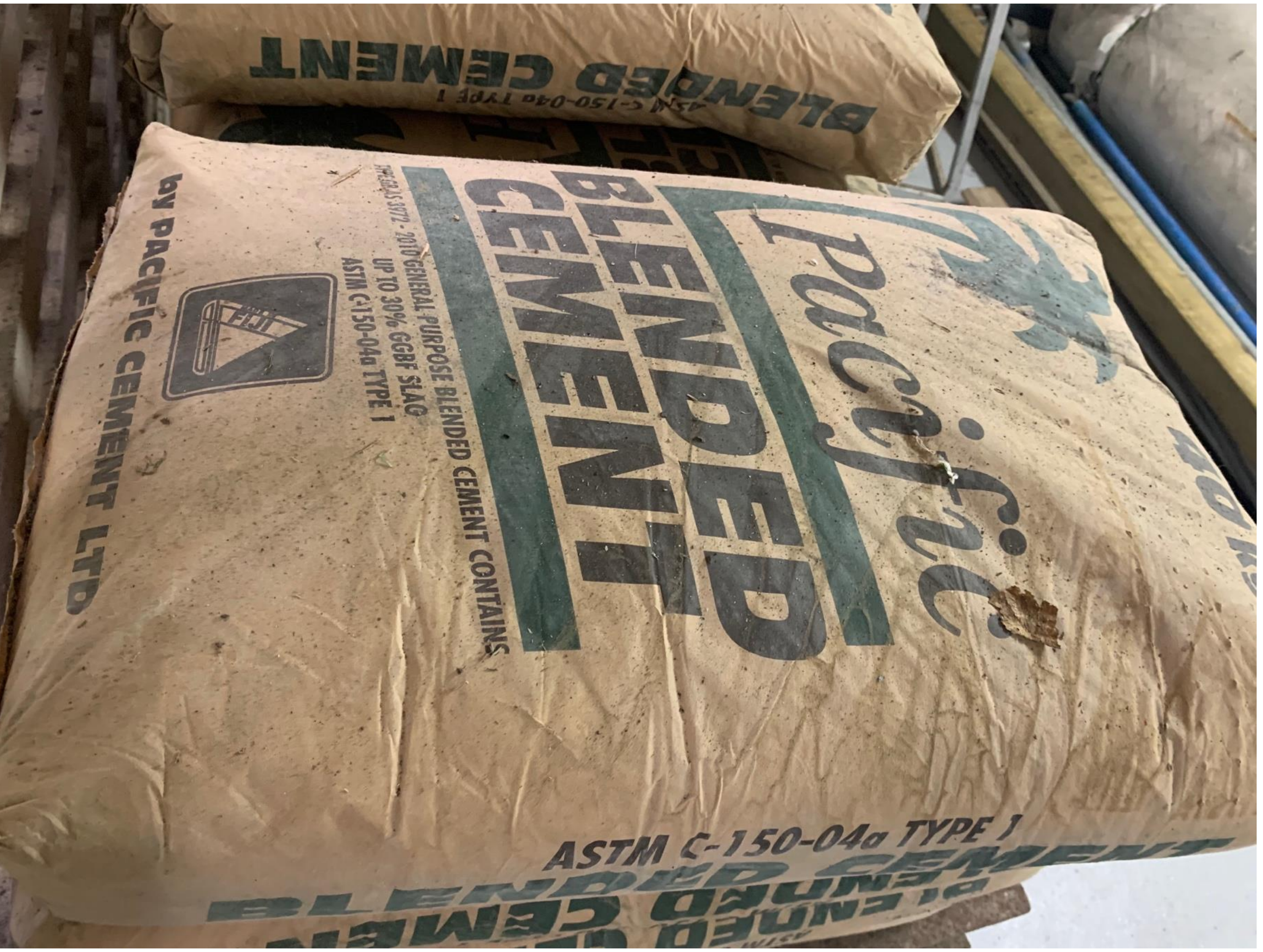

Low Carbon Concrete Options for Pacific Infrastructure

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THE UNIVERSITY OF QUEENSLAND
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Abbreviations and Acronyms

AAM	Alkali activated material
Aggregate	Construction material derived from sand, gravel, crushed stone etc.
APCP	Australia Pacific Climate Partnership
ASTM	Formerly, the American Society Standard for Testing and Materials, ASTM International defines and sets standards for materials, including procedures and for testing cements.
ASR (Alkali-silica reaction)	A swelling reaction between materials in concrete that occurs over time causing cracking and damage.
Blended cements	A mix of ordinary Portland cement (OPC) and materials such as silica fume, fly ash, limestone, and slag.
Clinker	The key component of cement production, typically containing a mix of limestone and clay.
GBFS / GGBS	Granulated Blast Furnace Slag / Ground Granulated Blast Furnace Slag
LC3	Limestone Calcined Clay Cement
Le Sland	By-product of nickel processing from New Caledonia with potential applications as both an SCM and an aggregate
OPC	Ordinary Portland Cement – cement containing 90-95% clinker
Pacific SIDS	Pacific Small Island Developing States
Participa	Australian-funded program to improve the access and quality of basic infrastructure and services in Timor-Leste
PLC	Portland Limestone Cement
PPC	Portland Pozzolana Cement
Pozzolan	A siliceous or siliceous and aluminous material that when finely divided and in the presence of moisture chemically reacts with calcium hydroxide at ordinary temperatures to form compounds having cementitious properties.
PSC	Portland Slag Cement
RWD	Roads for Development
SIIP	Solomon Islands Infrastructure Program
SCM	Supplementary Cementitious Material – a material that contributes to the hardening of concrete through hydraulic or pozzolanic activity.
Ternary Blended Cement	Cement blends with two complementary SCMs
TSSP	Transport Sector Support Program, PNG

1. Executive Summary

- Concrete is the most widely used building material in the world and is produced by combining cement with aggregates (sand and gravel) and water. Concrete is a major contributor to global climate change, with cement accounting for around 7-8 percent of all anthropogenic CO_2 emissions.
- The Pacific Islands are a net importer of cement and cement inputs. In 2021, the value of imports totaled USD 52.2 million while exports were USD 3.32 million. Cement supply in the region comes from two pathways: import of bagged or bulk cement from Asia; and supply from the five grinding plants in Fiji, PNG, and New Caledonia – all of which currently import the raw materials for making cement. Clinker, the main ingredient in cement, is currently not available locally in the Pacific, and the price of imported clinker to the region is amongst the most expensive in the world, inhibiting development, as well as climate change adaptation and the construction of resilient coastal infrastructure and housing.
- The Asian Development Bank has estimated that over US$30 billion would need to be invested in Pacific SIDS infrastructure by 2030, which will require large quantities of building materials, including cement, aggregates, and concrete. There is a need for these materials to be sustainably sourced, affordable and durable, produce lower CO_2 emissions, and protect against the increasing impacts of climate change.
- In recent decades, significant effort has been made to reduce the carbon footprint of cement and concrete while also improving the broader environmental credentials of these materials. Terms such as ‘low carbon cement’, ‘green concrete’, and ‘Blue Concrete’ are now being used to refer to cements and concretes where extra steps have been taken in their formulation, alternative materials are used to reduce emissions and energy use, and key materials are sustainably sourced.
- Pacific Small-Island Developing States only account for 0.03% of global emissions yet are taking concrete steps to reduce emissions and lead by example. In 2022, H.E. Dr. Satyendra Prasad Head of Fiji’s Delegation to COP27, launched the Blue Concrete Initiative and called on the global community to “follow the Pacific's lead and urgently reduce cement emissions as our future depends on it.”
- Two main strategies are available at the present time that are capable of delivering significant and cost-effective reductions in global CO_2 emissions from the manufacture of cement and concrete: the use of low CO_2 supplementary cementitious materials (SCMs) as a partial replacement for high carbon intensive clinker; and more efficient use of Portland cement clinker in concrete and mortars. Many of these SCMs are by-products of industry and agriculture, and few are available in sufficient quantities in the Pacific region. Each of these materials is different in terms of the CO_2 emissions reductions possible, cost, performance, and availability – which varies significantly depending on geographic location.
- The addition of SCMs to produce lower emissions cements and concretes typically *reduces the cost* of cement production. This is because of the high energy costs of producing clinker and the fact that many SCMs are by-products of other industries. There is therefore significant potential that any investment by aid programs to assist the Pacific to produce low carbon cement and concrete will lead to significant savings in infrastructure costs, as well as bring other benefits such as local employment, strengthened supply chains and enhanced mineral security.
- Among the stakeholders consulted as part of this study, all were either open to, or strongly in support of using low carbon concrete materials in roads and other infrastructure in countries they had worked but with caveats, with cost being the primary concern. Furthermore, while all were aware of low carbon cements and concretes, few appeared to have a detailed understanding of the full range of options and types of cement being used in different parts of the world or their performance and the typical lower production cost of the low carbon options.

- This scoping study aims to provide information to assist Australian aid programs and their infrastructure partners in the Pacific Islands region in decision making about the use of concrete; outlines potential options to reduce emissions and increase the sustainability of key ingredients; and describes further actions necessary to support the availability of responsible and sustainable concrete in the region.
- The study assesses the main low carbon cement options available globally and their feasibility to be used in Pacific infrastructure. Each of the main cement options are assessed based on their cost, availability in the Pacific, emissions reduction potential, and overall performance (e.g., strength, durability) and suitability for different types of infrastructure.

Recommendations:

- **Summary of low carbon cement options** (see Table 1 for comparison of options):

  Immediate options: The study finds that there are low carbon cement options that can be introduced almost immediately (though with some limitations) including:

  - Ready to go: Natural pozzolans like volcanic ash are already available to be used as a SCM in Fiji and could potentially supply a much wider market in Fiji and the Pacific. Volcanic ash is already used by Pacific Cement to produce a 20-25% blended cement, while Tengy uses around 5% at the moment, which could easily be increased with both clinker and emissions reductions benefits. Direct engagement with both Pacific and Tengy to discuss supply capacity is recommended. In the meantime, further investigation is need to determine full emissions reduction potential, performance parameters and suitability for various uses, and other considerations in the Pacific context.
  - Possible quick adoption: Fly ash and GBFS blends are proven technologies, widely produced, regulated, and sold globally, and could be imported into the Pacific SIDS market relatively quickly as a short-term option. Indeed, two of the region's companies, PNG's Taiheiyo and New Caledonia's Tokuyama, already produce fly ash and GBFS blends at their other operations in Japan and elsewhere and clearly have the expertise and access to key material inputs to supply Pacific SIDS, providing economic drivers exist.
  - Possible quick adoption: Limestone, which is locally abundant in at least two of the cement producing countries, Fiji and PNG, can be added as a filler to reduce the embodied emissions of cement, though the extent of replacement is limited (10-15%). Indeed, one of Fiji's cement companies is currently investigating its potential. Further analysis of the range of CO_2 emissions reduction possible is necessary.
  - Possible quick adoption: Limestone Calcined Clay (LC3) could be imported from producing countries like India. LC3 has excellent performance parameters and emissions reduction potential. Introducing imported LC3 to the Pacific market would help pave the way to production based on local home-grown resources.

  Best overall option: LC3 appears the most promising low carbon cement option for Pacific SIDS in the medium term and, indeed, many other countries. Immediate actions should be taken, such as resource assessment to commence necessary implementation steps for producing LC3 in the region, particularly in Fiji where both cement companies have expressed interest in producing it. Of all the low carbon cement options currently proven or under development LC3 has:

  - the greatest potential to reduce emissions at large scale (by up to 40% relative to OPC)
  - excellent performance parameters relative to OPC including strength and durability and as a General Purpose Cement is suitable for all types of infrastructure
  - produces concrete with qualities that make it particularly suitable for marine and coastal environments, including having low porosity and reduced chloride ingress (this makes it a good

choice for building coastal infrastructure in the Pacific given their increasing exposure to climate change related extreme weather events such as cyclones, flooding and coastal wave inundation)
    - the potential to be produced locally in the region – LC3 can provide resilience in regional cement supply chains, which is particularly important when countries and regions are recovering from natural disasters and imported construction materials are in short supply
    - lower transport related emissions and costs when produced locally (e.g., associated with clinker imports) and creates local quarry and cement manufacturing jobs

  The development of LC3 could occur via support for the Fiji Government's Blue Concrete Initiative, including detailed evaluation of mineral resource reserves, technology transfer, capacity building for government, local industry and universities, and development of new policies and standards.

