a lack of research into the potential for high strength concrete to reduce concrete and cement use across the whole construction sector. A 20% saving in cement is achievable only for structures designed to bear a large load and where a significant reduction in volume is possible. This applies to structures such as tall buildings, bridges and tunnels. If we assume conservatively that a 20% saving could be achieved in 15% of structures, we could avoid 3% of cement use.

Achieving this in a way that is consistent with our pathway to zero carbon cements requires the development of geopolymer and blended cements capable of making high strength concretes. To date this has not been an area of extensive research, but it is entirely possible. Researchers have already made geopolymer concretes with compressive strengths well in excess of 100 MPa. This includes geopolymers based on slag (above 170 MPa[108]); fly ash (above 120 MPa[109]) and metakaolin (130 MPa[110]).

Reducing cement by design

Construction is a conservative sector, and rightly so. Structures are built to support their load – the weight of the structure itself plus its contents such as people and furniture. Due to the dire consequences of collapse, Australian Standards[111] provide a high degree of insurance by requiring structures to be designed to withstand a greater load than they are likely to encounter in practice.

In addition, the design of buildings provides further protection. Structural engineers usually receive a set fee, giving them the incentive to work quickly. This means they often add further redundancy, as designing a structure to meet its load requirements in a materially-efficient way takes longer. Research has demonstrated this leads to inefficient use of concrete by designers.[112] Some structures are likely to be over-engineered to a level that goes beyond prudence into outright wastefulness.

International evidence supports the claim that concrete can be overused. For example, extensive national surveys have shown that buildings in Brazil typically use 50% less concrete per unit of floor area than equivalent buildings in China and the Middle East.[113] We can't draw precise conclusions from such findings, as structure design involves many factors in addition to load-bearing capacity such as fire resistance, acoustics performance and earthquake resistance. But it does suggest there is room for improvement.

Two innovations in structural engineering have considerable promise in improving the efficiency of concrete use. One is greater use of computers to optimise building design. New software can generate structural elements that use far less concrete than traditional solutions. These computer-designed elements can look quite different to those designed by people. For example ground piles are normally capped with a rectangular block of concrete. But software analyses shows a more complex truss-like structure could be used instead, with a theoretical saving of more than 90% of concrete in certain cases. Similar analysis of bridge piers, beams and other structural elements shows large material savings are often possible through smart design.

Capitalising on the opportunity of optimised designs will require advances in techniques to enable construction of unconventional shapes. One technique is flexible formwork – the mould into which fresh concrete is poured. Flexible formwork takes advantage of the fluidity of concrete with a system of low-cost fabric sheets. This allows us to create structures whose geometry reflects the requirements of their load. This has been shown to make possible material savings of up to 40%.[114]

If we could apply smarter design to 20% of structures and achieve a 20% saving in concrete each time, we would avoid at least 4% of cement use.

The 10-year geopolymer strategy for using less concrete by design

We can reduce cement use through using high strength concrete and better design, though it is difficult to quantify the potential of these approaches. In some situations the potential reduction is substantial – in the order of 20-40%. However, this potential will only be realised on projects large and complex enough to require structural engineers – such as high-rise buildings and most types of infrastructure.

We have assumed that such projects account for 60% of cement use in Australia, and that we can save an average of 12% of cement per project. This conservative assumption suggests we can reduce cement use by 7% using these approaches.

Strategy 4.2 - Replacing concrete with timber

Wood used to be the dominant building material across much of the world, but has declined significantly in recent centuries. In medieval Europe stone and brick began to replace timber, especially in grander buildings. In the modern era, widespread uptake of concrete and steel have further reduced the role of timber.

However, we have never stopped using wood to build. In Australia, most houses are still timber framed, although the average use of wood per unit of floor area has fallen significantly.[115] In recent years timber has undergone a renaissance and is now emerging as the building material of the future, driven by new technologies and construction methods and its role in limiting greenhouse gas emissions. The more we use timber, the less concrete and cement we need.

Table 7.2: Timber products used in construction

	Timber product	Raw material	Description	Use
	Sawn timber	Softwood or hardwood logs	Rectangular lengths cut from logs	Lightweight structural timber for low to mid-rise buildings
Engineered wood products (EWPs)	**Plywood**	Softwood or hardwood veneer	Layers of timber veneer glued together with alternating grain direction	Surface for walls or floors
Engineered wood products (EWPs)	**Cross laminated timber (CLT)**	Softwood or hardwood logs	Layers of timber board stacked in alternating grain directions, bonded with adhesives, and pressed to form a solid rectangular panel	Walls, floors, roofs
Engineered wood products (EWPs)	**Glue laminated timber (glulam)**	Softwood or hardwood logs	Similar to CLT but the layers are stacked in the same grain direction	Structural beams and columns
Engineered wood products (EWPs)	**Laminated veneer lumber (LVL)**	Softwood or hardwood veneer	Boards made from bonding multiple layers of thin wood veneer	Rafters, beams, lintels, joists, columns
Engineered wood products (EWPs)	**Laminated strand lumber (LSL)**	Softwood or hardwood fibres (reconstituted)	Boards made from strands of wood are glued and pressed together	Similar to LVL

Why is timber construction making a comeback?

Traditional timber construction uses sawn timber cut from a log. Sawn timber may be treated to preserve it against infestation and decay, but is otherwise unprocessed. Sawn timber is relatively inexpensive and lightweight, and is suitable for construction of buildings up to about six storeys in height. Pioneering new wood products are now boosting the height limit of timber buildings.

Timber construction is being revolutionised by a range of materials known collectively as engineered wood products (EWPs - Table 7.2). EWPs are manufactured by bonding smaller pieces or strands of wood, to make a composite unit. Compared to traditional sawn timber, EWPs are stronger, more uniform and can be designed to reduce fire damage and decay. They can be used to build a much wider range of buildings than sawn timber, including high-rise buildings. Engineers around the world are rapidly extending the possibilities of what can be achieved with timber construction.

Timber in building standards

Until recently national building standards presented a barrier to timber buildings of more than three storeys. The National Construction Code required taller timber buildings to undergo expensive assessments for fire, acoustic and thermal performance. Changes to the code in 2016 mean these additional assessments are no longer needed for timber structures up to 25 metres in height (eight storeys).

The code allows both sawn timber and engineered wood, though they must be clad with fire-resistant plasterboard.[116] This change to the National Construction Code is likely to contribute to an increase in timber construction, particularly for low and mid-rise buildings. It brings Australia into line with many European countries where standards allow timber buildings up to at least 20 storeys in height, providing they are installed with sprinkler systems.

10-year timber strategy

Our 10-year timber strategy is to replace 7% of the Australian cement market (Table 7.3). This can be achieved by employing timber construction for 20% of new buildings. EWPs can be used to build almost any new structure up to 20 storeys including offices, apartments, schools, libraries and retail outlets, while sawn timber can be used for buildings up to eight storeys. In the short term the biggest market for timber is likely to be multi-storey apartments.[117]

The strategy requires 2.8 million cubic metres of timber which would replace an equivalent volume of concrete. This equates to 1.1 million tonnes of cement. As shown below this quantity of wood is available in Australia from existing plantations and waste timber. In the long term we can greatly increase supply of plantation timber, replacing a greater proportion of concrete and cement. Table 7.4 also presents a longer term strategy for sourcing 6 million cubic metres of wood to replace 15% of domestic cement demand.

Table 7.3: Cement replacement by timber - 10-year and 30 year strategies

	% Buildings made from timber	Sawn timber (million m^3)	Engineered Wood Products (million m^3)	Concrete replaced (million m^3)	Cement replaced*	
					million m^3	Percentage
10-year strategy	20%	1	1.8	2.8	1	7%
30-year strategy	40%	1	5	6	2.2	15%

**Based on assumption of 14MT demand in 2027*

The following assumptions inform the timber strategy and the figures in Table 7.2:

- On average timber replaces an equivalent volume of concrete.
- 60% of Australian cement use is in buildings.
- 20% of new buildings will be timber in 10 years' time.
- 60% of concrete in buildings can be replaced with timber. (On average, timber can replace all above ground concrete. Concrete is still used for foundations, slabs and basements.)
- Concrete has a density of 2400 kg/m3, and cement constitutes 15% of concrete.
- In the longer term (30-40 years) 40% of buildings will be timber.

Timber wood products are a carbon bank

Timber products can be substantially carbon negative. In other words their production can remove more carbon than they emit. According to the Australian Government's State of the Forests Report 2013:

The average plantation softwood log contains sequestered carbon equivalent to 787 kilograms of CO_2-equivalents per cubic metre (kg CO_2-e/m^3), while the average native forest hardwood log contains sequestered carbon equivalent to 982 kg CO_2-e/m3. Total greenhouse gas emissions from forestry operations for production of these average logs represent 3.2% of the CO_2 sequestered in the softwood log and 7.3% of the CO_2 sequestered in the hardwood log.[118]

When we subtract forestry industry emissions, we find softwood logs sequester about 762 kilograms of CO_2 per cubic metre (kg CO_2-/m^3). When we take into account the manufacture, transport, use in construction, maintenance and disposal of a cubic metre of engineered wood product, it has net negative emissions of at least -500 kg CO_2.[119]

This assumes that the carbon is permanently stored, rather than being released at the end of life because the wood is burnt or decomposes. This is a reasonable assumption as after a timber building is dismantled engineered wood products can either be reused, repurposed or turned into biochar. Even if they are used as landfill research has shown the carbon will be retained indefinitely.[120]

If our timber strategy is pursued in the long term, it will lead to a significant sequestration of carbon stored in wood products. Assuming net negative emissions of at least -500 kg CO_2:

- The 10-year strategy using 2.8 million m^3 of timber would sequester 1.4 million tonnes of CO_2.
- The long-term strategy using 6 million m^3 of timber would sequester 3 million tonnes of CO_2.

Other environmental impacts

Our strategy proposes using only plantation timber, not native forest. When properly planned and managed plantations are sustainable and more productive than native forests, as they require much less land for the same yield. Plantations should be seen as an agricultural crop, and in Australia they can be expanded by using land that is already cleared. We propose that as a minimum all plantations should be certified by independent accreditation schemes such as the Forestry Stewardship Commission and the Programme for the Endorsement of Forest Certification. Managing plantations according to these international standards mitigates environmental risks such as depletion of water resources, soil erosion and silting of waterways.

Performance of timber for buildings

Timber can now be used to construct almost any type of building, residential, commercial or industrial. Modern EWPs can be used for flooring, walls, beams and multi-storey frames and most other structural components except foundations and ground floor slabs. Table 7.4 below lists examples of the use of EWPs in many different types of construction.

Timber construction can achieve both wide spans and great heights. The timber arches of Richmond Olympic Oval in Vancouver span more than 100 metres, and Brock Commons, an apartment block also in Vancouver, has 17 storeys made of timber. The versatility of EWPs is demonstrated by innovative buildings such as the undulating timber roof of the Centre Pompidou in Metz (Figure 7.2), a timber fire station in Oregon (US)[121] and plans for a new UK football stadium made entirely of wood.[122]

For our purposes the key advantage of timber is its ability to replace concrete, eliminate emissions from cement manufacture and, potentially, sequester a significant quantity of carbon (see below).

As a construction material timber has better durability than concrete. Whereas reinforced concrete has a lifespan of around 100 years, many timber structures remain intact after several centuries. The world's oldest timber building, Hōryū-ji Temple in Japan, was built around 600 AD and is still in good condition. An equivalent temple made from reinforced concrete would have been rebuilt 10 times in that period.

Other benefits of timber construction include:

- **Speed of installation –** Timber construction products can be prefabricated with great precision – individually tailored to account for the position of windows, services, stairs and ducts. This means that they can be quickly slotted into place, enabling faster construction.
- **Cost –** For many buildings larger than an individual house, the overall cost of timber construction is around 10% less than traditional construction due to the faster construction time and fewer workers required.[123] The savings from labour costs outweigh the higher cost of timber.
- **Design flexibility –** Timber is lighter than concrete or steel, making it more adaptable to different types of design and site conditions. Using timber can allow taller construction where building mass is limited by site conditions (e.g. on top of an existing concrete structure or above unstable ground). Timber also makes it much easier for changes to be made on site with simple tools.[124]
- **Building stability –** Timber buildings can be designed to be more resistant to horizontal forces from wind and earthquakes. Recent experience in New Zealand has shown that timber buildings tend to withstand seismic activity better than those made from concrete.[125]
- **Fire resistance –** CLT provides good fire resistance because panels char slowly, and the charred outer layer protects the wood from further fire damage. (European standards consider exposed CLT to provide sufficient fire protection,[126] whereas in Australia CLT panels must be covered by fire protection plasterboard.) Timber buildings are less prone to sudden collapse during a fire.
- **Thermal performance –** CLT provides better insulation than concrete (R-Value of 1.6-1.7 versus 0.3-0.4 for 200 millimetre thickness[127]).