- **Raise awareness:** There is limited understanding and practical application of sustainable, low carbon cement and concrete options across the Pacific as well as the typical lower production cost of these options. Engage, raise awareness, and seek feedback with national governments and the region's cement producers, major cement importers, and key infrastructure developers and contractors. There is a need to support and strengthen supply chains and market development for these options in the Pacific.

- **Capacity building:** Develop a simple capacity building training program for national governments and the private sector working in the construction and infrastructure sectors to ensure concrete is used as efficiently as possible. Research suggests that up to 30% efficiency can be lost by improper use, design, and placement of concrete.

- **Pilots and trials:** Deeper market analysis and pilot studies can be used to trial options for making low carbon cements and concrete in the Pacific SIDS market. There are opportunities for partnerships between donors, national governments and the private sector to pilot and trial options. Alternative SCMs and aggregates can be explored including undertaking detailed carbon emissions, and environmental, market and supply chain analyses. Country-level initiatives like Fiji's Blue Concrete Initiative should be encouraged and supported.

- **Incentives:** Infrastructure programs or governments could specify the use of low carbon concrete in infrastructure tenders or require options to be proposed that meet this objective. Prior to this, however, a period of capacity building would be required so that government, infrastructure program staff, and infrastructure contractors fully understand the advantages and disadvantages of using different types of low carbon cements and concretes and are able to choose the best option for them.

- **Sustainable aggregates:** Explore alternative sources of sustainable aggregate that are necessary to produce concrete, such as Le Sland from New Caledonia, dolomite from Nauru, and ore-sands from mines in countries such as Fiji and PNG. This could entail commissioning studies to understand the economic, environmental and supply chain aspects of using these alternatives in different parts of the Pacific.

- **Regional guidelines:** Support the development of a region-wide set of sourcing guidelines on aggregate, cement and concrete building on the PRIF-funded Responsible Sourcing of Aggregates study that considers the full range of circumstances and geological conditions of Pacific SIDS.

- **Recycling:** Develop a set of guidelines that can help Pacific SIDS effectively and cheaply recycle concrete from demolished roads, buildings etc. for use as aggregates.

- **Regional partnerships:** Explore partnerships with key actors such as the Pacific Community, The University of Queensland's Sustainable Minerals Institute, Fiji National University, and the ACP-EU Development Minerals Programme, implemented by UNDP, who have been working together on sustainable construction materials in the Pacific since 2015; PRIF; the Pacific Resilience Partnership, Resilient Infrastructure Working Group; the Coalition for Disaster Resilient Infrastructure and Accelerating Resilient Infrastructure in SIDS, among others.

Table 1: Summary of low carbon cement options for Pacific SIDS

Options	Suitability for Pacific SIDS	Explanation
Limestone Calcined Clay Cement (LC3)	Local production of LC3 the best overall option for Pacific SIDS; can be phased to first produce based on imported clinker with later full-scale local production.	• **Emissions reduction:** Significant clinker reduction potential (up to 50%) and emissions reduction of up to 40%. • **Availability:** Cheap and abundant material inputs of kaolin clay and limestone in the Pacific, with proven reserves in major cement producer, Fiji. • Pacific-based production (e.g., in Fiji) would increase resiliency of cement supply chains in the region, reducing reliance on expensive imports and ensuring key materials are available for climate change adaptation and disaster response. • Both cement producers in Fiji willing to adopt with support. • **Production Cost:** is comparable to or less than Ordinary Portland Cement (OPC). • **Performance:** Excellent performance across all aspects, including durability, strength and, particularly important for coastal Pacific countries, reduced salt ingress. • Growing adoption world-wide with standards across many countries, including in India, the United States and Europe. • **Overall:** Best overall option. Phased development potential: calcined clay and limestone can be produced locally in countries such as Fiji and blended with imported clinker; local clinker production from limestone resources could be later undertaken to produce LC3 from 100% local resources. • Product configuration possible as LC2 (limestone and calcined clay) which can be sold independently and blended with OPC by customers.
Volcanic Ash Blended Cement (PPC)	Ready to go, good option with moderate emissions reduction potential. Available now in Fiji.	• **Emissions reduction:** Potential to reduce clinker by up to 30%, as well as similar reductions in emissions and costs. • **Availability:** Natural volcanic pozzolans are abundant in cement producing countries such as Fiji and PNG. • **Production Cost:** is comparable to or less than Ordinary Portland Cement (OPC). • **Performance:** Data on the level of potential CO_2 reduction and other performance characteristics are variable and should be investigated in the Pacific context. • **Overall:** Pacific Cement in Fiji now uses local volcanic ash as an SCM so is a feasible option for Pacific cement producers.
Fly Ash Blended Cement (Portland Pozzolana Cement; PPC)	Good short-term option but with drawbacks	• **Emissions reduction:** Well-established supplementary cementitious material (SCM) in many countries with emissions reductions of between 25-35%. • Currently considered a carbon-neutral by-product, whose emissions are already accounted for in coal combustion. • Carbon emissions associated with shipping will mitigate the carbon reduction potential of these cements. • Potentially subject to environmental loads in the future, undermining value as a low carbon cement. • **Availability:** Fly ash is a by-product of thermal coal power plants which are not present in the Pacific. Fly-ash and fly-ash blended cement must therefore be imported. • Fly-ash blends available in countries such as Japan that already supply Pacific SIDS so it is possible that shipments could occur in a relatively short period of time. • Drawbacks include insufficient global supply to meet demand and expected decline in future production as coal power phased out raising costs and creating supply insecurity.

Options	Suitability for Pacific SIDS	Explanation
		• **Production Cost:** is comparable to or less than Ordinary Portland Cement (OPC) depending on availability. • **Performance:** Reduced early strength but improves over the long term and other cement properties are either the same or better than OPC. • **Overall:** Nevertheless, should be kept in the basket of short-term options for use by Pacific SIDS
Granulated Blast Furnace Slag Blended Cement (GBFS)	Good performance but unlikely to form a key part of a long-term low carbon concrete strategy in Pacific SIDS	• **Emissions reduction:** GBFS has the highest clinker substitution potential of all SCMs (up to 70%) and a potential CO_2 reduction of 35-65%. • **Availability:** GBFS is a by-product of steel making which is not undertaken in the Pacific. Importing requires long shipping distances creating insecurity of supply. • Already used by the parent company of PNG's Taiheiyo Cement and so could feasibly be supplied to the Pacific market. • Globally there is insufficient supply to meet demand, which could make it increasingly costly. • **Production Cost:** is comparable to Ordinary Portland Cement (OPC) depending on availability. • **Performance:** Apart from reduced early strength, GBFS cements have good performance, are already recognised by international standards. • **Overall:** Potential short-term option for lowering the CO_2 emissions of cement and concrete in the Pacific SIDS region, though at least one pacific cement supplier has shifted from GBFS to local volcanic pozzolan due to import costs.
Portland Limestone Blended Cement (PLC)	Ready to go, good short-term option but with limitations	• **Emissions reduction:** Modest clinker substitution potential (10-15%) leading to modest emissions reductions • **Availability:** Limestone is abundant in all countries of the Pacific, including cement producers (e.g., Fiji, PNG) • **Production Cost:** is comparable to or less than Ordinary Portland Cement (OPC). • **Performance:** Already recognised under official US cement standards which allow up to 15% limestone content. • Limestone filler does have poorer performance characteristics in some areas when more than 10% of clinker is substituted. • **Overall:** Remains a cheap and effective short-term option to reduce emissions by a modest amount, reduce costs and, up to a certain level of substitution, maintain acceptable strength and other properties relative to OPC.
Silica Fume Blended Cement	Silica fume cements unlikely to be adopted on any significant scale	• **Emissions reduction:** Size of the clinker substitution and CO_2 emissions reductions that are possible is also small, with a maximum 10% reduction. • **Availability:** Very limited availability globally and shipping distances would be long, increasing cost and transport related emissions. • **Production Cost:** is higher than Ordinary Portland Cement (OPC). • **Performance:** Value is as a niche cement where chemical resistance (e.g., to concrete damaging alkali-silica reaction; ASR) and increased strength are priorities. • **Overall:** On a cost-basis alone, it is very unlikely to find a large market in the region given cost remains the most important priority for infrastructure developers and contractors in most countries.

1. Introduction

Concrete is the most widely used building material in the world and is produced through the combination of mineral aggregates (sand and gravel) with water and cement. Concrete is a major contributor to global climate change, with cement accounting for around 7-8 percent of all anthropogenic CO_2 emissions. At the same time, however, without concrete, much of the built environment would not be possible, including houses, roads, railways, ports and bridges.[1] Concrete is also a crucial material for climate and disaster resilience.[2] Clinker, one of the main raw ingredients of cement, is currently not available locally in the Pacific, with imported clinker to the region amongst the most expensive in the world, inhibiting development, as well as climate change adaptation and the construction of resilient coastal infrastructure and housing.

The availability of concrete is a key aspect of mineral security, which is described to exist when all people have sufficient and affordable access to the minerals necessary for human development, including for shelter, mobility, communication, energy and sustenance.[3] Population growth, urbanization, and the need to achieve a more sustainable and equitable world, including protecting communities against the impacts of climate change, will drive greater demand for concrete-based materials in the coming years and decades, including in Pacific Island Developing States (Pacific SIDS). However, unless action is taken to reduce the carbon emissions from cement and concrete production, this demand will lead to an unacceptable increase in CO_2 emissions. Furthermore, the extraction, transport, and use aggregates, which accounts for up to 75% of the total volume of concrete[4], can also generate CO_2 emissions and environmental and social issues, particularly when they are sourced from rivers, beaches, and coral reefs, as is common in the Pacific Islands.

In recent decades, significant effort has been made by governments, international institutions, and industry to reduce the carbon footprint of cement and concrete while also improving the broader environmental credentials of these materials. Terms such as ‘low carbon cement’, ‘green concrete’, and ‘Blue Concrete’ are now being used to refer to cements and concretes where extra steps have been taken in their formulation, alternative materials are used to reduce emissions and energy use, and key materials are sustainably sourced. Global initiatives such as UNEP’s Sustainable Buildings and Climate Initiative (UNEP-SBCI) and the Global Cement and Concrete Association’s (GCCA) 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete are reflective of the global community’s desire to reduce emissions and improve the sustainability.

It is within this context that the Australia Pacific Climate Partnership (APCP) has engaged The University of Queensland’s Sustainable Minerals Institute to undertake this scoping study of low carbon concrete options for Pacific infrastructure. The scoping study aims to provide information to assist Australia aid programs and their infrastructure partners in the Pacific Islands region in decision making about the use of concrete; potential options to increase sustainability and reduce emissions, and; further actions necessary to support the availability of responsible and sustainable concrete in the region. This scoping study, which spans the broader Pacific region, complements a second study focused on the ‘Climate implications and options for the construction of reinforced concrete roads in Vanuatu.’

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[1] United Nations Environment Programme (2018). ‘Eco-efficient Cements: Potential Economically Viable Solutions for a Low-CO2 Cement-based Materials Industry’. UNEP, Paris. https://wedocs.unep.org/20.500.11822/25281 Accessed 06/07/2023.

[2] Rogers, P., Maher, R., Lee, G., Naidelage, C., Flomenhoft, G., Junior, P., Franks, D.M., 2023. Building disaster and climate resilience through Development Minerals. United Nations Development Programme (UNDP), Pacific Community (SPC) and The University of Queensland (UQ), Suva, Fiji. https://doi.org/10.14264/9052c85

[3] Franks, D.M., Keenan, J. & Hailu, D. Mineral security essential to achieving the Sustainable Development Goals. Nat Sustain 6, 21–27 (2023). https://doi.org/10.1038/s41893-022-00967-9

[4] Portland Cement Association. https://www.cement.org/cement-concrete/concrete-materials/aggregates#:~:text=Aggregates%2C%20which%20account%20for%2060,categories%2D%2Dfine%20and%20coarse. Accessed 06/07/2023.

The study is organised into 6 major sections. Section 2 provides an overview of the methodology used in the study. Section 3 describes some of the main low carbon concrete technologies and global efforts to reduce emissions and improve the sustainability performance of materials. Section 4 describes the cement and concrete industries in the Pacific Islands region, covering current and future demand for materials, the focus on new infrastructure development, and discussion of cement, concrete and aggregate supply chains. This is followed in Section 5 by an assessment of low carbon cement and concrete options that may be available to Pacific Small Island Developing States (Pacific SIDS), looking at both the cement and aggregates aspects of concrete. Bearing in mind existing data limitations, the section aims to summarise low carbon concrete options in terms of their design mix, carbon emissions profile, durability for construction purposes, costs, environmental sustainability, social impacts of aggregates production, regional availability and supply chain issues, and climate and disaster resilience. Chapter 6 provides, recommendations on further actions necessary to support the availability of responsible and sustainable concrete in the Pacific.

2. Methodology

This scoping study of low carbon concrete options for Pacific infrastructure included remote (via Zoom) and in person consultations with 47 stakeholders in 21 organisations operating in various countries. These included Australian funded infrastructure development programs in selected countries in the region including representatives of the Roads for Development (R4D) Program in Vanuatu, Solomon Islands Infrastructure Program (SIIP), the Transport Sector Support Program in Papua New Guinea (PNG), and the Participa infrastructure program in Timor-Leste.

Fieldwork was undertaken in Vanuatu, as well as in Fiji during the course the study. In Vanuatu, consultations were held with the World Bank, Asian Development Bank, Japanese Agency for International Cooperation, as well as key government agencies, including the Departments of: Geology and Mines, Climate Change, Meteorology and Geohazards, Energy and Environment. Consultations were also held with the Cement and Concrete Association of Australia, several infrastructure contractors operating in the region both remotely and during fieldwork in Fiji, leading experts on cement in Australia and India, representatives of both cement producers in Fiji and representatives of the nickel processing industry in New Caledonia. Finally, a detailed literature review and other desktop research such as use of online trade databases was undertaken.

Unlike the Vanuatu study which focused primarily on roads, this study encompassed infrastructure more broadly, such as roads, bridges, and buildings. The scope of the study encompassed all countries that are recipients of Australian infrastructure development aid, including the 14 PRIF member countries, and Timor-Leste.

3. Global trends in low carbon cement and concrete production

3.1 Cement and concrete basics

Concrete is made by combining cement (a binder) with aggregates such as sand and gravel. How these two components are sourced, made, transported, and used determines the level of carbon emissions produced and their overall impact on the natural environment. The traditional and most common type of cement produced globally is Ordinary Portland Cement (OPC). OPC contains around 90-95% clinker, which is made by grinding and calcining (heating) limestone and clay, two materials that are relatively cheap and found in most parts of the world.[5] After grinding and heating, the clinker is ground to a fine powder before being

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[5] United Nations Environment Programme (2018). 'Eco-efficient Cements: Potential Economically Viable Solutions for a Low-CO_2 Cement-based Materials Industry'. UNEP, Paris. https://wedocs.unep.org/20.500.11822/25281 Accessed 06/07/2023

mixed with a small amount of gypsum (~3-5%) to form the OPC. The combustion of fossil fuels to produce the energy for making clinker accounts for around 40% of the CO_2 emissions released – the remainder comes from the decomposition of limestone ($CaCO_3$ or $CaO.CO_2$) during calcination. On average about **842kg CO_2 per ton of clinker are released when making OPC**.[6]

Meanwhile, the use of aggregates to make concrete may also have a significant carbon footprint and broader environmental impacts. The blasting of hard rock in quarries, crushing of gravel extracted from rivers, mining of sand from beaches and reefs, and transporting aggregates can all produce carbon emissions and negatively impact the environment. Sourcing more sustainably might entail developing hard rock quarries as an alternative to beach or river extraction, recycling building demolition debris to produce aggregate, using by-products from metal mining (i.e., ore sand), and following responsible river gravel extraction guidelines, such as those recently developed by Fiji's Mineral Resources Department.[7]

3.2 Industry developments

It is estimated that global cement production will increase by 12-23% by 2050 from 2017 levels[8], driven by population growth, urbanization, and the need to build new infrastructure, particularly in developing countries.[9] If no action is taken by the sector, global CO_2 emissions from the cement and concrete sector will result in an increase of 3.8Gt by 2050, undermining global efforts to reach 'net zero' by the same year.

It is for these reasons that over the past few decades, the international community and industry have made a concerted effort to reduce the climate and environmental impacts of this essential industry. Important steps have been taken as a result of the Cement Sustainability Initiative, a joint program of the International Energy Agency and the World Business Council launched in 1999, and the United Nations Environment Programme's Climate and Sustainability Initiative (UNEP-SBCI), established in 2015. More recently, industry led initiatives such as the Global Cement and Concrete Association's (GCCA) have outlined the broad range of technologies and approaches, ranging from carbon capture and storage to savings in clinker production that will be required to achieve the goal of net zero by 2050.[10]

3.3 Strategies for reducing emissions in the cement sector

The 2009 IEA / WBCSD Cement Technology Roadmap laid out four strategies to reduce carbon emissions in the cement sector.[11] They included improving energy efficiency, switching to less carbon intensive fuels, implementing new technologies such as carbon capture and storage (CCS) and carbon capture and use (CCU), and reducing the clinker to cement ratio by use of supplementary cementitious materials (SCM). However, in a comprehensive review of existing and new technologies and approaches to reducing emissions, the authors of a 2017 UNEP report concluded that there are essentially only two main strategies at the present time capable of delivering significant and cost-effective reductions in global CO_2 emissions from the manufacture of cement and concrete. These include: 1) the increased use of low CO_2 SCMs as a partial

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[6] United Nations Environment Programme (2018). 'Eco-efficient Cements: Potential Economically Viable Solutions for a Low-CO_2 Cement-based Materials Industry'. UNEP, Paris. https://wedocs.unep.org/20.500.11822/25281 Accessed 06/07/2023

[7] Approximately 90% of all cement is currently produced by non-OECD countries (which includes the BRICS countries) and this is unlikely to change in the near future.

[8] International Energy Agency and World Business Council for Sustainable Development (2018). 'Low-Carbon Transition in the Cement Industry: Technology Roadmap'. Available https://iea.blob.core.windows.net/assets/cbaa3da1-fd61-4c2a-8719-31538f59b54f/TechnologyRoadmapLowCarbonTransitionintheCementIndustry.pdf Accessed 11/07/2023.

[9] United Nations Environment Programme (2018). 'Eco-efficient Cements: Potential Economically Viable Solutions for a Low-CO_2 Cement-based Materials Industry'. UNEP, Paris. https://wedocs.unep.org/20.500.11822/25281 Accessed 06/07/2023

[10] GCCA (2021) 'The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete' Available https://gccassociation.org/concretefuture/ Accessed 06/07/2023

[11] IEA / WBCSD (2009). Cement Technology Roadmap 2009: Carbon Emissions Reductions up to 2050.

replacement for high carbon intensive clinker; and 2) more efficient use of Portland cement clinker in concrete and mortars.[12] While still useful, CCS/U were assessed as being less effective and more costly than materials-based solutions, particularly the use of SCMs.

It is worth noting here that among the various stakeholders consulted as part of this study, including the various infrastructure programs like R4D in Vanuatu, all stakeholders were either open to, or strongly in support of using low carbon concrete materials in roads and other infrastructure in countries they had worked but with caveats, with cost being the primary concern. Furthermore, while all were aware of low carbon cements and concretes, few appeared to have a detailed understanding of the full range of options and types of cement being used in different parts of the world or their performance.

The rest of this section outlines the various cement types developed in recent years that are already proven and adopted globally, as well as emerging technologies, which might be feasible options for reducing emissions from cement and concrete in the Pacific region. Most of the options available are variations in blends of Portland cement.

Portland cements with supplementary cementitious materials

SCMs are mineral additives that are used as a partial substitute for carbon intensive and expensive clinker, as well as to enhance the properties of concrete. Several types of SCMs are currently used in various cement blends globally. Many of these are by-products of industry and agriculture. Common materials include fly ash from coal fired power plants, granulated blast furnace slag (GBFS) from pig iron production, almost inert limestone filler, and less commonly, silica fume. Currently, more than 80% of SCM used in cement are either limestone[13], fly ash or slag.[14] Each of these materials is different in terms of the CO_2 emissions reductions possible, cost, performance, and availability – which varies significantly depending on geographic location. Portland cements containing either naturally occurring pozzolans (e.g., volcanic ash / rock, clay) or artificial pozzolans (e.g., like fly ash and silica fume) are called Portland Pozzolana Cement (PPC).[15] Some cement blends contain a combination of two or more different SCMs (termed ternary cements; e.g., fly ash and slag together) to overcome performance limitations.[16]

It is important to note that the addition of SCMs to produce lower emissions cements and concretes typically ***reduces the cost*** of cement production. This is because of the high energy costs of producing clinker and the fact that many SCMs are by-products of other industries.

The IEA / WBCSD Roadmap suggests that dwindling supplies of fly ash and GBFS mean that there is limited potential for further clinker substitution, and hence CO_2 reductions, from these materials.[17] In the case of limestone, it has been suggested that substitution of clinker by more than 10% using existing grinding technology tends to increase porosity and reduce performance and so despite being in abundant supply, it has only limited potential to reduce emissions at a global level.[18] Each of the main SCMs currently used in

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[12] United Nations Environment Programme (2018). 'Eco-efficient Cements: Potential Economically Viable Solutions for a Low-CO_2 Cement-based Materials Industry'. UNEP, Paris. https://wedocs.unep.org/20.500.11822/25281 Accessed 06/07/2023

[13] Limestone is technically not an SCM but is often included in this category.

[14] Scrivener et al. (2018). 'Calcined clay limestone cements (LC3)'. *Cement and Concrete Research*. Vol 114, 49-56, https://doi.org/10.1016/j.cemconres.2017.08.017

[15] Husain, M. (2021). 'Sustainable natural pozzolana concrete – A comparative study on its environmental performance against concretes with other industrial by-product'. *Construction and Building Materials*.

[16] Gupta and Chaudhary (2022). 'State of the art review on supplementary cementitious materials in India – II: Characteristics of SCMs, effect on concrete and environmental impact. *Journal of Cleaner Production* 357

[17] International Energy Agency and World Business Council for Sustainable Development (2018). 'Low-Carbon Transition in the Cement Industry: Technology Roadmap'. Available https://iea.blob.core.windows.net/assets/cbaa3da1-fd61-4c2a-8719-31538f59b54f/TechnologyRoadmapLowCarbonTransitionintheCementIndustry.pdf Accessed 11/07/2023.