Examples of modern timber construction

Timber buildings are common in Canada and northern Europe. But with the development and proliferation of the new generation of EWPs, the use of timber for construction is expected to soar across the world.

Perhaps the best known Australian example of a large timber building is the Forte - a 10-storey apartment block in Docklands, Melbourne (Figure 7.3). When it was built in 2012 it was the world's tallest timber building. Five labourers took just 10 weeks to assemble it, which is 30% less than the typical construction time.[128]

Another cutting-edge Australian project is The Green – a five-storey apartment building in Parkville, Melbourne built in 2014.

The Green is the tallest building in Australia made from sawn timber (rather than engineered wood). The timber floors, wall panels and roof trusses were prefabricated, enabling construction to be completed 25% faster than usual for a building of this size and type.

Figure 7.3: Forte building – 10-storey apartment block, Docklands, Melbourne

Figure 7.2: Timber roof of Centre Pompidou in Metz (Photographer: Didier Boy de La Tour)

Table 7.4: Selection of Australian and international examples of CLT construction

Building	Year	Description	Wood products	Concrete avoided (estimated)
Australia				
The Green, Melbourne	**2014**	5-storey apartment building. All timber construction apart from foundation and basement.	Sawn timber	
Forte, Melbourne	**2012**	10-storey apartment building. Concrete foundations and a 70mm insulating layer on floors.	CLT	1000 m^3
Library at the Dock, Melbourne	**2014**	3-storey library	CLT	574 m^3
Our Lady of the Assumption Primary School, North Strathfield, NSW		Rebuilt school replacing 1970s concrete buildings. Timber facade, decking, flooring, sliding panels and door frames	CLT, glulam	
Kent Town, Adelaide	**2016**	5-storey apartment building – upper 3 storeys CLT	CLT	
Southbank building	**2018**	10-storey apartment tower on top of pre-existing 6-storey office	CLT	
5 King, Brisbane	**2018**	10-storey office. Will be tallest timber building in Australia, and world's largest timber office building by floor area.	CLT, glulam	
International House, Sydney	**2018**	6-storey office	CLT, glulam	
International				
Earth Sciences Building – Univ of British Columbia, Vancouver	**2012**	5-storey education building. Timber roof, walls, beams and walls.	CLT, glulam and LSL	
Stadthaus, UK	**2009**	9-storey apartment building		930 m^3
T3, Minneapolis	**2016**	7-storey office	CLT	3,600 m^3
Treet Apartments, Norway	**2015**	14-storey apartment block	CLT, glulam	935 m^3
Brock Commons	**2017**	18-storey student residence. Steel connectors and concrete foundation and cores.	CLT floors and walls, glulam columns	2,650 m^3

Availability of timber

Our two-phase timber strategy has the following requirements for wood.

- Phase 1 – 10 years. Requires 2.8 million cubic metres of timber
- Phase 2 – 30 years. Requires 6 million cubic metres of timber.

Phase 1 - Sourcing 2.8 million cubic metres of timber in 10 years

The 10-year timeframe of Phase 1 is too short for new plantations to mature, so we must source the 2.8 million cubic metres of timber from existing stocks. We envisage three main sources for this timber:

Softwood plantations – There are 1.04 million hectares of softwood plantation in Australia producing nearly 10 million cubic metres of sawn and veneer log annually.[129] There is currently demand for all this production but an estimated 25% of it is for low value uses such as wooden crates, pallets and packing materials. We have assumed that around half of this low value product use can be diverted to higher value structural timber, yielding 1.2 million cubic metres.

Hardwood plantations – There are 0.93 million hectares of hardwood plantation in Australia producing more than 12 million cubic metres of timber annually. The vast majority of this is pulped for paper and mostly sold for export. Wood pulp is a low value use for timber, and we have assumed we can divert 0.6 million cubic metres (5%) to make engineered wood products such as Laminated Veneer Lumber and Laminated Strand Lumber.

Waste timber – Currently Australia generates around 4 million cubic metres of waste timber every year. Around 15% of this has been treated with preservatives, making it hard to reuse. However, more than half is untreated and not recycled for any purpose. Sustainability Victoria estimates that around 244,000 cubic metres of waste timber could be made available for engineered wood products.[130] On a national scale this would make 1 million cubic metres available.

Table 7.5: Using 2.8 million cubic metres of wood products to make 20% of Australian buildings in 10 years

	Softwood (million m^3)	Hardwood (million m^3)	Waste (million m^3)
Sawn Timber	0.3	0	0
CLT and glulam	0.3	0	0.4
Laminated veneer lumber	0.1	0.3	0
Laminated strand lumber	0.3	0.5	0.6
TOTAL	1.0	0.8	1.0
% current annual production	6% hardwood production (13% sawn softwood timber production)	6% hardwood production	25% waste timber generation

Phase 2 – Sourcing six million cubic metres of timber in 30 years

In the long-term we would need 6 million cubic metres of timber to replace 15% of national cement demand. This would require about 460,000 hectares of new plantation – comprised mostly of the softwood Radiata pine that takes 20-30 years to mature. This would require an annual increase in plantations of around 1% per year, which is in line with recommendations from all Australian Governments[131] and the Australian forestry industry.[132] This expansion would create nearly 7,000 regional jobs in timber management, harvesting, haulage and processing.[133]

To put this additional hectarage in context it would require a 23% increase in the current area of timber plantation (2 million hectares[134]), and is less than the area under chickpea cultivation in 2016.[135] The main climatic requirements for softwood plantations are an annual rainfall of at least 600 millimetres, and mean annual air temperature of 8–18°C which would favour elevated areas of southern Australia.[136]

We strongly oppose using productive farmland or areas of native vegetation for new plantations. Instead we propose that the space required could be found on three types of land:

1. Existing hardwood plantation – can be converted to Radiata pine when harvested.
2. Areas affected by soil salinity (timber plantations alleviate salinity problems).
3. Areas of marginal animal agriculture.

To be economically viable individual plantations must be at least 30 hectares and within 200 kilometres of processing facilities.

Supply of engineered wood products

One factor holding back the growth of timber construction in Australia is the absence of domestic manufacturers of engineered wood products for structural purposes. To date projects such as the Forte have had to rely on imported wood, adding extra risk. However, later in 2017 New Zealand company XLam plans to open a factory in Wodonga capable of producing 60,000 cubic metres of CLT every year. As the timber construction industry matures, we expect more such factories will follow.

Table 7.6: Sourcing 6 million cubic metres of timber in 30-40 years[137]

	Production method 1 Sawn timber plus reconstituted fibres		Production method 2 Rotary peeling	Total annual production (m³)
	Sawn timber, CLT and glulam	LSL (Reconstituted)	Laminated Veneer Lumber	
Annual harvest area (hectares)	11,375		4,000	
Recovery rate	34%	22.5%	90%	
Annual production per hectare (m³)	203	135	540	
Annual production (m³)	2,309,125	1,535,625	2,160,000	6,004,750

Assumptions: Additional plantation area is 461,000 hectares of which 1/30th is harvested each year. Annual timber production of 600 m3/hectare. Production method 1 uses same area of land to produce sawn timber suitable for sawn timber, CLT and glulam, with some offcuts being reconstituted to make Laminated Strand Lumber. Production method 2 is based on rotary peeling which produces thin veneer suitable for Laminated Veneer Lumber with a high (90%) recovery rate.

Strategy 5 – Carbon negative cements

Magnesium-based cement

Experimental cements based on magnesium oxide (MgO) could present an enormous opportunity to turn cement from a climate problem into part of the solution. This is because MgO cements could capture significant amounts of carbon dioxide when manufactured and as they cure and age, meaning they have the potential to be carbon negative. If implemented on a global scale these cements could make a substantial contribution to reducing atmospheric carbon dioxide, and maintaining our climate at a safe level for human societies.

The most suitable sources of low carbon magnesium oxide are magnesium silicate rocks, such as olivine or serpentine – the same naturally-abundant minerals used in carbon mineralisation discussed in Strategy 3. Basic magnesium silicates contain no carbon dioxide and can be processed with only modest carbon dioxide emissions to produce magnesium oxide. This can then be made to react with carbon dioxide and water to form a hardened cement consisting of stable magnesium hydroxy-carbonate hydrates which can, in principle, capture more carbon dioxide than emitted during the manufacturing process.

Despite the potential of magnesium-based cements there is a lack of research dedicated to their development. A stronger research push is needed, as there are two significant challenges to overcome before they can be commercialised. Firstly the current process by which magnesium oxide is extracted from magnesium silicates consumes too much energy. Making this process more efficient is an area of active research by Mineral Carbonation International (see Strategy 3) and others.[138]

Secondly the performance and durability of magnesium-based cements is as yet unproven. UK start-up company Novacem made progress in this area by developing a magnesium-based cement made from serpentine. Novacem claimed one tonne of their cement had a negative carbon footprint of 0.6 tonnes carbon dioxide, taking account of both production emissions and carbon dioxide absorption. Novacem regrettably folded before the company was able to fully demonstrate the viability of its cement, though Australian company Calix has bought the technology.[139]

Long-term strategy for magnesium-based cement

Magnesium-based cements are not sufficiently developed to be part of our 10-year strategy. Over the longer term, however, they have the potential to transform our cities into carbon sinks. If half the world's cement were made this way, it could remove one billion tonnes of carbon dioxide from the atmosphere every year – more than twice Australia's current emissions.

This potential should be explored through dedicated research. Australia is well-positioned to lead this effort as we have an abundance of magnesium silicate, and Australian companies like Calix and Mineral Carbonation International are already advancing magnesium oxide research.

Availability of raw materials for 10-year pathway to zero carbon cement

In this section we describe the availability of raw materials required to deliver our proposed 10-year pathway to zero carbon cement. Figure 9.1 shows the material requirements for each of the four strategies in the pathway.

Strategies 1 and 2

Strategies 1 and 2 require 10.2 million tonnes of material: fly ash, slag, metakaolin, limestone and alkali activator. Table 9.1 shows the required amounts of each material and Figure 9.2 shows how production would ramp up to meet the 2027 target.