[18] Scrivener et al. (2018). 'Calcined clay limestone cements (LC3)'. *Cement and Concrete Research*. Vol 114, 49-56, https://doi.org/10.1016/j.cemconres.2017.08.017

cement are summarised in Table 2, including their potential emission reductions compared with OPC as well as other performance parameters. These and other SCMs are also discussed in the text which follows. It should be noted that the exact recommended clinker replacement may vary according to specific country standards but here we have stated those commonly reported in the literature.

Fly ash

Fly ash is a waste product from coal combustion in power plants. It is estimated there are around 900 Mt of fly ash produced each year, though varied quality means only about a third of this is suitable for cement production.[19] It is possible to replace clinker by up to around 25-35%[20] and, with all things being equal, achieve the same levels of CO_2 reduction relative to OPC. Following broader trends in the reduction in the energy coming from coal fired power plants, availability of fly ash varies significantly regionally, and the overall global trend is declining and will continue to do so. Supplies are still abundant in many countries in Asia, and even make their way (from India) to Fiji for inclusion in some prefabricated concrete products, though not as SCMs in the cement making process.

The performance of fly ash in cements is very good, with reduced emissions, good early and late strength, and reduced chloride ingress with one benefit being that it has better resilience to the effects of seawater compared to OPC. The main drawbacks to using fly ash in countries where there no domestic supplies is the declining availability, cost of shipping and associated CO_2 emissions.

It is important to note that with the exception of Silica Fume SCMs generally have reduced resistance to carbonation, which can lead to steel corrosion within concrete.[21] One way to address this risk is to prioritise the use of Calcium rich particles or very fine particle sized SCMs.[22]

Granulated blast furnace slags

Granulated blast furnace slag (GBFS), or ground granulated blast furnace slag (GGBS), can replace up to 70% of clinker in cement with corresponding excellent emissions reductions. Unlike fly ash, GBFS is not a true waste product, since it requires the slag to be granulated through an additional process, requiring energy use and associated CO_2 emissions. Supply is also limited to iron-making factories, meaning its use as an SCM in cement often entails additional handling and shipping. Although it has reduced early strength compared to OPC, other performance parameters are good, including permeability and chloride ingress.[23]

The major disadvantage of GBFS as an SCM is its availability. Global supply is around 330 Mt per year but blast furnace production of iron and steel is declining.[24] This not due to declining steel demand but rather a consequence of more efficient steel making processes and the increased availability of recycled scrap steel. The declining supply may explain why in 1980, up to 17% of cement production used GBFS but is now not expected to exceed 8% of cement production over the long term. In addition, the additional processing required to make GBFS mean it often costs more than it costs a cement producer to make Portland clinker.

Silica fume

Silica fume is a fine pozzolanic material that is a by-product of the silicon metal / alloy industry. Its main advantages in cement are that provides resistance to chemically aggressive environments, inhibits alkali-silica

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[19] United Nations Environment Programme (2018). 'Eco-efficient Cements: Potential Economically Viable Solutions for a Low-CO_2 Cement-based Materials Industry'. UNEP, Paris. https://wedocs.unep.org/20.500.11822/25281 Accessed 06/07/2023

[20] Team IIT Delhi Detailed Technical Report on Limestone Calcined Clay Cement (LC3)

[21] Mackechnie, J. (2021). 'Removing the barriers to the use of significant levels of SCMs in concrete production in New Zealand'. BRANZ. Available https://www.branz.co.nz/pubs/research-reports/er-66/ Accessed 20/07/2023

[22] Gupta and Chaudhary (2022). 'State of the art review on supplementary cementitious materials in India – II: Characteristics of SCMs, effect on concrete and environmental impact. *Journal of Cleaner Production* 357

[23] Team IIT Delhi Detailed Technical Report on Limestone Calcined Clay Cement (LC3)

[24] United Nations Environment Programme (2018). 'Eco-efficient Cements: Potential Economically Viable Solutions for a Low-CO_2 Cement-based Materials Industry'. UNEP, Paris. https://wedocs.unep.org/20.500.11822/25281 Accessed 06/07/2023

reactions that can severely damage concrete structures, and early increased strength which makes it suitable for precast concrete products.[25] Silica fume is of most valuable in niche applications where high strength and durability are the primary concerns.[26]

These benefits are offset, however, by various disadvantages. From a low carbon concrete perspective, clinker replacement can only reach 4-10%, meaning it will not form any significant part of a strategy to reduce CO_2 emissions in the cement and concrete industries. Availability is also very limited, is difficult to handle and consumes significantly more water than other additives to concrete.

Calcined clay

Clays are a natural pozzolan that have long been used as a substitute for clinker. Kaolin clays in particular are found almost everywhere with vast reserves available globally. In addition to their natural occurrence, these clays are often found as stockpiled waste where superior grade clays are used for higher value products such as ceramics and paper or as residual weathering clays in overburden of volcanic aggregate quarries.[27] These clays can be calcined and used for their pozzolanic properties as an SCM, making clinker reductions of 25-30% and emissions reduction of 10-20% possible. Nevertheless, the calcination of the clay effects the economics of substitution when compared with other materials. When combined with other SCMs, like limestone, calcined clay offers much greater emissions reduction potential and economic efficiency (see further details on LC3 below).

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[25] Global Cement and Concrete Association. https://gccassociation.org/cement-and-concrete-innovation/clinker-substitutes/silica-fume/ Accessed 16/07/2023

[26] Mackechnie, J. (2021). 'Removing the barriers to the use of significant levels of SCMs in concrete production in New Zealand'. BRANZ. Available https://www.branz.co.nz/pubs/research-reports/er-66/ Accessed 20/07/2023

[27] LC3 Technology and Resource Centre, nd. 'Limestone Calcined Clay Cement: A Viable and Sustainable Alternative to Existing Cement Varieties

Table 2: Performance of common SCMs used in cement compared to OPC

Performance parameter	Fly ash	GBFS	Silica fume	Calcined clay (kaolin)	Limestone
Clinker reduction	25-35%	40-70%[28]	4-10%	10-35%[29]	10-15%[30]
Potential CO_2 emissions reduction[31]	25-35%	35-65%	~4-10%	~15-20%[32]	~10%[33]
Factors affecting CO_2 reductions	Potentially long shipping distances, quality of fly ash	Requires additional processing and hence energy use. Potentially long shipping distances	Potentially long shipping distances	Clay has to be calcined but at much lower temperatures and emissions compared to clinker so lower emissions.	Limestone quality
Production cost	Comparable or lower (subject to availability)	Comparable (subject to availability)	Higher	Comparable or lower	Comparable or lower
Availability	Limited to areas with coal fired power plants, which do not exist in Pacific SIDS. Needs to be imported, either as cement blend or raw material	Limited and is a diminishing resource globally. Not available in Pacific but blend could be potentially could be imported from Japanese suppliers in PNG	Very limited. Not available in Pacific	Potentially abundant supplies in Pacific SIDS Requires calcination in a kiln (at lower temperatures than clinker).	Abundant across Pacific SIDS

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[28] UNEP (2018). Eco-Efficient Cements: Potential Economically Viable Solutions for a Low-CO2 Cement-based Materials Industry'. UNEP, Paris. https://wedocs.unep.org/20.500.11822/25281 Accessed 06/07/2023

[29] IIT Delhi Team (2022).'Detailed Technical Report on LC3'.

[30] ClimeCo LLC (2022). 'Low carbon cement production: issue paper'.

[31] Emissions reductions calculated from data provided in Gupta and Chaudhary (2022). 'State of the art review on supplementary cementitious materials in India – II: Characteristics of SCMs, effect on concrete and environmental impact. *Journal of Cleaner Production* 357

[32] VDZ (Nd.). Decarbonisation Pathways for the Australian Cement and Concrete Sector

[33] Bushi, L. and Meil, J. (2014). 'An Environmental Life Cycle Assessment of Portland-Limestone and Ordinary Portland Cements in Concrete'. Technical Brief. Cement Association of Canada. See also Portland Cement Association https://www.cement.org/sustainability/portland-limestone- cement#:~:text=Portland%2Dlimestone%20cement%20(PLC),footprint%20of%2010%25%20on%20average. Accessed 28/07/2023. Also see World Business Council for Sustainable Development. https://www.wbcsdcement.org/disadvantages-of-portland-limestone-cement/

Performance parameter	Fly ash	GBFS	Silica fume	Calcined clay (kaolin)	Limestone
Strength at 3 days	Reduced	Reduced	Increased	Increased	Slightly higher[34] [35]
Strength at 28 days	Reduced or no effect	Reduced or no effect	Generally increased	Generally increased	No effect
Carbonation	Increased	Increased	Reduced	Increased	No data
Permeability	No effect	Reduced	Reduced	Reduced	No effect
Chloride ingress	Reduced	Reduced	Reduced	Reduced	Negligible but increases with substitution above 15%[36]
Summary	Reduced early strength but improves long term. Varied regional availability with supply declining over time as energy from coal decreases.	Reduced early strength, otherwise good performance. Declining global supply.	Small clinker reduction, otherwise good performance. Costly and very limited availability.	Early stages of industrial production but good performance as an SCM. Addition of limestone (LC3) makes it a much superior cement across all parameters.	Similar strength to OPC up to 10-15% but reduced after this level of substitution. Abundant resource with modest CO_2 emissions potential

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[34] GCC. Portland-Limestone Cement Datasheet. Available https://www.gcc.com/wp-content/uploads/2022/03/GCC-PLC-032022-web.pdf Accessed 27/07/2023.

[35] IIT Delhi Team (2022). 'Detailed Technical Report on LC3'.

[36] Elgalhud, A.A., Dhir, R.K. and Ghataora, G., (2018). Chloride ingress in concrete: limestone addition effects. Magazine of Concrete Research, 70(6), pp.292-313.

Agricultural biomass

Agricultural biomass waste, such as rice husks, cassava peel and sugar cane, once fired at temperatures of 600-700°C, can produce a silica-rich pozzolan ash that can be used as an SCM additive to replace naturally occurring or artificial pozzolanic material (e.g., fly ash) by up to 30%.[37] Strength can also be increased and chloride ingress reduced. However, the availability of agricultural ash is limited to agricultural areas and tends to be in small amounts and is subject to seasonal variability.[38] The diversion of some agricultural biomass from other uses, such as being used as animal feed, a mineral fertilizer or in industrial applications can potentially have deleterious effects on livelihoods, creating greater dependence on carbon intensive mineral fertilizers. Furthermore, despite considerable research, there are few success stories of agricultural ash being used on an industrial scale in the cement industry. It is for these and other reasons that UNEP has concluded that agricultural ash is unlikely to make significant contributions to CO_2 emissions at a global level, though it may be of value at a regional level, such as the case with sugar cane ash ('bagasse') discussed in the next section.

Cost considerations

Except for silica fume, low carbon blended cements are typically cheaper to produce than OPC. However, they tend to attract a premium in the market and so cement companies often set a price that may be equal to, or only slightly lower than OPC. Prices per unit, whether bagged or bulk may also differ significantly depending on the location and market. Factors such as costs of shipping and supply and demand factors in local markets all affect prices, though in some countries, like Fiji, price caps (for OPC / GP) are set by the government. It is important to note that the consultations revealed cost considerations are primary for most infrastructure developers in the region, even when there is recognition of the importance of environmental considerations. This discussed further in section 5.1.

Shipping related emissions

Carbon emissions from the transport of goods depends on the method of transportation (e.g., road, rail, ocean), distance travelled and weight of product. Using one logistics company's emissions calculation tool[39], shipping one tonne of clinker or cement from Tokyo to Suva (a distance of 7,406 kms) approximately 75.5kgs CO_2^e would be produced. Therefore, the total cement production and shipping related emissions for one tonne of OPC sourced by Fiji from Japan would be 917kg CO_2^e versus 842 kgs CO_2e for just the production of OPC component. This represents an increase in CO_2 emissions of around 9%, not an insignificant number.

Other technologies

Limestone Calcined Clay Cement (LC3)

With the support of the Swiss Agency for Development and Cooperation, researchers from Switzerland, Cuba and India have developed a new form of cement using kaolin clay, along with limestone, Portland clinker and gypsum that has proven to have great potential to reduce emissions in the cement industry at lower investment and production costs.[40] Known as Limestone Calcined Clay Cement, or 'LC3', production involves the calcination / heating of kaolin clay to between 700˚C to 800˚C to make it reactive with other materials. This contrasts with a required temperature for calcination in OPC of 1,400-1,500°C.[41] The combination of the calcined clay with limestone enables clinker substitutions of up to 50% compared with OPC[42] (Figure 1) while using only around half of the energy. In addition, limestone with as little as 65% carbonate content can be used which at this level is usually rejected by cement plants. One of the main appeals of LC3 is that it uses existing raw materials and technologies used by the cement industry with a production process that is very similar to production of Portland cement.

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[37] Martirena and Monzo Balbuena (2018). 'Vegetable ashes as Supplementary Cementitious Materials'. *Cement and Concrete Research*. Vol 118, December

[38] Martirena and Monzo Balbuena (2018). 'Vegetable ashes as Supplementary Cementitious Materials'. *Cement and Concrete Research*. Vol 118, December

[39] https://www.cevalogistics.com/en/eco-calculator

[40] LC3 Technology and Resource Centre, nd. 'Limestone Calcined Clay Cement: A Viable and Sustainable Alternative to Existing Cement Varieties

[41] LC3 Technology and Resource Centre. https://lc3.ch/why-lc3/ Accessed 16/07/2023.

[42] Scrivener et al. (2018). 'Calcined clay limestone cements (LC3)'. *Cement and Concrete Research*. Vol 114, 49-56, https://doi.org/10.1016/j.cemconres.2017.08.017

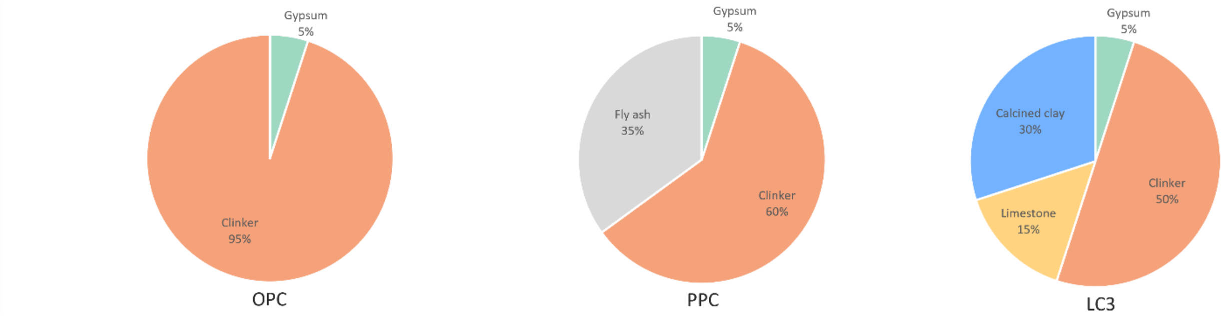

Figure 1: Comparison of material inputs between OPC, PPC and LC3-50. Source: LC3 Resource Centre

The performance of LC3 has been assessed as “excellent”.[43] CO_2 emissions reductions of up to 40% are possible and strength at both 3 and 28 days is increased (Table 2). In addition, both permeability and chloride ingress are reduced meaning that like fly ash LC3 is particularly suited to coastal environments exposed to saltwater. These performance characteristics make LC3 cement an excellent choice for infrastructure development in the Pacific regions and other Small Island Developing States (SIDS) that are experiencing the effects of climate change induced extreme weather events such as cyclones and floods.

Recently released data indicate that LC3 is now being trialled or investigated in 35 countries and commercially produced in 10, including in the advanced economies of the United States, France, Denmark and Switzerland. It has successfully been used in housing, commercial buildings and large infrastructure projects like bridges and highways.

Geopolymers

Among the other technologies capable of reducing CO_2 emissions in concrete are alkali activated materials (AAMs), otherwise known as geopolymers. These are made from a range of alumina silicate materials, usually industrial by-products such as GBFS and fly ash, but also calcined clays and vegetable ashes. The manufacturing process entails adding an alkali like sodium hydroxide to the GBFS or other AAMs to activate them to create a cement binder. Due to the fact that Portland Cement is not used, there are essentially no or few CO_2 emissions released in the production process.

However, global use of geopolymers is very small at present given the material inputs are currently used as SCMs in Portland Cements.[44] The ideal materials for making geopolymers are GBFS, which can be used to produce AAMs at room temperatures and comprise most geopolymers globally. However, while GBFS can result in lower emissions than Portland Cements, its diversion as an SCM in Portland Cements would result in higher global CO_2 emissions of SCM cements, given that a) the overall CO_2 emissions of Portland Cements relying on GBFS will increase; and b) there are emissions associated with the production of the alkali activator.

Recognition of low carbon cements under national standards

Many Pacific SIDS building codes use a range of national standards that recognise various types of low carbon cements. Several countries, such as the Cook Islands, Fiji, Kiribati and Tonga follow New Zealand standards (e.g., NZS 3122:1995 and NZS 3123:2009) that have certified the use limestone filler cement, Portland Pozzolana Cement, and Blended Cements (e.g., fly ash, GBFS, silica fume). Other countries, such as Samoa, Tuvalu and Vanuatu use Australian standards, which also approve the use of SCMs (e.g., AS 3582). Information on cement standards in other countries in the region, including those in the northern hemisphere such as Palau, FSM and the Marshall Islands were not available at the time of writing, but these may be based on US standards which also recognise use of SCMs. LC3, which can be used in all types of infrastructure is now recognised under a variety of standards, including those in the United States (and hence can be used in Pacific SIDS using US standards), Europe, India, Cuba and other countries. Calcined clay is currently recognized as a supplementary cementitious material by Australian Standards

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[43] The Indian Institute of Technology Delhi (2022). ‘Detailed Technical Report on LC3’.

[44] UNEP (2018). ‘Eco-efficient Cements: Potential Economically Viable Solutions for a Low-CO_2 Cement-based Materials Industry’. UNEP, Paris. https://wedocs.unep.org/20.500.11822/25281 Accessed 06/07/2023

(through AS3582.4).[45] AS3582 allows for the addition of up to 7.5% limestone in General Purpose (GP) cement, which falls short of the 15% required to produce LC3-50, but would allow for the production of an LC3-25. The same standard includes General Purpose Limestone Cement (GL), which allows for up to 20% limestone, though the standard restricts the use of SCMs like calcined clay to a maximum of 5%, and an overall minimum clinker content of 80%.

Finally, it is worth noting that PRIF is working on building codes and standards in the region and is currently advocating for the development of a regional standard for energy efficiency. PRIF could potentially lay the groundwork for developing other regional standards for cement and concrete in the Pacific region.

Suitability of low carbon cements for infrastructure applications

Research and expert consultations indicate that the main low carbon cements currently in use globally are suitable for use in a wide range of infrastructure applications. This includes LC3, which as a General Purpose Cement has been used in all types of infrastructure (e.g. bridges, roads and buildings) in various countries (Table 3).

Table 3: Type of low carbon cement and infrastructure applications. Sources: The Constructor, Constrofacilitator, Carbon Cure

Type of cement	Infrastructure applications[46]	Notes
Type IS (X)* - Portland-Slag Cement (PSC)	Concrete construction Dams Bridges Roads Buildings Marine structures	Made with Portland cement clinker, granulated blast furnace slag, and gypsum
Type IP (X) - Portland-Pozzolan Cement (PPC)[47]	Hydraulic structures Dams Marine structures / construction near the seashore Pre-stressed and post-tensioned concrete members Precast sewage pipes	Fly ash is the most commonly used pozzolan
Type IL (X) - Portland-Limestone Cement (PLC)[48]	Roads Dams Bridges Sidewalks Buildings	Most commonly used clinker substitute globally
Type IT - Ternary Blended Cements	Major engineering projects Domestic construction Precast concrete Stabilisation including pavement recycling for road construction Mining applications	Blends of Portland Cement with more than one SCM
LC3*	General Purpose Cement suitable for all applications, from large commercial buildings to bridges.	Certified by US (ASTM), European, Indian and other standards

* LC3 is also technically a ternary blend

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[45] Australian Standard 3582 Part 4 (Supplementary Cementitious Materials – Manufactured Pozzolans) provides for the use of calcined clay in cement, however, the Australian Standards for concrete structures (AS3600) and bridges (AS5100) have yet to be revised to include blended cements with calcined clays.

[46] https://theconstructor.org/concrete/portland-pozzolana-cement/23161/ https://constrofacilitator.com/blended-cement-advantages-types-and-applications/

[47] https://constrofacilitator.com/blended-cement-advantages-types-and-applications/

[48] https://www.carboncure.com/concrete-corner/what-is-portland-limestone-cement-and-is-it-becoming-the-new-norm/

4. The cement and concrete industry in the Pacific Islands

The cement and concrete industries in Pacific SIDS are considerably smaller than in other regions of the world. Nevertheless, cement and concrete are of significant economic, social and environmental importance. Most Pacific SIDS need large infrastructure investments over the coming decade to address increasing urban migration, raise living standards, and manage the impacts of climate change, which disproportionately affect Pacific Island countries relative to other regions. The Asian Development Bank estimated that from 2017 over USD30 billion would need to be invested in Pacific SIDS' infrastructure by 2030.[49] This infrastructure development will require large quantities of building materials, including cement, aggregates, and concrete. Various international bodies are involved in helping the Pacific SIDS meet these challenges, notably Australia through the Australia Infrastructure Financing Facility for the Pacific (AIFFP), and bilateral and multilateral agencies through the PRIF. Of significant importance to Pacific countries and their bilateral donors is that the materials that make concrete are sustainably sourced, produce lower CO_2 emissions, are durable and cost effective, and can protect against the increasing impacts of climate change, such as cyclones, floods and storm surges.

4.1 Production of cement in Pacific SIDS

Ordinary Portland Cement (OPC) is an inorganic binder that is manufactured from the combination of clinker (produced through the sintering of limestone and clays in a kiln) and gypsum. There are currently five cement plants in the Pacific Islands region, all of which are grinding plants that import almost all their raw materials, including clinker, to produce OPC (Table 4). Fiji has three cement plants: one owned by Pacific Cement, which was established in the British colonial era, and a more recent entrant, Chinese-owned Tengy Cement, established in 2014, which has two sites. All three plants are located on Fiji's main island of Viti Levu. PNG has one plant, located in Lae owned by PNG Taiheiyo Cement, a subsidiary of a large Japanese cement producer with operations in Japan, the United States, the Philippines, and China.[50] The fifth plant is in New Caledonia and is owned by a Japanese company, Tokuyama, a large, diversified chemicals and advanced materials company.[51]

Of particular interest are plans by Brisbane-based Mayur Resources to build a vertically integrated quicklime and cement manufacturing facility 25km from Port Moresby that the company claims will be carbon neutral and has the potential to meet 100% of PNG's cement, clinker, and quicklime requirements, and may also export to other countries in the region.[52] Discussions with this company indicate that it will produce OPC and carbon neutrality will be achieved through a combination of carbon offsets, alternative fuels, carbon, capture and storage (CCS), production efficiency and new technologies.[53] The company has access to a limestone deposit next to its proposed plant and expects lime production to occur in phase 1, with cement production in phase 2 expected to commence in 5-7 years.