Figure 9.1: Materials requirements for 10-year pathway to zero carbon cement ('000 tonnes)

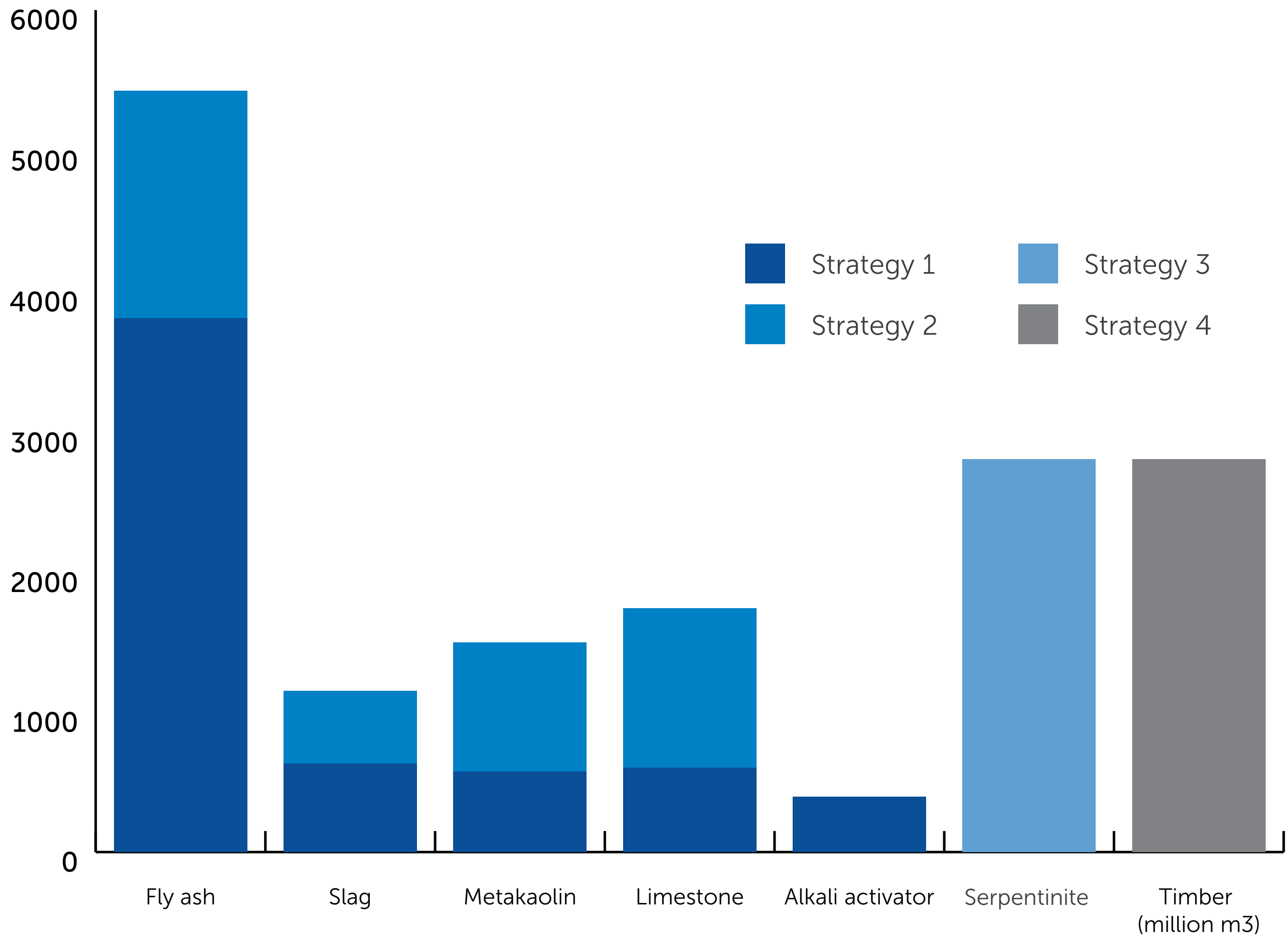


Table 9.1: Material requirements for strategies 1 and 2 in 2027

	Fly ash	Slag	Metakaolin	Ground limestone	Alkali activator
Strategy 1	3,804	630	573	600	393
Strategy 2	1,623	519	921	1,137	0
Total	**5,427**	**1,149**	**1,494**	**1,737**	**393**

Table 9.2: Fly ash requirements and availability to supply 50% Australian cement with geopolymer

	Maximum annual requirement (tonnes)	Domestic availability (tonnes)
Fly ash (fresh)	2,300,000	5,000,000* (2015)
Stockpiled fly ash	5,400,000	100,000,000+

** Estimate assumes 50% of fresh fly ash is suitable*
+ Estimated total stockpile based on 400 million tonnes and 25% suitability

Figure 9.2: Material requirements for strategies 1 and 2 over 10 years

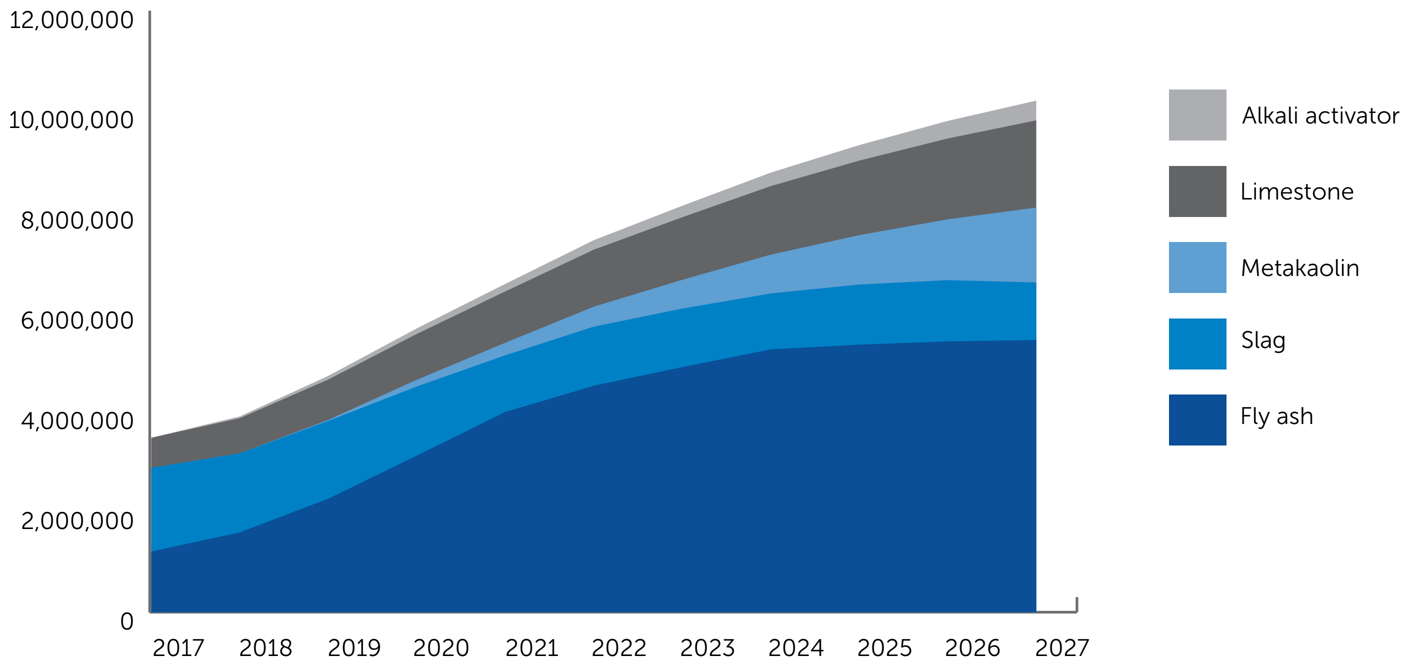
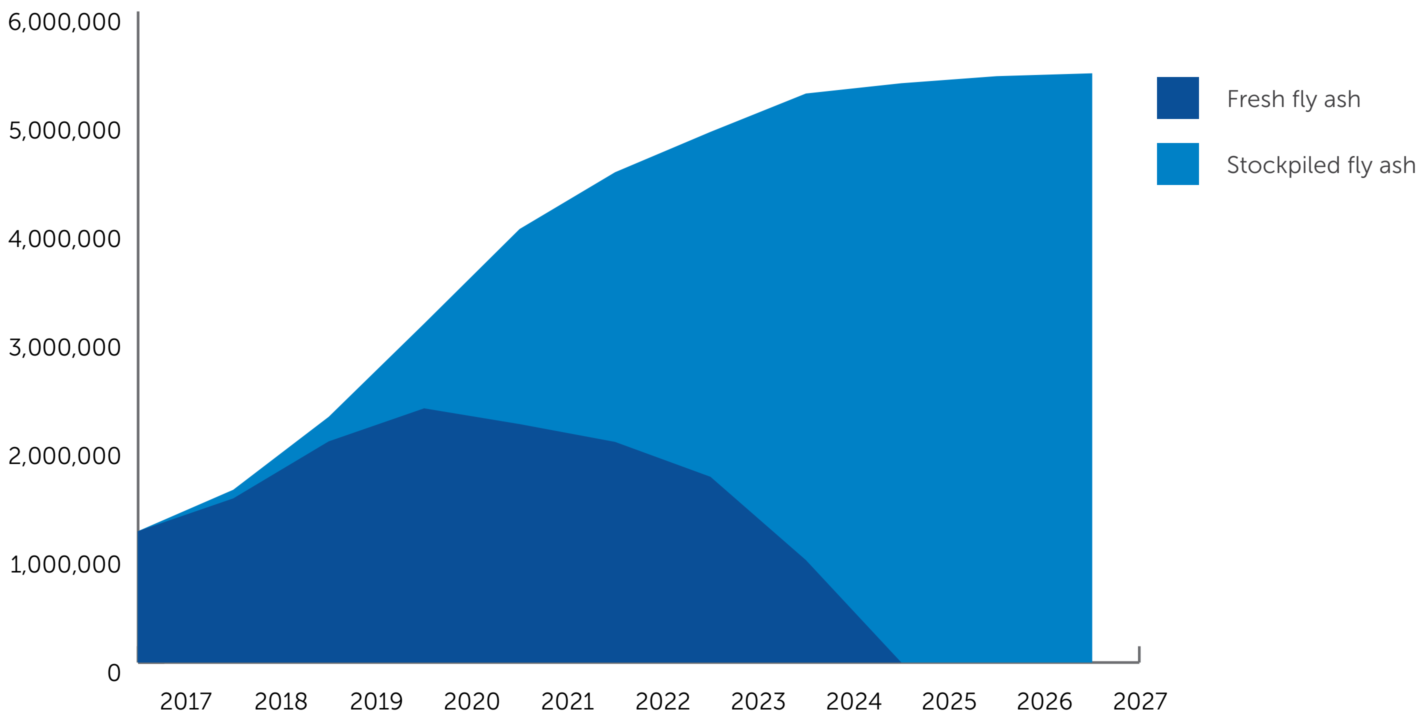
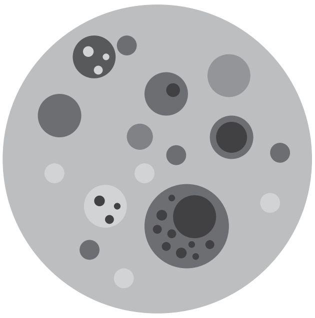


Figure 9.3: Sourcing fly ash exclusively from stockpiles by 2027



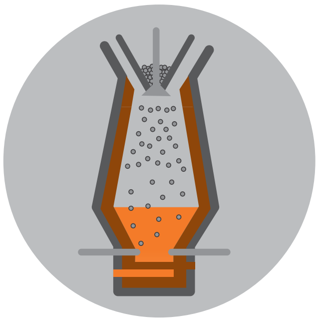
Meeting material requirements for Strategies 1 and 2



Fly ash

Fly ash is the main waste product of coal-fired power stations. More than 1 million tonnes a year is already used in Australia as a supplement in Portland cement. Strategies 1 and 2 rely on the annual availability of 5.4 million tonnes of fly ash by 2027. We have assumed fresh fly ash will be available only until 2024 due to the shift away from coal to renewables. The maximum amount of fresh fly ash (in 2020) is estimated to be less than 2.3 million tonnes – less than a quarter of the 10.7 million tonnes of fly ash produced in Australia in 2015.[140]

Once Australia moves to 100% renewable electricity, geopolymer cement manufacturers will be able to rely exclusively on Australia's massive stockpiles of fly ash. Based on the conservative assumption that 25% of stockpiled fly ash will be suitable after processing, there is likely to be at least 100 million tonnes available in Australia, enough to supply 20 years of alternative cement production (Table 9.2).



Slag

Strategies 1 and 2 would require 1.1 million tonnes of slag per year in 2027 (Table 9.1). Initially this slag will be entirely composed of ground granulated blast-furnace slag (GGBS), a by-product of making iron in a blast-furnace. GGBS is a glassy material chemically similar to Portland cement clinker.

Current domestic consumption of GGBS is around 1.6 million tonnes – of which only 0.5 million tonnes is produced in Australia and the remainder is imported, mostly from Japan.[141] The vast majority of this GGBS is used as a supplement in Portland cement. Therefore Strategies 1 and 2 do not rely on the consumption of more GGBS than today, but instead assume that it will be used in geopolymer and high-blend cements rather than traditional Portland cement.

Iron blast-furnace is an extremely carbon-intensive production process. Future instalments of BZE's Zero Carbon Industry Plan will present alternatives to the iron blast-furnace, one consequence of which would be the end of the production of GGBS. During our 10-year pathway we will need to find replacements for GGBS in cement. Possible alternatives include landfilled blast-furnace slag, other metal slags from steel, lead, copper and nickel production or slags specially manufactured for use in cement. These sources are discussed in more detail in Appendix 2.