In Fiji, neither of the two cement companies currently produce clinker. Imported clinker prices have reportedly been as much as US$160/tonne during the COVID-19 pandemic – among the highest in the world – and are still very high at US$120/tonne. Pacific Cement produced clinker locally in Fiji until around 2004/05 when the introduction of the Environmental Management Act was considered to be at odds with the extraction of carbonate sands from the reef lagoon and the company moved to a clinker import model.[54] Prior to 2004, the company employed 500

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[49] DFAT (2018). AIFFP Design Document. Available https://www.aiffp.gov.au/documentation

[50] Taiheiyo Cement Corporation (2019). '2019 Annual Report'. Available https://www.taiheiyo-cement.co.jp/english/ir/pdf/2019/all.pdf (Accessed 17/07/2023

[51] https://www.tokuyama.co.jp/eng/products/cement/portland_cement.html

[52] Mayur Resources, Central Cement and Lime Project. https://mayurresources.com/central-cement-lime-project/ Accessed 20/07/2023

[53] The use of carbon offsets, and CCS are less preferable than the reduction of emissions at source through the use of low carbon alternative materials and represent options that are situated lower on the waste management hierarchy. Emissions reduction has been demonstrated in the global concrete sector through innovations in materials. Carbon offsets and CCS have not yet proved a viable path to large-scale emissions reduction.

[54] Pacific Cement and Tengy Cement have been under scrutiny over environmental impacts of dust associated with cement production in Lami Bay, Viti Levu. Environmental and social concerns. For example, see https://www.fijitimes.com/three-companies-to-pay-1-33m/#:~:text=Pacific%20Cement%20Ltd%2C%20Tengy%20Cement,loss%20due%20to%20closure%20of

people but reduced its staff numbers to 70 once clinker production ceased. Interestingly, between 2016 and 2018 Pacific Cement mixed 30% GBFS into its Portland Cement but stopped doing so after the costs of imported slag increased. Recent correspondence with the company indicates they are currently making a blended cement with 20-30% local volcanic pozzolan and so are essentially selling a Pozzolan Portland Cement.

Tengy, meanwhile, uses about 5% of volcanic rock in its cement mix, however, it has not made firm plans to produce low carbon cements via supplementary cementitious materials (SCMs) in significant quantities, though both have expressed interest in exploring the possibility of producing Limestone Calcined Clay Cement (LC3). A summary of the key production characteristics of these and the other plants in the Pacific are provided in Table 4.

Table 4: Operational characteristics of cement companies operating in the Pacific Islands region

Company & location	Type of plant	Type of cement produced	Plant annual capacity (tons)	Latest annual production (tons)	Current export destinations
Pacific Cement, Fiji	Grinding but rotary kiln available	Currently PPC but OPC most common historically	150,000	100,000	Only 1-2% of production currently exported
Tengy Cement, Fiji (2 sites)	Grinding but rotary kiln available at one site	OPC with 5% volcanic rock mixed	60,000 (2 sites combined)	92,000 (2 sites combined)	All countries in the region except Solomon Islands and New Caledonia
Taiheiyo, PNG	Grinding	OPC with limestone mixed	N.d.	N.d.	Mainly domestic market but also exported to countries such as the Solomon Islands
Tokuyama, New Caledonia	Grinding	OPC	180,000[55]	69,000	Domestic market only
Total			390,000	262,000	

Sources: Stakeholder consultations June-July 2023; company annual reports

PNG's Taiheiyo plant imports materials from its parent company in Japan where use of SCMs like granulated blast furnace slag (GBFS) and fly ash is commonplace.[56] Based on available data, however, it does not appear that Taiheiyo is producing or importing low carbon cement in PNG. Discussions with one of PNG's biggest infrastructure contractors suggests that Longfa, an importer and distributor of OPC (but not a local producer), is eroding Taiheiyo's dominant market share. It is the preferred cement supplier for Chinese contractors and other project developers in the capital, Port Moresby, and surrounds.

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[55] Latest available data is 2019. See US Geological Survey (2019). The Mineral Industry of New Caledonia. Available https://pubs.usgs.gov/myb/vol3/2019/myb3-2019-new-caledonia.pdf Accessed 19/07/2023.

[56] Taiheiyo Integrated Report (2022). https://www.taiheiyo-cement.co.jp/english/csr/csr_fr.html

Finally, Tokuyama’s facility in New Caledonia also produces OPC and consultations with industry representatives in New Caledonia reveal that the company also does not produce any low carbon blends but does add a small amount of Granulated Blas Furnace Slag (GBFS) to its cement (a few percent of total composition) as a mineral additive to enhance the cement’s properties.[57]

Figure 2: Pacific Cement Grinding Facility, Lami Bay, Suva, Fiji.

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[57] Stakeholder consultation 19/07/2023. Using GBFS as an additive can enhance some of the properties of cement, such as reduced risk of cracking and increased strength over time. See Global Cement and Concrete Association https://gccassociation.org/cement-and-concrete-innovation/clinker-substitutes/granulated-blastfurnace-slag-gbfs/ Accessed 19/07/2023.

4.2 Trade in cement products

The Pacific Islands are a net importer of cement and cement inputs like clinker and gypsum. In 2021, the value of imports totaled USD 52.2 million while exports were USD 3.32 million. Fiji is also a net importer (USD 8.2M) but plays an important role in the cement supply chain in the region. For example, in 2021 it exported US$ 3.2M of cement to Tonga, Samoa, Kiribati, Vanuatu and Wallis and Fortuna. Tengy Cement was responsible for the vast bulk of these exports with Pacific Cement only exporting a small amount (1-2% of its production of 100,000 tons / year in the last financial year). However, the company intends to refocus on the export market in 2024. The biggest suppliers of cement and cement products for the region are Indonesia (USD 26.6M)[58], Thailand (USD 6.17M), Japan (USD 5.12M) and China (USD 3.43M (Figure 3). The rest is sourced from a range of countries such as New Zealand, Australia and the Philippines, as illustrated in Figure 4.

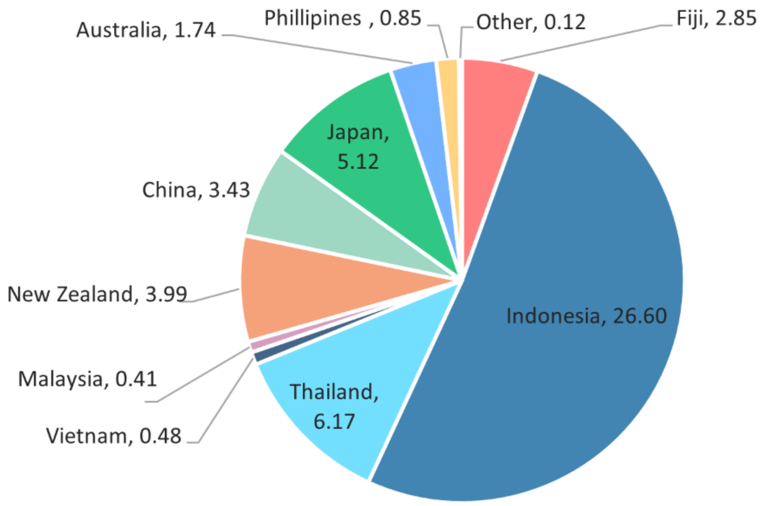

Figure 3: Source and value of imports to Pacific Island States, 2021 (as % of total imports in USD million). Source: Observatory of Economic Complexity database; UN Comtrade database

Neither PNG nor New Caledonia exported cement in 2021 (latest data) but recent field reports indicate that Taiheiyo's 'Paradise' cement is currently been sold in the Solomon Islands. Nevertheless, both countries are heavily reliant on cement and cement product imports from Asia, notably Japan and Indonesia (Figures 4 and 5).[59] OEC data portray a relatively minor role for Vietnam as a cement supplier, but anecdotal evidence suggests its role may be more important in the region.

Cement costs in selected countries

Data on the price of bagged and / or bulked cement in all countries included in this study could not be sourced during the research period and would require communications with the major cement suppliers in the 15 countries covered. However, data were acquired for a limited number of countries during consultations with infrastructure program representatives and contractors. These are summarised in Appendix 2 and are for OPC. Cement prices in some countries such as Fiji are capped by the Competition and Consumer Division.[60] As of March 2022, caps were FJ$ $322.59 / tonne for General Purpose Bulk Cement and FJ$ 339.77 for General Blended Bagged Cement. Data for the various blends of low carbon cements also could not be acquired and would require further engagement in a range of countries that currently supply OPC to the Pacific.

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[58] The region's reliance on Indonesia is somewhat misleading since around USD 16.3 million of Indonesia's exports to the region, or approximately 31%, are to Timor-Leste

[59] Observatory of Economic Complexity database. Accessed 01/07/2023

[60] See https://fccc.gov.fj/wp-content/uploads/2022/03/Final-Authorisation-for-Tengy-Cement-Fiji-Company-Limited-and-Tengy-Cement-Lautoka-Pte-Ltd.pdf

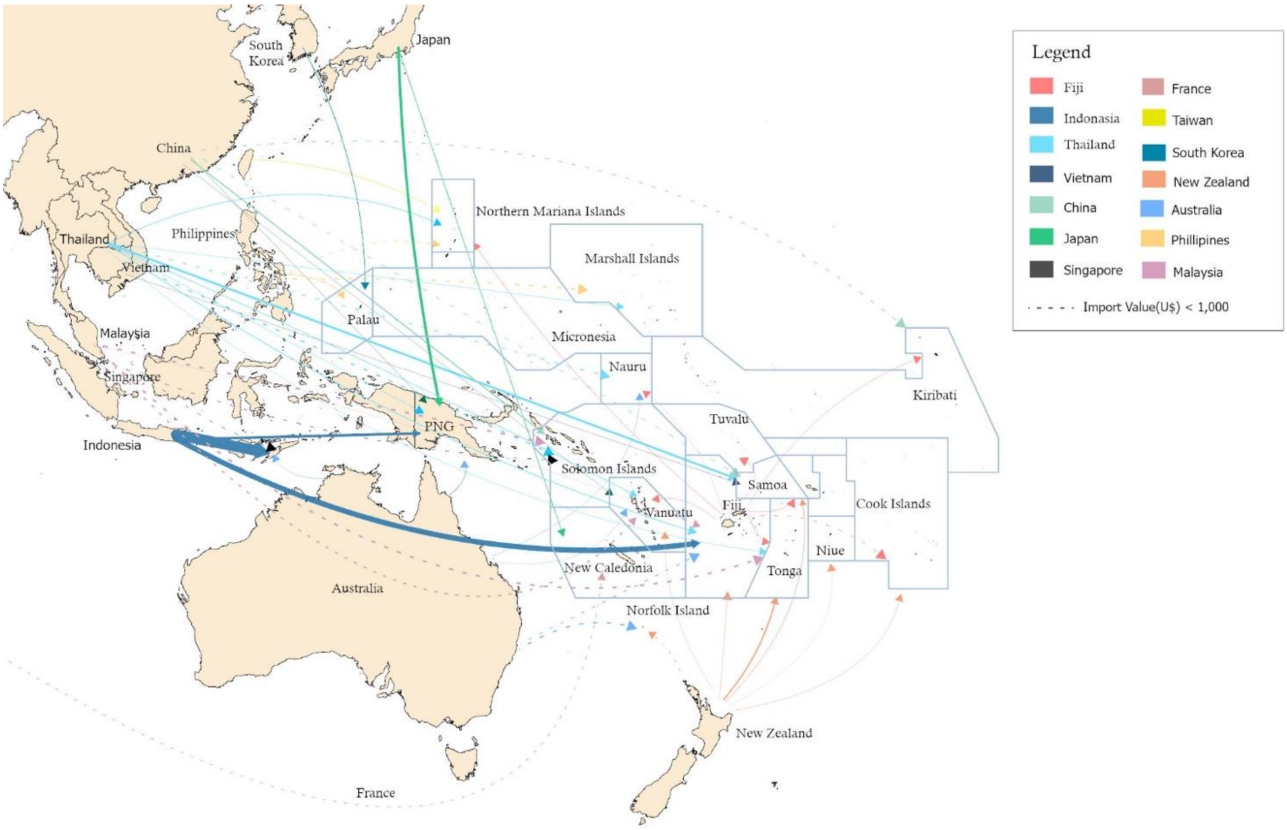

Figure 4: Cement and clinker supply chains in the Pacific Islands region, 2021. Source: Observatory of Economic Complexity database; UN Comtrade database.