Alkali activator

Geopolymer cements rely on an activator – usually a strong alkali – to trigger the chemical reactions that produce a hardened cement. We have assumed here the activator will be sodium silicate, as it is not only the most effective activator but is safer than some alternatives. To produce the target of 6 million tonnes of geopolymer cement, we will need 393,000 tonnes of sodium silicate per year.

Australia already imports enough caustic soda (the main chemical ingredient of sodium silicate) to manufacture nearly 20 million tonnes of sodium silicate. In the future we could manufacture sodium silicate from raw materials readily-available in Australia – salt, sand and water. The other main input is energy, mostly in the form of electricity. The electricity required to make 393,000 tonnes of sodium silicate would require less than 0.1% of generation in a national 100% renewable energy grid.

As our understanding of geopolymer chemistry improves we will be able to reduce the concentration of activator and find alternatives to sodium silicate. Researchers are currently exploring a range of alkalis and other chemicals to play the activation role. Alternative activators have been successfully employed overseas including a salt activator (Murray and Roberts) and hydroxycarboxylic acid (Ceratech).

Metakaolin

Much early research into geopolymers focussed on clays with a high aluminosilicate content, particularly kaolinite soils.[142] Through heat treatment, kaolinite can be converted into metakaolin which can produce high performance geopolymer cement.[143] Banah is now demonstrating this on a commercial basis (See BanahCEM in Strategy 1).

Our strategies rely on the use of 1.5 million tonnes of metakaolin by 2027. This quantity of metakaolin is readily available in Australia, as there are hundreds of millions of tonnes of kaolinite distributed across the country. In fact, much of this kaolinite demand can probably be sourced from the billions of tonnes of waste material dumped at the edge of existing mines.

Transitioning to metakaolin-based cements will be crucial as Australian fly ash will eventually run out, and most developing countries do not have large stockpiles of fly ash. There is enough kaolinite to supply the entire world cement demand for the foreseeable future (Figure 9.4).[144] Australian development and deployment of metakaolin-based geopolymers would make a substantial contribution to a global shift towards zero carbon cement.

Other waste products in geopolymers

A successful Australian geopolymer industry is likely to have a significant side benefit: the ability to make high-value use of problematic wastes. Several waste streams currently difficult to deal with could be used to make geopolymers (Table 9.3).

Waste glass – Australia produces about one million tonnes of glass waste every year, only about half of which is recycled back into glass. The remaining half million tonnes is either used for low grade products such as road aggregate, or dumped in landfills.[145] In Victoria alone there are stockpiles of 300,000 tonnes of waste glass.[146] This waste glass is a problem as it is hard to recycle, and when reused it is largely driven by a need to find a way of disposing of waste glass rather than demand. Waste glass could be used as one of the raw materials for geopolymer cement, and could even play a role in activation, replacing part of the need for sodium silicate activator.

Sugar cane bagasse ash – Bagasse is the pulpy residue left after the extraction of juice from sugar cane. Australia produces 10 million tonnes of bagasse annually.[147] Much of this bagasse is burned to generate heat and electricity for sugar mills. If we estimate that 5% of burned bagasse remains as ash[148] , this means we dump 0.5 million tonnes of bagasse ash in landfills each year. Sugar cane bagasse ash could therefore supply 8% of the geopolymer industry for Strategy 1.

Red mud - Australia is the world's second largest producer of alumina. In 2014-15 Australia produced 20 million tonnes of alumina, and an equivalent tonnage of alumina's main waste product, red mud, which is toxic.[149] It is likely that Australia has hundreds of millions of tonnes of toxic red mud stored in ponds. After thermal treatment red mud could be used to produce geopolymer cement.

Waste clays - Every year the mining industry extracts and dumps about 7 billion tonnes of waste material, much of which consists of clay-rich minerals.[150] For example, there are large kaolinite deposits left around the Morwell and Yallourn coal mines in Victoria's Latrobe Valley.[151] This waste material could be the source of metakaolin used in cement.

Coal bottom ash – about 10% of the ash from coal-fired power stations is coal bottom ash. Although it is heavier and less reactive than fly ash, it can also be used in geopolymer cements.

Table 9.3: Potential uses in the geopolymer cement industry of wastes that are hard to dispose of or reuse

	Availability (tonnes)		
Waste product	Annual	Stockpiled	**Potential use**
Waste glass	500,000	1.2 million	Raw material and alkali activator
Sugar cane bagasse ash	200,000	n/a	Raw material
Waste clays	500 million +	10 billion +	Raw material
Red mud	20 million +	100 million +	Raw material
Coal bottom ash	1 million	40 million	Raw material

Global availability of raw materials

Australia can show other countries how to achieve a zero carbon cement.

One of the aims of BZE's Zero Carbon Industry research is to develop strategies and technology that Australia can sell to the rest of the world. This is particularly important for cement as most future demand is likely to come from large developing countries such as India, Indonesia and Brazil. This report presents an affordable zero carbon cement pathway reliant on abundant materials, and hence will be applicable in many other countries.

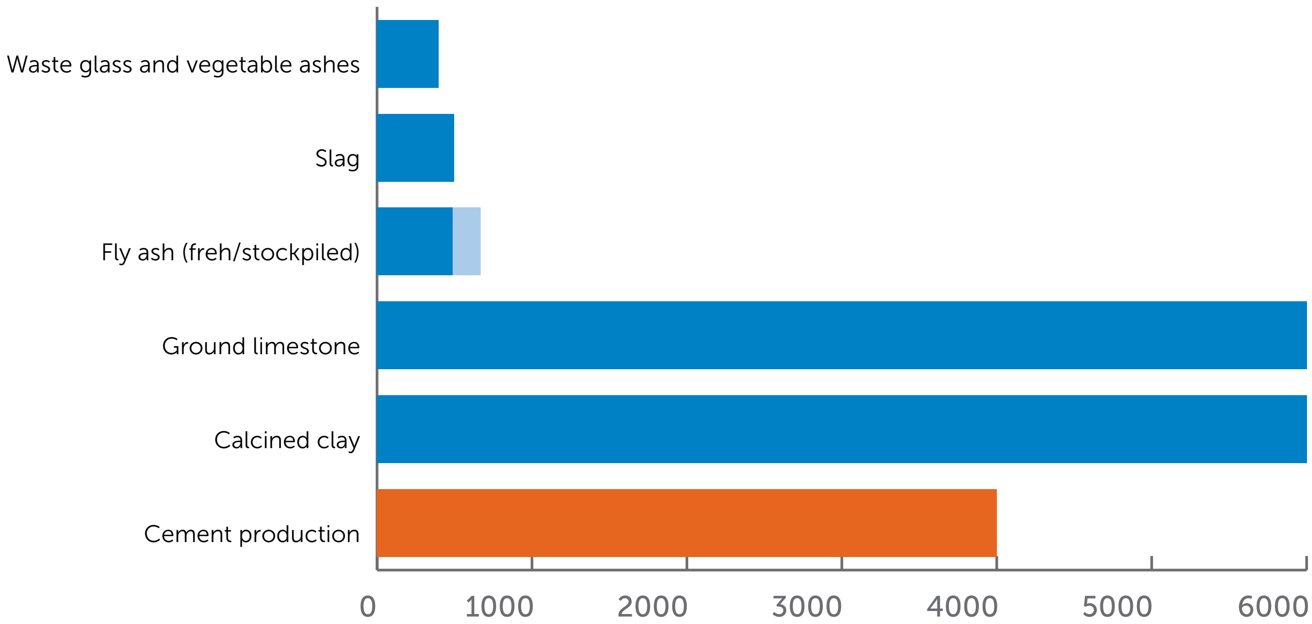
For example, many countries have underutilised supplies of fly ash. China and India produce 300 million tonnes and 100 million tonnes of fly ash per year respectively. Worldwide production is estimated to be 700-750 million tonnes per year, of which 70% is likely to be suitable for high-blend cements[152] and 50% for geopolymer cement.[153] This is sufficient to supplant 12% of the world's Portland cement clinker.

There are no reliable figures on global stockpiles of fly ash. One estimate is 6 billion tonnes, and given at least 400 million tonnes is currently landfilled every year, this looks conservative. Using this figure and assuming 30% of global stockpiles can be used for geopolymers, we could replace an additional 4% of current global production of Portland cement each year for 10 years.

On a global scale fly ash provides only a short-term and incomplete remedy to high-emitting cement. It can provide the material for around 16% of cement only while coal-fired generation continues and stockpiles last. As Figure 9.4 shows, slag, waste glass and vegetable ashes are also available in insufficient quantities to replace a large proportion of global cement demand.

Fortunately kaolinite clay is a widely-distributed material, and abundant enough to make all the world's cement (Figure 9.4). It is particularly prevalent in tropical zones which also happens to be where much future cement demand is likely to be located. This shows the importance in the long term of developing geopolymer and high-blend cements based on metakaolin and other calcined clays. An important supporting role can be played by ground limestone, which is also available in sufficient quantities. (In fact we need less of it to make alternative cements compared to Portland cement.)

Figure 9.4: Global annual availability of raw material for low carbon cement (million tonnes)



Putting the strategies into action

There are many opportunities to support Australian innovation in cement.

This section highlights actions that governments and industry can take to modernise cement and decarbonise this essential industry.

Standards

Australian standards are flexible enough to allow our cement strategies to be partially achieved, but amendments are required for full implementation.

Official standards for materials, products and methods are vital for ensuring product functionality, compatibility, safety and sustainability. Standards Australia carries out the important role of developing standards.

The main standard for cement, AS 3972 (General purpose and high-blend cements), enables more flexibility in cement mix design than many other national standards. AS 3972 allows fly ash and Ground Granulated Blast-Furnace Slag (GGBS) with no upper limit in high-blend cements (Type GB). This means both geopolymer cements and high-blend cements with a high level of fly ash or slag are permitted under Australian standards.

However, the standard does not explicitly refer to geopolymer cement, or make any mention of alkali activators. This lack of acknowledgement can make it harder for engineers to specify geopolymer cement, and can be an obstacle to their use. This issue will be resolved once Standards Australia releases a Standard Specification for Construction with Alkali-Activated and Geopolymer Concrete.

AS 3972 currently presents two other barriers to the implementation of Strategies 1 and 2:

- there is no provision to use any alternative materials other than fly ash and GGBS. This excludes the use of other types of slag, calcined clay and volcanic ash
- up to 20% limestone can be included (Type GL) but only if the remainder of the binder is Portland cement. This prevents implementation of Strategy 2 where 20% limestone is combined with calcined clay or fly ash.

Actions:

- Accelerate publication of Standard Specification for Construction with Alkali-Activated and Geopolymer Concrete
- Revise standards to allow a wider variety of cements including those described in Strategies 1 & 2.

Costs of alternative cement production

Geopolymer and high-blend cements are likely to become cheaper than Portland cement after widespread take-up.

The majority of clinker substitutes discussed in Strategies 1 and 2 cost less than Portland cement (Table 10.1). This means that both geopolymer cements and high-blend cements can already be cost-competitive with regular Portland cement. High-blend cements are likely to be cheaper than standard cement due to the lower material cost, and have driven the cement industry to progressively increase clinker substitution in recent years.

In South Africa geopolymer cement is already cheaper than Portland cement due to a plentiful local supply of fly ash and GGBS. In Australia geopolymer cements are currently 10-15% more expensive than Portland cement due to the cost of sodium silicate activator. Geopolymer cements are already a cost-effective choice for hot or acidic environments. Rocla states that if their geopolymer precast products were produced at the same scale as regular precast concrete, they would be the cheaper option.

Costs of establishment

Geopolymer cement production has a major advantage: it does not require a kiln, which makes the set-up cost of a new plant relatively low. A standard cement clinker plant costs around $400 million to set up, a geopolymer plant costs less than 10% of that. This vastly lower cost will encourage the market to move towards distributed geopolymer production, with plants established at or close to sources of stockpiled fly ash. (See Nu-Rock on p33 who are using the stockpiled fly ash at Mount Piper Power Station.) Locating geopolymer production at the site of coal-fired power stations has the additional benefit of providing alternative employment for locals when power stations close.

The price of both geopolymers and high-blend cements will fall once they are more widely adopted. Mass market take-up will lower the cost of the input materials, and achieve economies of scale.

Requiring cement companies to pay for their carbon emissions would be a powerful stimulus to widespread uptake of geopolymer and high-blend cements. Paying for cement carbon emissions would also support the use of timber, commercialisation of mineral carbonation and incentivise the use of less concrete.

Action:

- Implement a national policy measure requiring the cement industry to pay for carbon emissions. Imported clinker and cement must also be subject to this carbon price, so as not to disadvantage Australian industry.

Table 10.1: Costs of cement materials

Material	Indicative cost per tonne ($)
Portland cement	$200
GGBS	$160
Fly ash	$90-130*
Limestone	$50
Metakaolin	$350
Sodium silicate solution	$600

** Heavily dependent on transport costs*

Improving incentives to use recovered waste materials

Low carbon cements can put difficult wastes to good use. Incentives should be given to recover these wastes and make them available to the cement industry.

Geopolymer and high-blend cements can use Australia's abundant fly ash, including stockpiles of around 400 million tonnes. Australia should view these stockpiles as a valuable resource and use them to make cement.

The domestic fly ash market is currently not well developed. Cement companies are sometimes unable to secure long-term contracts, which means they lack confidence to invest in facilities to store and handle fly ash. As a result most of Australia's daily production of fly ash goes unused.

One solution is to encourage energy companies to find markets for their fresh and stockpiled fly ash.[154] This could be achieved in several ways, including financial incentives to use fly ash, or financial disincentives or restrictions on stockpiling fly ash.

Geopolymer cement can also use other waste materials that are currently hard to recycle and dispose of, including waste glass, red mud and bagasse ash. In the longer term incentives can encourage the recovery and use of these wastes.

Waste wood is also a material that is currently difficult to recover and recycle in Australia. Incentives can help develop markets for recovering and recycling this waste into construction products that can replace cement.

Actions:

- Introduce new regulations or financial incentives to encourage operators of coal-fired power stations to find markets for their fresh and stockpiled fly ash.
- Introduce incentives to recover waste glass, red mud and bagasse ash for cement production.

Sustainability Ratings Tools

Sustainability ratings tools are a powerful incentive for sustainable building and infrastructure. They should be updated to incentivise the uptake of zero carbon cement and practices that minimise the use of Portland cement.

The most commonly used tools in Australia are the Green Building Council Australia's Green Star certification for buildings, and the Infrastructure Sustainability Council of Australia's IS Rating Scheme for infrastructure.

The popularity of these tools is increasing. More than 700 building projects have been awarded Green Star certification, and more than 60 infrastructure projects have been awarded or registered for the IS rating.

These schemes and others have successfully encouraged the reduction of Portland cement content, through incentives such as:

- **Green Building Council Australia –** Green Star Design & As Built – a maximum of 2 points where the Portland cement content is reduced by 40% (average across all project concrete)

- **Infrastructure Sustainability Council of Australia (ISCA) –** IS Rating Scheme – replacing Portland cement can contribute to the 6 points available for the Materials credit. ISCA acknowledges clinker substitution up to 80%, as well as geopolymer pipes

- **Good Environmental Choice Australia –** Cement must contain at least 30% supplementary cementitious materials, or come from a manufacturing plant with emission reduction methods, or use alternative cement chemistries.

Sustainability rating tools can drive uptake of geopolymer cements and high blend cements in Australia. Criteria should be amended to incentivise clinker replacement up to 100%, offering greater rewards for using lower carbon cement.

The current Green Star ratings only reward a 40% replacement of Portland cement, and the highest ISCA rating of 'Excellent' can be achieved with only a 30% reduction in clinker.

Recognising a project's overall embodied emissions can incentivise the use of low carbon cements. The Living Building Challenge takes this approach. Projects certified under this scheme must purchase carbon offsets for the total embodied carbon of construction, providing a large incentive to minimise or avoid the use of traditional cement. Projects certified under this scheme are often built with timber.

Actions:

- Infrastructure Sustainability Council of Australia and Green Building Council Australia to increase incentives for:

  - reducing the clinker content of cement up to 100%

  - using waste material in cement.

- Infrastructure Sustainability Council of Australia and Green Building Council Australia to introduce incentives related to a project's embodied emissions.

Procurement

Government and industry can lead geopolymer and high-blend cement procurement, encouraging rapid and widespread adoption and stimulating industry growth and jobs

Federal, state and local governments and property developers purchase large quantities of concrete for buildings, developments and public infrastructure.

Australians are embracing sustainability and green buildings, and zero carbon cement is an opportunity to take sustainable cities to the next level. Government and developer procurement is also a powerful tool for growing the market for alternative cements.

Some Australian Governments and developers are already showing great leadership:

- Transport for NSW projects must achieve an average reduction in Portland cement of at least 30% across all concrete mixes
- the Victorian Government's Melbourne Metro project is aiming for 36% Portland cement replacement
- Lendlease specified at least 30% Portland cement replacement at Barangaroo South development.

More can be done to achieve world best practice for Portland cement replacement in Australia, and to use geopolymer cement in construction projects.

Industry and governments at all levels should adopt procurement policies that help establish Australia as the world leader in low carbon cement. One strategy would be to set targets for procurement of alternative cements, similar to the renewable energy procurement targets of some local and state governments. Organisations could begin by specifying alternative cement targets for projects perceived as low-risk such as non-structural infrastructure. Geopolymer cement should also be specified where it confers an obvious construction and maintenance advantage, such as in sewers or other acidic environments.

A high proportion of pre-mixed concrete goes to small-scale domestic applications such as house slabs. This is a low risk application and is a sector where low carbon cements could quickly gain a foothold. Building firms should familiarise themselves with alternative cements so they can recommend them to clients, and request them from the concrete industry.

Actions:

- Governments at all levels and companies to set procurement targets for high levels of Portland cement replacement.
- Public sector bodies such as councils and roads authorities to introduce standards requiring geopolymer cement for non-structural purposes.
- Water companies and others to specify alternative cements where they offer a technological advantage over Portland cement.
- Building firms to make greater use of low carbon cement concrete for domestic applications.

Investment

Investment into alternative cements can be stimulated through policies that emulate the success of renewable energy policies.

Governments can play a positive role in encouraging industry innovation and investment through setting a national target to reduce the carbon intensity of cement. Cement manufacturers would be required to meet the target, or buy credits from lower emitting creditors if they exceed it. This is similar to the Emissions Intensity Scheme proposed for the electricity sector by the Climate Change Authority.

Allowing the Clean Energy Finance Corporation to invest in commercial, low carbon cement manufacturing and construction projects would be another positive step towards modernising cement in Australia. The Corporation can also measure performance through collecting and monitoring data.

Actions:

- Establish a national target to reduce the carbon intensity of cement, which becomes progressively more stringent.
- Allocate a portion of the Clean Energy Finance Corporation's budget to invest in low carbon cement manufacture and construction projects.
- Give the Clean Energy Finance Corporation responsibility for monitoring and collecting performance data on low carbon cements.

Research

Research into alternative cements should be increased.

Most research into alternative cements has been carried out by a small number of companies and academics. This research has helped increase knowledge, confidence and use of alternative cements, but needs to be upscaled to drive rapid and industry-wide use of geopolymer and high-blend cements.

Advancing mineral carbonation and carbon-negative magnesium cements is particularly dependent on research. Both technologies have huge potential for tackling climate change. CSIRO, Australian universities and industry should be encouraged to put far more effort into their development.

The Australian Renewable Energy Agency's investment in renewable energy is a successful model that could be applied to zero carbon cement research and development.

Actions:

- Expand the remit of the Australian Renewable Energy Agency to encourage further research into mineral carbonation and carbon-negative magnesium cements.
- Provide policy incentives for further research into widespread development and application of geopolymer and high-blend cements.

Cement industry leadership

Major Australian and global players in the cement industry do not have a strategy for rapidly moving to zero carbon cement. Many cement manufacturers have argued - with some success - that cement should be exempt from the transition to zero emissions. An industry representing 8% of all global carbon emissions needs to start its transition to zero emissions. Companies with no transition strategy risk financial exposure to carbon.

As far as BZE is aware, no major Australian cement company has launched a geopolymer cement or a cement with a very high proportion of fly ash or metakaolin.

Many small to medium sized companies have launched alternative cements, and there is an opportunity to encourage and expand this much needed innovation.

The move to zero carbon cement will be smoother if the main players participate, for they are the repositories of much cement knowledge. The best way to encourage this is to provide the right incentives, with the expectation that the cement industry will respond. The main manufacturers will then have a choice similar to that faced recently by traditional energy generators: to embrace change and opportunity, or to stick doggedly to an old and polluting model.

Actions:

- Australian cement industry to:
    - set an industry-wide zero carbon cement target
    - advocate for policies and market tools that incentivise the national industry to rapidly move to zero carbon cement.

Incorporating into engineering education

Students in engineering courses do not usually learn about geopolymer or blended cements. This means they are likely to leave university with the view that cement means standard Portland cement. Universities and engineering institutes need to start including low carbon cements as a standard part of education about cement, concrete or construction.

Professional development should also include zero carbon cements in the Australian and international context, design and construction approaches that minimise cement or use high strength cements, and use of engineered wood products.

Actions:

- Australian universities to include geopolymer and high-blend cements in courses on cement, concrete and construction.
- Engineers Australia to develop and include education about low carbon cements, minimising cement use and engineered wood products as part of continuing professional development.

Ensuring long-term availability of timber

Investment in new forest plantations in Australia is stagnant.

This contrasts with the agreement by all Australian governments to dramatically increase plantations to 3 million hectares by 2020 (compared to 2 million hectares today); a goal that will not be achieved.[155] Reasons for weak investment in plantations include:

- their carbon abatement benefits are not fully rewarded
- some plantations are too far from forestry industry infrastructure to be economic.

The forestry industry believes that addressing these issues would help stimulate the new softwood plantations required to achieve this report's long-term vision for timber construction.

Actions:

- The Australian Government to:
  - amend the Carbon Farming Initiative to provide greater recognition of the carbon abatement benefits of plantations
  - encourage the establishment of new softwood plantations within 100 kilometres of sawmills and wood product factories.

Table 10.2: Actions to accelerate implementation of zero carbon cement pathway

Responsible	Recommended action
Standards Australia	• Accelerate publication of Standard Specification for Construction with Alkali-Activated and Geopolymer Concrete • Revise standards to allow a wider variety of cements including those described in Strategies 1 & 2
Australian Government	• Introduce a carbon price which includes the cement industry, as well as imported clinker and cement • Establish a national target to reduce the carbon intensity of cement, which becomes progressively more stringent
Australian and State Governments	• Introduce new regulations or financial incentives to encourage use of fresh and stockpiled fly ash
Australian Government (CEFC)	• Reserve a portion of the budget of the Clean Energy Finance Corporation for investment in low carbon cement manufacture • Give the Clean Energy Finance Corporation responsibility for monitoring and collecting performance data on low carbon cements
Australian Government (ARENA)	• Expand the remit of the Australian Renewable Energy Agency to encourage further research into mineral carbonation and carbon-negative magnesium cements
Sustainability ratings tools (eg ISCA and GBCA)	• Increase the incentives to reduce the clinker content of cement and use waste material in cement • Introduce incentives related to a project's embodied emissions
Governments at all levels, public sector bodies and business	• Set procurement targets for low carbon cement and Portland cement replacement • Make geopolymer cement obligatory for non-structural purposes and where they confer a technological advantage • Building firms to make greater use of low carbon cement concrete for domestic applications
Cement industry	• Set an industry-wide zero carbon cement target • Advocate for a price on carbon which includes cement industry
Universities and Engineers Australia	• Include geopolymer and high-blend cements in courses on cement, concrete and construction, and as part of continuing professional development
Australian Government	• Amend Carbon Farming Initiative to provide greater recognition of the carbon abatement benefits of plantations, and encourage the establishment of new softwood plantations within 100 kilometres of sawmills and wood product factories

Conclusion

Concrete is a remarkable material – strong, versatile and durable – and cement is the technology that makes concrete possible. We'll continue to need huge quantities of cement, but we urgently need to change the way we make it.