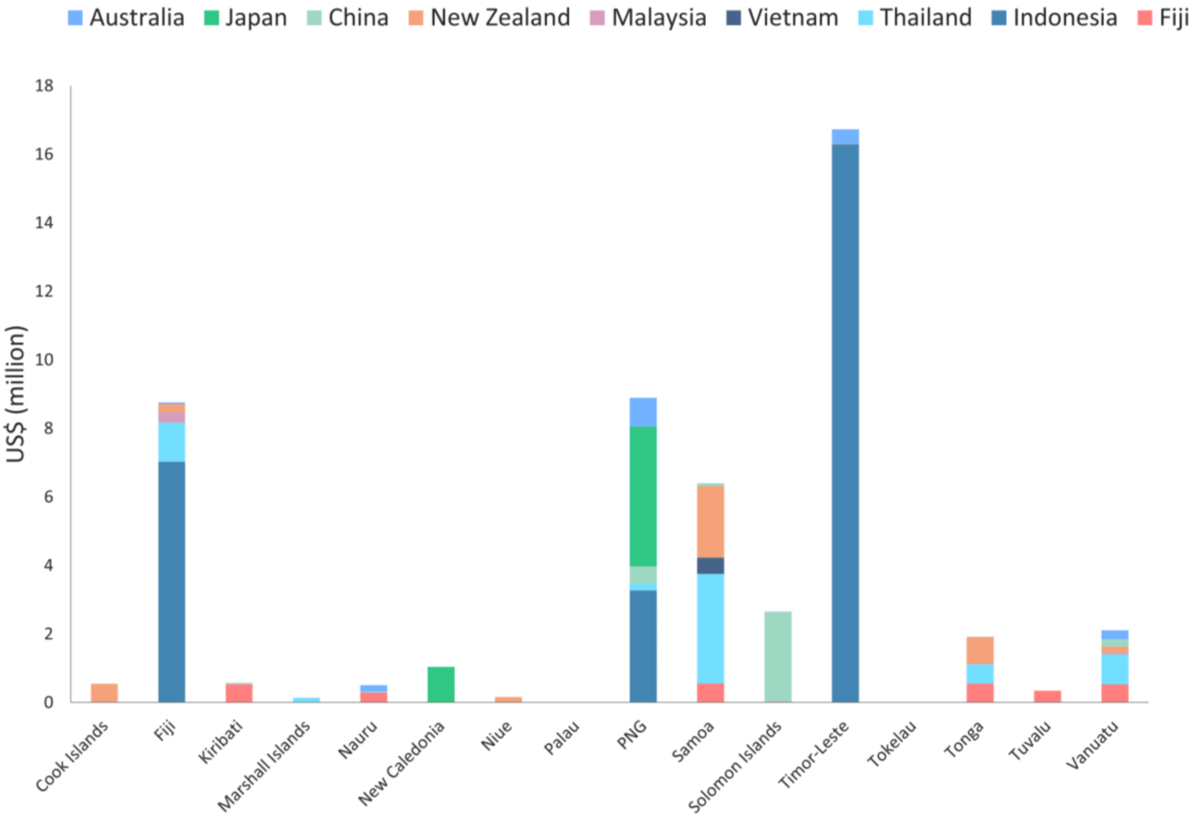

Figure 5: Source of cement / cement product imports to Pacific Island States, 2021 (value USD M). Source: Observatory of Economic Complexity (OEC), UN Comtrade Database

4.3 Aggregate supply and sustainability

A critical factor in determining the best options for low carbon concrete in the Pacific Islands is knowing where the aggregate to be used in the concrete (which may be up to 75% of the mix) is sourced, and how it is extracted, processed, transported, and used. Infrastructure developers in the region are increasingly facing challenges obtaining aggregate that is not only affordable and of adequate quality and supply to meet increasing demand but is responsibly sourced. Currently, sand is sourced from beaches, lagoons and rivers, gravel from rivers, crushed rock from hard-rock or limestone quarries, and coral from reefs. Unfortunately, sustainable supplies of these resources vary significantly geographically given the size and geology of Pacific SIDS and, for many countries, "on land" hard-rock quarries are limited or non-existent, particularly "atoll countries" like Tuvalu and Kiribati.[61]

SOPAC (now the Pacific Community) observed in 2006 that this had led to the greatly intensified mining of sand from riverbeds, beaches, and reefs, since these were often the easiest and cheapest options available to commercial operations and local people.[62] These practices continue to this day with significant impacts on these "traditional" sources of aggregate, reducing the natural protection provided by beach systems to extreme weather events, resulting in chronic erosion, reduction in land area, and damage to housing and coastal infrastructure. Inappropriate aggregate extraction practices in coastlines and rivers also impacts local water quality and can disrupt coastal ecosystems. A summary of these impacts is provided in Table 5.

Table 5: Aggregate resources and environmental and social issues in Pacific SIDS. Source: Compiled by author.

Type of aggregate	Source	Factors affecting CO_2 emissions	Environmental / social impacts
Sand	Beaches, lagoons, rivers	Relatively low amounts of energy used in extraction; distance to place of use	Beach and coastal erosion, turbidity, erosion and impacts of fisheries and riparian vegetation
River gravel	Rivers	CO_2 emissions from fuel used in extraction, crushing / processing; distance to place of use	Disruption to river ecosystems; turbidity and erosion; potentially increased flooding; impacts on drinking water supplies and amenity (e.g., for tourism); impacts on fisheries and riparian vegetation
Coral	Coral reefs	CO_2 emissions from fuel used in extraction, crushing / processing; distance to place of use	Damage to coral reefs and marine biodiversity; increased exposure to storms.
Limestone / 'coronous' material	Limestone quarries	Higher energy use in extraction, crushing / processing; distance to place of use	Comparatively limited impacts; road hazards, land use-conflicts, occupational health and safety hazards.
Crushed rock and manufactured sand	Hard rock quarries	Higher energy use in extraction, crushing / processing; distance to place of use	Comparatively limited impacts; road hazards, land use-conflicts, occupational health and safety hazards.
Ore-sand	By-products of mineral ores	Distance to place of use	Arguably environmentally and socially positive since there is a reduction in mine waste

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[61] Tawake, A., Webb, A., and Pelesikoti, N. (2006). 'Proceedings of the Pacific Islands Regional Workshop on Aggregates Resources of Coastal and Marine Systems'. EU-SOPAC Project Report 154. SOPAC Secretariat, June 2006.

[62] Tawake, A., Webb, A., and Pelesikoti, N. (2006). 'Proceedings of the Pacific Islands Regional Workshop on Aggregates Resources of Coastal and Marine Systems'. EU-SOPAC Project Report 154. SOPAC Secretariat, June 2006. See also UNDP (2018). 'Baseline assessment of development minerals in Fiji'.

There is limited and, in some case, no data on aggregate reserves, their extraction, use, and cost in many Pacific SIDs. With a few exceptions, such as the Environmentally Safe Aggregates for Tarawa project (ESAT) there is also a lack of adequate safeguards and appropriate regulations to guide responsible extraction. Moreover, education about the potential negative impacts of aggregate extraction is lacking and there is an overall lack of capacity within governments to adequately evaluate and manage resources in a sustainable manner. These challenges are the primary reason that the Pacific Region Infrastructure Facility has recently commissioned The University of Queensland's Sustainable Minerals Institute and Smith Geoscience Consulting to undertake an assessment of responsible sourcing of aggregate resources in 14 Pacific SIDS, the scope of which is to build an aggregates knowledge base for the region, understand the needs of infrastructure developers, and what is needed to ensure responsible sourcing of materials.

The distance between location of extraction and location of aggregate use adds to the overall embodied carbon emissions of concrete. Unfortunately, there is currently very patchy information about aggregate supply chains in the region making it difficult to assess the full embodied emissions of the concrete used in infrastructure development. In Fiji, knowledge of the sector is reasonably comprehensive, in large part thanks to the Baseline Assessment of Development Minerals undertaken by the ACP-EU Development Minerals Programme in 2018.[63] Most of Fiji's aggregate supply comes from local quarries and rivers and does not require lengthy shipping distances. Discussions with local contractors in Fiji indicate that quality aggregate from a prominent river gravel operation, one of Fiji's biggest suppliers, costs around FJ$ 75/m3. Shipping costs are currently 75 cents / km / m3. However, it has also been reported that two of the largest suppliers of river gravel to the export market are running low on reserves. Furthermore, even in Fiji, where there is environmental oversight, river gravel extraction for the concrete and construction industries is having detrimental impacts.

In contrast to Fiji, there is limited understanding of aggregate extraction and supply chains in many other countries. Furthermore, while sand and coral-derived aggregate obtained in countries such as Tuvalu may not have high embodied emissions, they are undesirable due to their significant environmental impacts, and lower quality for some uses. As will be discussed in sections 5 and 6, there are a number of strategies that should be considered to improve the sustainability and emissions profile of the aggregates used in concrete in the region.

Major international development donors are currently sourcing aggregate for climate change adaptation projects in the Pacific with material unsustainably sourced from Pacific rivers with significant sections of river irreplaceably transformed (Figure 6).

Figure 6. River gravel extraction site in the Pacific where aggregate is exported for major infrastructure projects, including for climate change adaptation and resilience projects. Photos show: a) before mining; b) during mining; and post-mining sites.

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[63] Smith, Robert, Lee, Gary, Tawake, Akuila, Waqavonovono, Epeli, Chambers, Ken, Bukarau, Tevita, Prasad, Christine, Roqica, Donato, Nagata, Isireli, Nainoca, Timaima, Peltovuori, Ville, Devi, Priya, Caniogo, Josefa, Stojkoska, Mihaela, Pakoun, Lacina, Ngonze, Caroline, and Franks, Daniel M. (2018). Baseline Assessment of Development Minerals in Fiji. Development Minerals in Africa, the Caribbean and the Pacific. Suva, Fiji: United Nations Development Programme.

5. Low carbon concrete options for the Pacific Islands

Identifying which low carbon concrete options might be most suitable for Pacific SIDS entails understanding both the cement and aggregate sides of concrete. For each, the following factors have been considered for this scoping report: the availability of alternative materials and / or technologies in the Pacific, potential CO_2 emissions reduction; their durability and strength for various types of infrastructure; challenges posed by supply chains, transportation and local geography and climate; costs; environmental sustainability; and the climate and disaster resilience of the concrete. Several other factors are also relevant in assessing low carbon concrete options, such as the efficiency with which various types of concrete can be used as well as how easy they are to use, which is particularly relevant for small local users with limited skills and experience.

5.1 The cement side

It is important to recall that cement supply in the region comes from two pathways: the first is from East and Southeast Asia where suppliers provide bagged or bulk cement to consumers in the region. The second is supply from the five plants in Fiji, PNG, and New Caledonia – all of which currently import the raw materials for making cement, such as clinker from East and Southeast Asia.

In the case of suppliers in Asia, the ability of infrastructure developers in the Pacific Islands to obtain specific types of cement other than OPC will depend on whether cement companies manufacture the preferred cements in their home countries, have access to key material inputs if they don't already, and whether they are willing to start supplying the Pacific region with low carbon cements.