Cement making causes 8% of world emissions, and this percentage is on track to rise substantially by 2050. The cement industry has outlined strategies to reduce emissions, but the reductions it anticipates are not enough even to offset projected growth in demand. This is because current strategies fail to tackle the main cause of cement-related emissions – the calcination of limestone to make Portland cement.

In the fight to limit climate change we need to recognise that calcining limestone and burning coal present very similar problems in releasing fossil carbon. In both cases, responses relying on tweaks to existing technology are inadequate. In the zero-carbon era the cement industry must transform as the energy sector is now doing. This means developing strategies that drastically reduce the use of calcined limestone and Portland cement. This transformation is long overdue. Portland cement was invented nearly two hundred years ago, and although it has been improved, the fundamental technology remains unchanged.

10-year pathway to zero carbon cement

The pathway presented in this report shows Australia can reduce cement emissions to zero in 10 years. As far as we're aware *Rethinking Cement* is the first comprehensive plan of its type anywhere in the world. *Rethinking Cement* is not a prediction or prescription, but a description of possibilities.

There will be other paths to zero-carbon cement, which may be variants of our strategies, or other methods entirely. Beyond Zero Emissions puts forward *Rethinking Cement* in the hope and expectation that policy makers and industry see our report as a stimulus and a challenge to make the cement we need while securing a safe climate.

We have designed the overall pathway to make best use of the knowledge and resources available in Australia. We have also selected options that can be applied overseas, particularly in developing countries where cement demand is expected to grow the most in the next few decades. By pursuing these strategies Australia will develop modern zero carbon technology that we can export to the rest of the world.

Rethinking Cement focuses mainly on reducing process emissions to zero. All other emissions are energy-related and can be tackled by a broader shift to a zero carbon energy sector, which will be explored in future installments of BZE's Zero Carbon Industry Plan.

The cement strategies

Our 10-year pathway for zero-carbon cement is based on four complementary strategies, plus a fifth long-term strategy for carbon negative cement.

Strategies 1 and 2 form the core of the pathway, reducing Portland cement to 15% of current consumption. These strategies envisage the replacement of all cement with two alternative technologies: geopolymer cement and high-blend cements. Neither technology is new and successful examples of their application go back decades. Recent advances in understanding and using both technologies mean they are now ready to supersede Portland cement. The proof of this is their application in a wide variety of structural applications including multi-storey buildings, major infrastructure projects and precast concrete products. These cements are not only capable of matching the performance of Portland cement, but present substantial benefits in several types of hostile environments.

Our pathway gives equal prominence to geopolymer cement and high-blend cement, and recognises that each has its advantages for particular applications. We expect and hope that these technologies will compete for market share, in the context of a zero carbon cement industry, just as wind and solar PV are doing in the energy sector.

To replace limestone in Strategies 1 and 2 requires large quantities of material, especially fly ash and metakaolin. Geopolymer production also requires GGBS and alkali activator, though in smaller quantities. This report shows that the required materials can be sourced or manufactured within Australia – sustainably and affordably. A secondary environmental benefit of these strategies is the beneficial use of millions of tonnes of stockpiled fly ash, and potentially other problematic wastes such as broken glass and toxic red mud. Countries with large reserves of these wastes can benefit from Australian development of cements which use them safely and productively. Countries lacking such stockpiles are likely to have alternative sources of suitable material such as kaolin clays and volcanic rock.

One exciting thing about these cements is their potential to evolve and improve even further. Although individual researchers and companies have invested impressive levels of resources, ingenuity and effort into their development, the overall research effort is minuscule compared to other materials technology like plastics, solar PV or even Portland cement. If equivalent resources are spent on developing alternative cements, their cost, performance and versatility are likely to improve dramatically.

Strategy 3 employs a new technology, mineral carbonation, to capture the emissions from the remaining production of Portland cement. Mineral carbonation treats carbon dioxide not as a waste but an input into a product with market value. As with Strategies 1 and 2, it relies on raw material abundant in Australia. A handful of companies have already commercialised mineral carbonation, but Australian companies are working to take it much further. We foresee its main application in the cement industry, but note that it has potential for any industrial process with unavoidable release of carbon dioxide.

Strategy 4 simplifies the overall task by allowing us to use less cement. For some purposes cement is irreplaceable but the new wave of timber products offers a more sustainable alternative. We have estimated that by building with timber we could reduce demand for concrete by at least 7%. Where we do use concrete we could use less of it through smarter design. Through a combination of these measures we could reduce overall cement consumption by 14%.

Longer term the prospect of negative emission magnesium-based cements demands dedicated attention from policy-makers and researchers. If proven viable they could provide an invaluable tool to combat climate change, transforming our cities into carbon sinks.

The opportunity for Australia

The transition to a zero carbon economy is underway, driven by the rapid shift to renewable energy.

For a sector with such a high level of emissions, cement has received remarkably little attention. This creates an enormous opportunity for Australia, which is already a global leader in low carbon cement research and development. If we become the first country to achieve a zero carbon cement industry, we will have developed products and technologies we can sell to the world, while making a major contribution to maintaining a safe climate for all.

Appendix 1 – Glossary

Alkali activator – alkaline chemical, usually in solution, which reacts with a powdery aluminosilicate such as fly ash to produce a cement capable of making concrete.

Aluminosilicate – material with a high level of silica (SiO_2) and aluminium oxide (Al_2O_3)

Calcination – process of heating to separate a chemical compound into simpler compounds.

Caustic soda – sodium hydroxide – an effective but highly caustic alkali activator, and the precursor to sodium silicate.

Cement – chemical agent which hardens into rock-like substance, binding aggregates (sand and gravel) to make concrete. Also mixed with water, lime and sand to make mortar.

Clinker – the main ingredient of cement, is a mixture of various calcium silicates. It is produced in a rotary kiln by heating a combination of limestone and clay. The vast majority of cement-related emissions are from clinker production.

Compressive strength – ability of hardened concrete to withstand a load, measured in megapascals (MPa).

Concrete – a building material made from a mixture of crushed stone or gravel, sand, cement, and water, which can be spread or poured into moulds and forms a stone-like mass on hardening.

Cross-laminated timber (CLT) – layers of timber board stacked in alternating grain directions, bonded with adhesives, and pressed to form a solid rectangular panel.

Engineered wood product (EWP) – a wood product used in construction made by binding strands, particles, fibres, veneers or boards.

Flexural strength – ability of hardened concrete to withstand bending, measured in megapascals (MPa).

Fly ash – main waste product of coal-fired power stations – a fine grey powder that collects in exhaust flues. Some fly ash is pozzolanic and useful as a clinker substitute or a raw material in geopolymer cement.

Geopolymer cement – a type cement made from aluminosilicate material (such as fly ash or metakaolin) reacted with a strong alkali source. The term geopolymer cement is used in this report to be synonymous with alkali-activated cement.

GGBS – Ground-granulated blast-furnace slag

Ground granulated blast-furnace slag – Glassy material chemically similar to Portland cement, and useful as a clinker substitute or a raw material in geopolymer cement. Made by quenching molten iron slag from a blast-furnace in water.

High-blend cement – our term for any cement where a high-level (>50%) of clinker is substituted.

Metakaolin – a calcined form of the clay mineral kaolinite.

MPa – megapascals. Used to measure the compressive strength of concrete.

Plasticiser – (also water reducer) chemicals added to concrete mix to improve workability and enable a lower water-cement ratio. Superplasticers are more powerful plasticisers.

Portland cement – the most common binding agent in concrete; a grey powder consisting of a blend of minerals, most importantly calcium silicates.

Pozzolan – any aluminosilicate material which, when mixed with water, reacts with calcium hydroxide to form cementitious compounds.

Slag – glassy by-product left over after processing raw ore to produce a metal.

Serpentine – a dark green mineral consisting of hydrated magnesium silicate. Raw material for both mineral carbonation and carbon negative cements.

Sodium silicate – the most useful alkali activator in geopolymer cements.

Supplementary cementitious materials (SCMs) – products that can be used to replace a proportion of the clinker in Portland cement, such as fly ash, ground granulated blast-furnace slag and metakaolin. SCMs react with clinker, playing a role in the strength development of concrete.

Waterglass – sodium silicate (see above).

Workability – the ease with which concrete can be poured, moulded, compacted and finished.

Appendix 2 – Materials for Strategies 1 & 2

Fly ash

Fly ash is the main waste product of coal-fired power stations – a fine grey powder that collects in exhaust flues, containing high levels of silicon and aluminium. For a long time power stations saw fly ash as an inconvenient waste to be dumped in ash dams. Today it is increasingly in demand as a supplement in Portland cement, and for other purposes such as road base and material to fill voids left by construction or mining.

How much fly ash is available for use in cement?

Worldwide production is estimated to be 700-750 million tonnes[156] per year, of which 70% is likely to be suitable for high-blend cements[157] and 50% for geopolymer cement.[158] Australia's domestic production of fly ash in 2015 was 10.7 million tonnes[159] - roughly twice the amount required for a zero carbon cement pathway. Rates of fly ash utilisation in Australia have been rising, but are still only around 20%.[160] Most of the fly ash that is sold is used as an additive in Portland cement. The remainder of sold fly ash is used in low value applications such as road base and filling. More than 8 million tonnes are dumped every year in ash dams. With the right incentives this ash could be used by a low carbon cement industry.

Is Australian fly ash suitable for geopolymer cements?

Fly ashes from different power stations vary considerably in their composition, and not all are likely to be good precursors for geopolymer cements. The most suitable type of fly ash is 'Class F', as it is high in aluminosilicates, and low in reactive calcium compounds.[161] Class F ash is produced by burning black coal, which is the fuel of power stations in NSW, Queensland, WA and, until recently, in South Australia. Victorian power stations burn brown coal, producing Class C ash which has fewer aluminosilicates, and sometimes unhelpful impurities such as sulphates.

Even for fly ash within a particular class, there is considerable variance in composition and suitability for geopolymer cements. The key desirable characteristics are fine particles, high surface area and a high content of aluminium and silicon.[162]

The fly ash from many Australian power stations is suitable for geopolymer cement. Fly Ash Australia sells graded ash from several power stations including Eraring (NSW), Bayswater (NSW), Northern (SA) and Collie (WA). Much of this ash is used by the Portland cement industry, suggesting it may be fit for geopolymers. Zeobond has used fly ash from Eraring and Bayswater in E-Crete, and Wagners has used fly ash from Gladstone and Millmerran in Queensland. Nu-Rock has tested ashes at Mount Piper, Northern, Tarong, Stanwell and Wallerawang power stations, finding them all suitable for their geopolymer concrete blocks. And at least one study has shown that ash from Collie (WA) power stations can be used to make geopolymer cement concrete of 30 MPa and above.[163] Rocla, who have been working with geopolymers for 20 years, consider that most fly ash from NSW and Queensland is suitable.

Other relevant characteristics of fly ash such as particle size need to be determined through analysis, and real confidence in any source of fly ash as a precursor for geopolymer cement comes only from experiment and use. However, the understanding of ash chemistry in geopolymerisation has reached the point where alterations can be made in the mix design to account for variations in ash properties, giving a dependable geopolymer product.[164] It is therefore highly likely that of Australia's annual production of 10 million tonnes of fly ash, at least 40% will be suitable for geopolymer cement. This enables us to meet our target of 4.1 million tonnes of fly ash to meet half of national cement demand with geopolymer cement.

Even less suitable fly ash might be usable in lower grade geopolymer cements or as part of a blend. Class C ash from the Latrobe Valley has often been dismissed as an ingredient in cement. However, at least one study has shown that it may have a role in blended geopolymer cements.[165] The study used ash from Loy Yang (both fresh and stockpiled ash) in geopolymer cement, mixed with Class F ash and slag. Mixes with 70% brown coal ash achieved 17 MPa, and mixes with 40% brown coal ash achieved 35-40 MPa (i.e. a high performance concrete). Ash from Latrobe Valley's other power stations, Yallourn and Hazelwood, are less suitable due to their low aluminium and higher sulphate content. However, even these fly ashes have potential for use in high-blend cements or low grade applications requiring less than 10 MPa.

What do we do when coal-fired power stations close?

BZE advocates a rapid transfer to 100% renewable electricity, and the closure of coal-fired power stations. Once this occurs fly ash can be sourced from existing stockpiles. Over a century of coal-burning has left Australia with more than 400 million tonnes of stockpiled ash.[166] These stockpiles, which currently present an environmental problem, should be valued as one of our most readily available mineral resources – easily accessible and needing minimal energy and resources to extract and process. Australia also has one great advantage in using fly ash in that for most power stations the coal has come from one source – usually a neighbouring mine – meaning there is consistency in the fly ash produced over time.

At the moment most cement makers prefer their fly ash to come directly from the power station, having been properly handled, stored and graded to produce an appropriate product. Stockpiled ash has been dumped with no expectation that it will be useful in future, and may have drawbacks such as moisture content, impurities and unsuitable physical and chemical composition. This means it will often need to undergo processing before it can be used in geopolymer cement. For example it will often need to be dried – a process which can be carried out using heat from the sun. Some stockpiled ash will perform better if it is mixed and/or ground into finer particles, and newer grinding technology facilitates this process.[167]

Exploitation of stockpiles is already occurring in some countries. For example in the US, Sefa Group developed its STAR® technology to optimise stockpiled ash by removing carbon and other undesirable constituents and improving particle size distribution.[168] STAR is able to blend fly ash from different sources to reduce variations in chemistry. Sefa Group now has three plants capable of processing hundreds of thousands of tonnes of stockpiled fly ash per year, producing a homogenous product that meets US specifications for fly ash in cement.

In the UK energy company RWE is exploiting ash reserves from Tilbury Power Station which closed in 2013.[169] RWE is excavating up to 500 tonnes of stockpiled fly ash per day for sale to the construction industry. Another UK company, Rocktron, developed a 'froth flotation' technology to treat fresh and stockpiled ash by removing impurities and separating according to particle size. The technology is able to tailor ash products to meet the requirements of specific cement types. Fiddler's Ferry, a coal-fired power station in the UK, implemented Rocktron's technology in a plant capable of producing 800,000 tonnes of processed ash product every year. Unfortunately due to the downturn in construction in Europe the plant is currently mothballed. However, the plant is now to be taken over by Stonehewer Limited, which plans to deliver thousands of tonnes of stockpiled fly ash per year to the cement industry.

The few efforts to explore the suitability of stockpiled ash in Australia have been positive. Nu-Rock is already using stockpiled ash from Mount Piper power station, and their analysis shows that stockpiled ash from Wallerawang (NSW) and Northern (SA) power stations (both closed) could also be used to make their product. Wagners have conducted successful trials with stockpiled ash stored at the mothballed Swanbank B power station (near Ipswich, Qld). As mentioned above, even brown coal stockpiled ash from Loy Yang in Victoria has been used successfully in geopolymer cement trials.[170]

We have assumed that 25% of stockpiles can be used to make geopolymers, once it has been processed to remove water and impurities.

Environmental benefits of using stockpiled fly ash

The existence of huge quantities of ash at every power station in Australia poses an on-going management problem. To stop it blowing into the atmosphere it needs to be kept wet, so it is constantly hosed down. Ash dams also need to be protected from flood risk. Tarong Power Station in Queensland spent $26 million building a channel to divert floodwater away from the stockpiled ash.

The seals on the ash dams are thin and fragile and liable to break up in hot weather. This occurred at Northern Power Station in January 2017 shortly before the arrival of windy weather. The wind blew fine ash dust around the town of Port Augusta causing distress and ill-health in the community. Finding a use for stockpiled ash will alleviate these environmental and public health issues.

Granulated blast-furnace slag

Slag is a collective term for by-products of metal production. The slag of most interest to manufacturers of cement is ground granulated blast-furnace slag (GGBS), a by-product of refining iron ore in a blast-furnace. GGBS is a glassy coarse material which is chemically similar to Portland cement clinker. Like fly ash it contains silicon and aluminium but its main component is calcium oxide (about 40%). The benefit of GGBS in both geopolymer and high-blend cement is that it promotes fast setting. For slag to fully develop the properties required by cement manufacturers it must be chilled rapidly as it leaves the blast-furnace.

Our pathway requires 1.1 million tonnes of slag per year by 2027. How easily can this be achieved in Australia?

Availability of granulated blast-furnace slag

Global annual production of GGBS is about 300 million tonnes.[171] There is large global demand for GGBS, mostly as a supplement in Portland cement. In Australia in 2015 we used around 1.5 million tonnes of GGBS of which only 0.5 million tonnes was produced domestically, the remainder being imported, mostly from Japan.[172] Therefore the quantity of GGBS required for our pathway is less than current Australian consumption.

However, one of our objectives is for a zero carbon cement industry that does not rely on imports, and it is unlikely that Australia will ever produce as much as 1.1 million tonnes of GGBS. An additional problem is that GGBS is a by-product of a method of iron ore refining which is itself very high emitting. For every tonne of steel produced in this way about three tonnes of CO_2e are emitted. In a future part of BZE's Zero Carbon Industry plan we will explore zero-emissions methods of producing steel. If successful such methods would inevitably make blast-furnaces obsolete, ending production of GGBS. So in the longer term we need to find alternatives to GGBS in pre-mixed geopolymer cement.

Alternatives to granulated blast-furnace slag

There are several possible alternatives to GGBS:

- **Stockpiled blast-furnace slag** – modern iron blast-furnaces have been operating for two centuries but only in the last 20 years has blast-furnace slag been routinely processed as GGBS. This means hundreds of millions of tonnes of blast-furnace slag is in landfills around the world. A survey of only three blast-furnaces estimated the presence of 100 million tonnes.[173] This represents a huge potential resource of raw material for geopolymer cement. The suitability of stockpiled slag would have to be investigated and would certainly need some processing.

- **Steel slag** – a by-product of making steel in an electric arc furnace (EAF). Another by-product of the iron and steel industry is steel slag. Steel slag is a by-product of electric arc furnaces (used for recycling steel) and basic oxygen furnace (the second stage of primary steel-making after the blast-furnace). Steel slags are a complex mixture of silicates and oxides and their composition varies greatly according to the process route and input materials.[174]

Despite their variable composition steel slags have potential for use in cement. This has been recognised in China where they are already used in cement-making and they handle the variable composition by the application of standards and quality control.[175]

Current Australian production of steel slag is relatively modest – around 35,000 tonnes of EAF slag in 2015. However, if Australia commercialises geopolymer cement production using steel slag there is an opportunity to import unused steel slag from elsewhere. Global steel slag production is 160-240 million tonnes.[176] China alone produced 90 million tonnes of steel slag in 2010 and has existing (environmentally hazardous) stockpiles of 300 million tonnes.[177]

- **Other metal slags** - Research has shown that slags from lead, copper and nickel works all have potential use in cement.[178] Zeobond and Hallett Concrete investigated the slag produced by Nyrstar's lead smelter at Port Pirie (SA), finding that it is suitable for geopolymer production.
- **Specially manufactured slag** – a replacement for GGBS could be specially manufactured for use in cement.

Alkali activator

In the manufacture of geopolymer cements, an alkaline chemical (the alkali activator) is mixed with aluminosilicate materials to trigger reactions that transform them into a binder. In contrast to the precursors, the alkali activator must be manufactured in a dedicated process. Most of the current emissions of geopolymer cements relate to the manufacture of activator, though as discussed below these emissions can be eliminated.

As our understanding of geopolymer chemistry has increased the amount of alkali activator required has reduced significantly. Early geopolymers used as much as 40% activator whereas some modern geopolymer mixes make do with as little as 5% of activator, and even for high-performance pre-mixed we need no more than 15%. The amount of activator we need to make 50% of Australia's cement with geopolymers is 393,000 tonnes (Section 9).

Manufacturing process

The most common alkali activators are sodium silicate (also known as waterglass) and sodium hydroxide (also known as caustic soda), or a combination of the two. Sodium silicate is considered the superior activator, especially when making cement from less reactive materials such as poorer quality fly ash. Sodium silicate has been manufactured for hundreds of years and is used in a wide variety of manufacturing processes including paper, soap and detergents.

There are two distinct manufacturing processes for producing sodium silicate. The first involves fusing sodium carbonate and silica in a furnace, which leads to emissions of around 540 kilograms per tonne of product.[179] The majority of these emissions come from fossil fuels burned to produce high temperatures required (>1000°C), and the release of carbon dioxide from sodium carbonate as it reacts. As these latter emissions are unavoidable, this way of producing sodium silicate should be omitted from any zero carbon cement pathway.

The second route to sodium silicate is a two-step process. The first is the electrolysis of brine (salt water) which produces caustic soda (sodium hydroxide), along with chlorine and hydrogen as by-products. This step is known as the chlor-alkali process and is carried out by several companies in Australia, including Coogee Chemicals[180] and Omega Chemicals[181]. The second step, called the 'wet process', involves reacting sodium hydroxide with silica sand (silicon dioxide) to produce sodium silicate in solution. This two-step process using cell-membranes is the most modern method of making sodium silicate, and is carried out by several Australian manufactures including Coogee Chemicals in WA and Hardman Australia in NSW.

Energy and emissions from chlor-alkali process

The emissions from producing sodium silicate result from the large amount of electrical and heat energy required, as quantified in Table A2.1. Electricity typically accounts for about half the cost of making caustic soda through the chlor-alkali process.

Table A2.1: Inputs to produce 1 tonne sodium silicate using chlor-alkali process

	Input materials	Output chemicals	Energy input
Stage 1	0.4T sodium chloride (salt) 2.5T water	0.209T caustic soda (NaOH) 0.19T chloride 0.006T hydrogen	1915 MJ (532 kWh - electrical)
Stage 2	0.314T silica sand 0.209T caustic soda 0.470T water	1T sodium silicate (Na2O•SiO2) (48% solid Na -silicate solution)	Average: 732 MJ (175MJ electrical; 557 MJ process) Lowest: 420 MJ (100MJ electrical; 320 MJ process)
Target production: 350,000 T	157,200 sodium chloride (salt) 122,390 sand 982,500 water	350,000 T sodium silicate (82,140 T caustic soda) 74,670 T chlorine 2,360 T hydrogen	752,600 GJ (208,850 MWh)

Assessments of the embodied emissions of sodium silicate solution vary widely and are the subject of some dispute.[182] A review of these assessments suggests an estimate of 0.5 CO_2 kg for sodium silicate in 48% solution seems reasonable.[183] However, a 100% renewable electricity system would make the first (chlor-alkali) stage of making sodium silicate a zero carbon process. Making our target of 393,000 tonnes alkali activator would require around 200,000 MWh of electricity. This amount of electricity demand can easily be handled in a 100% renewable energy system, since it is less than 0.1% of Australia's electricity generation and less than 10% of the electricity currently used to smelt aluminium.

The second stage in the process is reacting caustic soda and silica sand to produce sodium silicate. This reaction takes place at a temperature of 900-1000°C for crystalline silica (quartz sand). A future instalment of BZE's Zero Carbon Industry Plan will show how high heat processes such as this can be conducted without using fossil fuels. An alternative second stage is to replace sand with amorphous silica in the form of silica fume, a by-product of silicon production. The only domestic source of silica fume is Simcoa in Western Australia, which produces around 11,000 tonnes of silica fume annually. Using silica fume enables a much lower temperature reaction with sodium hydroxide.

Availability

In the short term, as a large-scale geopolymer industry develops, Australia could easily meet the requirement for caustic soda and sodium silicate through imports. Australia is already the world's largest importer of caustic soda – more than 4 million tonnes a year, mostly to process alumina.[184]

However, our goal is to produce 393,000 sodium silicate domestically using local materials and renewable energy. As shown in Table A2.1 this would require about 160,000 tonnes of common salt; 120,000 tonnes of silica sand and 1,000,000 tonnes of water per year. This is very manageable in the Australian context. It represents about 1% of national salt production and less than 3% of silica sand production, and in terms of water use around one day's residential supply in Melbourne.

Chlorine production

For every 1.1 tonnes of caustic soda produced through the chlor-alkali process, 1 tonne of chlorine and 30kg of hydrogen is also produced. This means that to reach our target we will produce about 82,000 tonnes of chlorine and 2,360 tonnes of hydrogen. The hydrogen will have a number of uses, including for energy. In fact, when produced using 100% RE it is a renewable energy, and it is likely that in a zero carbon future hydrogen will play a role providing industrial energy.

Chlorine has many commercial and industrial applications, in particular in plastics manufacture and to sanitise swimming pools. However, chlorine is also a toxin so we have to ensure that we have safe commercial uses for production of 82,000 tonnes. This represents only about 0.2% of world production of 56 million tonnes.[185] Australian companies are already making around 100,000 tonnes of chlorine every year,[186] and imported products (mostly plastics) contain several times this quantity of chlorine.

As our understanding of geopolymer chemistry improves we will be able to reduce the concentration of activator and find alternatives to sodium silicate. Researchers are currently exploring a range of alkalis and other chemicals to play the activation role. Alternative activators have already been employed with success, including a salt activator (Murray and Roberts) and hydroxycarboxylic acid (Ceratech).

Metakaolin

Much early research into geopolymers focussed on clay,[187] as clay soils often contain high levels of aluminium and silicon. The most suitable clay is kaolin which is primarily composed of kaolinite - an aluminosilicate with a chemical composition $(Al_2(Si_2O_5)(OH)_4)$ similar to some types of Class F fly ash.

Kaolinite can be converted into metakaolin through calcining – heating to a high temperature to drive off the hydroxide component. Many studies have shown that metakaolin can produce high performance geopolymer cement.[188]

Many studies have confirmed the viability of metakaolin as a precursor for geopolymers either alone or in combination with fly ash or slag.[189] Until now no one has produced metakaolin-based geopolymers commercially. However, one company is nearing large-scale production of a geopolymer cement made from a locally sourced clay. Banah, based in Coleraine (UK), has developed BanahCEM, a cement product made from 60% metakaolin, 26% activator and 14% water. BanahCEM can achieve impressive strength of up to 130 MPa, which it gains rapidly - 50% of its 28 day strength in just 9 hours. Its other advantageous properties are resistance to fire, sulphates and acid, as well as an attractive terra-cotta colour which distinguishes it from other cements.

Some accelerated ageing tests have indicated that cements made with metakaolin lack durability, and will lose strength over time.[190] However, the same tests carried out on cement mixes similar to BanahCEM did not reveal this problem, suggesting that BanahCEM can provide long-term strength similar to traditional cement.[191] This is partly because Banah's source of kaolin is an impure multi-mineral clay. Research has shown that kaolin mixed with sand and other minerals actually improves geopolymer cement. In fact the source material needs to contain a minimum of only 40% kaolin.

It was once thought that using metakaolin-based cements needed more water. However, this problem is avoided when the metakaolin is produced through flash calcination, which produces small, spherical particles. The only Australian producer of metakaolin, Calix, does not use flash calcination but it is common in Brazil and elsewhere. Further research is required to determine how chemistry and mix design affect performance of metakaolin-based geopolymers.

Energy and emissions

Metakaolin-based geopolymers have a similar potential to reduce emissions as other types of geopolymer cement. BanahCEM, for example, has been independently assessed to achieve an emissions reduction of 80% compared to Portland cement.[192]

As with other types of geopolymer cement there are no process emissions, and the majority of the emissions relate to the energy required to produce the alkali activator. There are additional emissions related to the flash calcination – a process which involves the rapid heating of the clay to 700-1000°C followed by rapid cooling. This can be done with fairly low emissions. Argeco, a French company that carries out flash calcination,[193] produces metakaolin with CO_2 emissions of 92.4 kg per tonne or product.[194]

One advantage of the calcination process is that it can be carried out with existing cement equipment such as rotary kilns.[195] However, establishing a new flash calciner costs far less than a cement kiln. The Argeco facilities cost €5 million in 2009 for a production capacity of 80,000 tonnes.[196]

Availability of kaolin

The raw material for metakaolin is kaolinite, which is the most ubiquitous mineral in Australian soils.[197] There are no precise figures on Australia's kaolin resources, but kaolinite-rich soils cover more than half the continent, including most of the western side of Australia. As shown in Figure A2.1, all major population centres in Australia except Adelaide are close to substantial sources of kaolinite. Not all deposits will be equally suitable as they will vary in terms of properties such as chemical composition and particle size. Even so Australia has more than enough kaolin to service any future metakaolin-based cement industry. Large deposits of kaolinite are currently mined in Victoria and Queensland, and a project is underway in Meckering, WA to mine 40,000 tonnes of kaolin per year.[198] Although no kaolin is currently mined in NSW, it is thought the state could contain hundreds of millions of tonnes.[199]

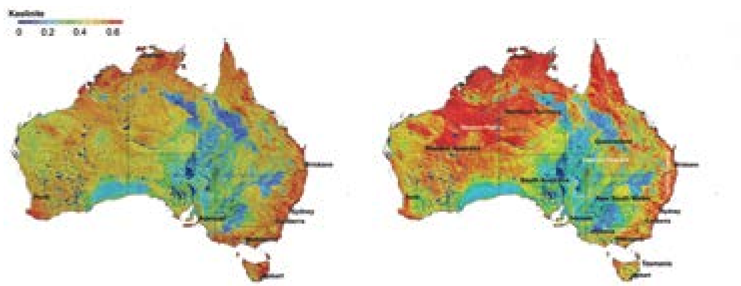
One enticing possibility is that the waste clays at the edge of mine sites could provide a source of kaolinite. Every year the mining industry extracts and dumps about 7 billion tonnes of waste material, much of which consists of clay-rich minerals.[200] This clay has already been excavated and is found at sites that have already been disturbed. For example, there are kaolinite deposits at the base of the Morwell and Yallourn coal mines in the Latrobe Valley.[201]

Kaolin clays are also very common globally, and are estimated to cover one third of the Earth's land surface. They are particularly abundant in tropical countries, which is where urbanisation (and hence cement use) is likely to be concentrated in the coming decades.

Other suitable clay types

Geopolymer cements have also been made with other clays high in aluminium and silicon such as illite and smectite (montmorillonite).[202] Large quantities of these clay minerals are commercially extracted around the globe, often as bentonites which have high smectite content. Bentonite soils are also present in Australia, and are already mined in Queensland, Victoria and Western Australia.[203] These clays tend to be more variable in composition than commercial kaolinites, so extensive research would be needed to understand their suitability in high-performance cements. One possibility is that kaolinite and bentonite could be used together. One study found good results from a geopolymer mix of kaolinite (20%) and bentonite (65%) clays with 15% sodium hydroxide.[204]

Figure A2.1: Relative abundance of kaolinite minerals in Australia[205]



Metakaolin in cement standards

The Australian Standard for cements (AS 3972–2010), does not currently recognise natural pozzolanic materials such as metakaolin, creating a barrier for its use in geopolymer cement. This is in contrast to the European standards (EN 197-1:2011) which allow incorporation of up to 55% pozzolanic material and the reduction of Portland cement clinker content to as low as 20%.

Metakaolin-based geopolymers require higher proportions of activator than other types of geopolymer cement, due to the low reactivity of the raw materials. For example, the proportion of activator solution in BanahCEM is 40%. (The precise composition of the activator is confidential, though it does contain some sodium silicate, along with other alkali materials.) Banah believe they will be able to reduce the proportion of activator over time, and are also working to develop an alternative activator.

Metakaolin cements tend to dry quickly and this causes concrete shrinkage. Concrete made with BanahCEM actually shrinks less overall than traditional concrete, but it does shrink more early in the curing process. This issue is overcome by covering the concrete in plastic as it cures. Banah can do this as they are currently making only precast products, but it would be more difficult if BanahCEM was used in pre-mixed concrete.

Metakaolin-based cements do not appear to provide as good a protection against chloride penetration. This is an issue for steel-reinforced concrete exposed to the elements – though as we should now be transitioning to more sustainable methods of concrete reinforcement, such as glass or basalt-based polymers.

Volcanic ash

Another aluminosilicate material with proven suitability for geopolymer cement is volcanic ash. Volcanic ash consists of pulverized rocks, minerals, and volcanic glass produced during volcanic eruptions. Over time volcanic ash consolidates to form dense rock called volcanic tuff.

Though less extensive than for fly ash and metakaolin, there is now a body of research demonstrating that volcanic ash-based geopolymer concretes can be designed to exhibit good physical properties and durability.[206] The most suitable types of ash are scoria and pumice. Volcanic ash tends to be less reactive than fly ash or kaolinite clay, but this can be dealt with by either heat calcination or mechanical grinding.[207]

Volcanic ash from different sites varies in chemical composition, and sometimes lacks sufficient silica or aluminium oxide. This deficiency can be addressed by adding other materials such as metakaolin, lime or fly ash.[208] Volcanic ash is abundant and well distributed throughout the world, including Australia. The Western Victorian Volcanic Plains are one of the largest volcanic plains in the world, covering roughly the triangular region between Melbourne, Ballarat and Portland. These Victorian ash deposits are currently mined for scoria, largely for use as lightweight aggregate. There are estimated resources of at least 50 million tonnes of scoria and tuff in Victoria alone.[209]

Notes on waste products in geopolymers

A successful geopolymer industry could bring a significant additional advantage: the ability to make high-value use of problematic wastes. There is potential for using several waste products to make both precursors and activators. Using these wastes in geopolymers would increase their economic value, meaning they could be diverted from landfill where they pose a long-term environmental problem.

Waste glass. Ordinary glass is more than 70% silicon and therefore has potential as a precursor material in geopolymers, used in combination with fly ash or metakaolin. This has been demonstrated at the laboratory scale where waste glass has been used to make a very high strength cement (60 MPa after 56 days of curing).[210] This study found that an additional advantage of making geopolymer cement with glass was that it could be activated using hydroxide solutions, rather than more expensive sodium silicate activators.

Research carried out in Spain points to an even higher value use for waste glass.[211] As well as containing a high proportion of silicon, glass also usually contains about 15% of soda (Na_2O), meaning its chemical composition is similar to sodium silicate alkali activator. The Spanish study demonstrated that waste glass can be used in combination with caustic soda in the formation of fly ash-based geopolymer cement. This allows waste glass to replace sodium silicate solution, providing an opportunity for a low-cost alkali activator, as well as a means of dealing with a problematic waste stream.

Sugar cane bagasse ash contains a high percentage of silica, and some aluminium, making it suitable for use in geopolymer cement. Geopolymer cements with high compressive strengths (up to 60 MPa) have been made using bagasse ash with both slag and fly ash.[212] But as with waste glass, an even higher value use for bagasse ash could be as a raw material for the alkaline activator.[213]

Red mud is a waste product of the alumina industry – alumina being the raw material for producing aluminium. For every ton of alumina extracted, about a tonne of red mud is produced. Red mud is mostly iron oxide (hence the redness) but also contains high amounts of silicon and some aluminium.

Worldwide 120 million tonnes of red mud is produced every year, and its high alkalinity means it presents a serious disposal problem. In 2010, one million cubic meters of red mud was accidentally released from an alumina plant near Hungary, killing ten people as well as all life in the nearby Marcal river.

Red mud has been used successfully to make geopolymer cements. Its high aluminium content means it works best when mixed with metakaolin[214] or fly ash[215]. Geopolymer cements have also been made in the laboratory using combinations of waste glass and red mud.[216] Red mud can also be recycled to extract caustic soda – which can then be used directly as an alkali activator or as a precursor for sodium silicate. CSIRO's Mineral Resources Flagship have patented a method of recovering caustic soda from red mud using acid dissolution and electrodialysis.[217] CSIRO's process has the beneficial side-effect of making red mud less polluting and easier to store.

Appendix 3 – Cement manufacturing in Australia

Table A3.1: Australian Cement manufacturing by producer and plant

Company	Plant Location	Annual Capacity (tpa)	Clinker Production
Boral	Berrima	1.4 million	Y
	Maldon	300,000	N
	Waurn Ponds	800,000	N
Sunstate*	Brisbane	> 1.5 million	N
Cement Australia	Gladstone	1.7 million	Y
	Pinkenba	1.2 million	N
	Railton	>1 million	Y
	Port Kembla	1.1 million	N
Adelaide Brighton	Birkenhead	1 million	Y
	Angaston	250,000	Y
	Munster	900,000	Y
Independent Cement**	Melbourne	1 million	N

* Jointly owned by Adelaide Brighton and Boral
** Part owned by Adelaide Brighton

Endnotes

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