Meanwhile, in the case of cement producers in the Pacific region, access to low carbon cements will depend on the availability of raw materials and their ability and willingness to start producing them. In Fiji, both cement producers (Tengy and Pacific) have expressed interest in producing LC3 (discussed in further detail below) but it is not clear whether those in PNG, and New Caledonia can or would supply low carbon cements. However, the parent company of PNG's Taiheiyo already produces Portland cements with GBFS and fly ash so potentially could be a supplier or even producer of low carbon cement in the region in the future. It is a similar case with New Caledonia's Tokuyama cement in Japan which produces Portland cements with GBFS.[64]

The rest of this section the best low carbon cement options for the Pacific and examines the perspectives of infrastructure developers in the region.

Silica fume cements unlikely to be adopted on any significant scale

As discussed in section 3, each the cements made with SCMs has advantages and disadvantages in terms of the level of CO_2 emissions reductions possible and various performance parameters, though some are clearly not feasible on any significant scale for infrastructure developers in Pacific SIDS. Silica fume falls into this category: on a cost-basis alone, it is very unlikely to find a large market in the region, given that cost remains the most important priority for infrastructure developers and contractors in most countries. Its availability is also very limited given that supply comes from the silicon metal and ferrosilicon industry, which doesn't exist in the region, or in many places globally, and shipping distances would be long, increasing cost and transport related emissions. The size of the clinker substitution and CO_2 emissions reductions that are possible is also small, with a maximum 10% reduction. And finally, it is also expensive relative to Portland Cement. Silica fume's value is as a niche cement where chemical resistance (e.g., to concrete damaging alkali-silica reaction; ASR) and increased strength are priorities.

Fly ash cements – good short-term option but with drawbacks

Fly ash is already well-established in many countries as an SCM that reduces cement emissions by between 25-35% with a cost that is comparable to or less than OPC. With current carbon allocations, it is also considered as a carbon-

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[64] Tokuyama 2020 CSR Report https://www.tokuyama.co.jp/eng/csr/report/index.html Accessed 28/07/2023

neutral by-product, whose emissions are already accounted for in coal combustion. Despite reduced early strength, this improves over the long term and other cement properties are either the same or better than OPC (Table 2). In addition, fly-ash cement blends are already available in countries such as Japan that supply Pacific SIDS so it is possible that shipments could occur in a relatively short period of time, provided the right market triggers are in place (e.g., requirements of infrastructure financiers and developers like AIFFP for Portland Pozzolana Cement to be used).

However, there are a number drawbacks that limit the fly ash cement blends as a long-term option to reduce emissions in the Pacific. One is that because coal production is being phased out, supplies of fly ash and fly ash cements will decline in the coming years, limiting supply and raising costs for buyers in the Pacific who usually prioritise cost and performance over environmental considerations. Another major consideration is that the Pacific does not host thermal coal power plants that produce fly ash as a by-product, and thus would face the continued insecurity of reliance on imported supply. Carbon emissions associated with shipping are also a factor which will mitigate the carbon reduction potential of these cements. Finally, there was some discussion over several years that fly ash, which is currently considered to be CO_2 free, might be subject to environmental loads in the future. If this is the case, the benefits of fly ash as a low carbon concrete strategy would be significantly reduced.[65]

GBFS cements – good performance but unlikely to form a key part of a long term strategy in Pacific SIDS

Of all the SCMs, GBFS has the highest clinker substitution potential, up to 70%, and a potential CO_2 reduction of 35-65% (Table 2). GBFS is already used by the parent company of PNG's Taiheiyo Cement and so could feasibly be supplied to the Pacific market. Yet as discussed in section 3, supplies of GBFS are dwindling, which will make it increasingly costly, and would require long shipping distances to many Pacific Islands, particularly in the south. Nevertheless, apart from reduced early strength, GBFS cements have good performance, are already recognised by international standards, and should therefore be kept as a potential short-term option for lowering the CO_2 emissions of cement and concrete in the Pacific SIDS region.

Locally available materials: limestone filler and volcanic ash / good short-term options but with limitations

With available local reserves of both limestone and volcanic rock (a natural pozzolan), Fiji's cement producers can reduce their clinker factor with cost and emission reduction benefits.[66] The use of raw limestone in cement, known as 'Portland Limestone Cement', has been recognised under official US cement standards such as ASTM C595 and AASHTO M240 since 2012, which allow up to 15% limestone content. This recognition resulted in a new type IL classification, which means the cement has similar properties to Type I and II cements, including in terms of strength development, durability, and workability.[67] Recent discussions with one of Fiji's cement companies indicated an interest in adding limestone. However, as discussed in section 3.3 and summarised in Table 2, limestone filler does have poorer performance characteristics in some areas when more than 10% of clinker is substituted. Meanwhile, volcanic materials in Fiji and other cement producers in the region, such as PNG, have the potential to reduce the clinker factor of cement, as well as costs. Studies have shown that volcanic scoria ground to a powder can substitute up to 30% of the clinker used in OPC, with similar potential reductions CO_2, depending on characteristics like reactivity.[68]

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[65] United Nations Environment Programme (2018). 'Eco-efficient Cements: Potential Economically Viable Solutions for a Low-CO_2 Cement-based Materials Industry'. UNEP, Paris. https://wedocs.unep.org/20.500.11822/25281 Accessed 06/07/2023
See also https://www.holcim.us/green-building-materials-and-solutions

[66] United Nations Environment Programme (2018). 'Eco-efficient Cements: Potential Economically Viable Solutions for a Low-CO2 Cement-based Materials Industry'. UNEP, Paris. https://wedocs.unep.org/20.500.11822/25281 Accessed 06/07/2023

[67] https://www.holcim.us/green-building-materials-and-solutions See also Portland Cement Association https://www.cement.org/cement-concrete/concrete-materials/cement-types

[68] Ayene, H et. al (2023). 'Potential Use of Scoria as a Cementitious Material for Green Concrete Production'. *Advances in Civil Engineering*. Vol. 2023 https://doi.org/10.1155/2023/5532027 It is interesting to note that one study has reported that a combination of 30% finely ground volcanic ash and 15% limestone powder with Portland Cement is capable of delivering a 48% reduction in CO_2 emissions, while providing good workability, high 28-day compressive strength (39 MPa), excellent one year strength (57 MPa), and very high resistance to chloride penetration. See Celik et al. (2014) High-volume natural volcanic pozzolan and limestone powder as partial replacements for Portland Cement in self-compacting and sustainable concrete. *Cement & Concrete Composites*. Vol. 45.

At least at the present time, limestone remains a cheap and effective short-term option to reduce emissions by a modest amount, reduce costs and, up to a certain level of substitution, maintain acceptable strength and other properties relative to OPC. Volcanic ash, which is abundant in Fiji and other countries in the region is already used to make blended cement in the region, and the case for wider uptake would benefit from further research on local performance and emissions reduction.

LC3 – the best medium-term option for Pacific cement producers

Potentially the best option for Pacific SIDS, is LC3, a new but proven and internationally recognised cement (discussed earlier in section 3.3). The combination of calcined kaolin clay and limestone produces a cementitious material that allows up to 50% of clinker to be substituted with carbon emissions savings of as much as 40%. Moreover, cement strength and durability are as good as, or superior to OPC, particularly in concrete structures in coastal environments, such as roads, bridges and buildings that need to withstand extreme weather events.

Another appeal of LC3 in the Pacific Islands context is that there are likely to be significant reserves of kaolin clay and limestone in at least two of the three cement producing countries in the region, namely Fiji and PNG. For example, Fiji has proven reserves of terrestrial limestone (as distinct from limestone from reefs and reef lagoons), that are of sufficient quality and quantity for use as raw limestone in LC3, but also for potential reactivation of local clinker production in Fiji. Based on preliminary investigations conducted by The University of Queensland and their partners (see below) there are kaolin clay deposits of sufficient quality that can support the production of LC3 in-country, some of which are by-products of the quarry sector and thus represent a circular economy approach

This would have numerous economic and environmental benefits for both Fiji and the region. These include reducing Fiji's reliance on clinker imports – currently amongst the most expensive in the world – and supporting new quarry and cement factory jobs. LC3 production would also lead to a significant reduction in Fiji's and the region's CO_2 emissions and given Fiji's importance as a regional cement supply hub, greater regional resilience in cement supply chains in the Pacific which are currently exposed to disruptions. The ability to have a strong regional supply of cement is particularly important following natural disasters when the building materials required for reconstruction are in short supply.[69]

The groundwork for introducing LC3, as well as ensuring responsible sourcing of aggregates to produce low carbon concrete, is currently being laid by the Blue Concrete Initiative (see case study below), which was launched at COP 27 in Sharm El Sheik, Egypt in November 2022 by the Fiji Government. The initiative involves 5 components: 1) assessing the availability, quality and quantity of required raw materials in Fiji, such as kaolinite clays and limestone; 2) economic and supply chain analysis of cement and aggregates in the Pacific Island region; 3) technology transfer for industry and demonstration projects; 4) developing and aligning local standards and policies for LC3, and developing responsible aggregates sourcing guidelines; and 5) determining the best implementation options and pathways, including development of strategies to help industry secure finance to commence LC3 production.

LC3 appears to be the best medium-term option for introducing low carbon cement to the region and pilot studies could begin almost immediately. This makes shorter term options such as using imported fly ash and GBFS cements feasible over the next few years. Other technologies, such as introducing limestone filler and using alternative SCMs such as volcanic rock / scoria – both of which are locally available in Fiji and perhaps in other cement producing countries – should also be investigated further.

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[69] Rogers, P., Maher, R., Lee, G., Naidelage, C., Flomenhoft, G., Junior, P. and Franks, D.M., (2023). Building disaster and climate resilience through Development Minerals. ACP-EU Development Minerals Programme White Paper. United Nations Development Programme (UNDP), Pacific Community (SPC), and The University of Queensland (UQ). UNDP Pacific Office, Suva Fiji.

The Blue Concrete Initiative

Pacific Small Island Developing States (PSIDS) like Fiji are reliant on imports of high-carbon, high-cost clinker to produce cement, concrete and the construction of infrastructure, with Fiji the main distribution point for PSIDS.

Clinker imported to Fiji is among the most expensive in the world, inhibiting development, as well as the ability to adapt to the effects of climate change due to a lack of affordable and reliable supply of materials to construct resilient coastal infrastructure and housing. Furthermore, key materials added to cement to make concrete, such as aggregate, are currently extracted with significant environmental damage to waterways and coasts, including rivers, beaches, and reefs.

The potential introduction of ground-breaking low-carbon cement technology, known as limestone calcined clay cement (LC3), to Fiji presents an opportunity to both significantly reduce carbon emissions from the production of cement and ensure a reliable and sustainable supply of construction materials. LC3 uses local resources, is less energy intensive, and produces up to 40% less CO_2 emissions compared to ordinary Portland cement (OPC). Successful transition to a local cement industry based on LC3 has the potential to reduce Fiji's carbon emissions by around 80 kt per year, or approximately 4% of the country's annual emissions, and deliver significant cost savings for local industry. Coupled with the creation of a regional knowledge base of aggregate resources, as well as new safeguards for their extraction, adoption of LC3 could ensure Fiji and neighbouring states have a reliable and sustainable supply of concrete, that is essential to mitigate and adapt to the impacts of climate change.

The Blue Concrete Initiative will ensure that the Pacific's leadership on climate change advocacy is complemented by leadership in climate change mitigation, while also improving access to concrete for climate adaptation actions and resilient development. The initiative will therefore support the adoption of concrete that embodies the values of the Blue Pacific. The project has three primary objectives: 1) Determine the best configurations for producing low-carbon cement in Fiji and support the government and private sector through technology transfer to adopt low-carbon cement in Fiji's cement industry; 2) Build resilience in regional supply chains to ensure PSIDS have reliable sources of affordable materials to produce concrete (cement and aggregate) for infrastructure development and climate change adaptation actions such as coastal protection and climate resilient housing; 3) Ensure that key concrete inputs such as aggregate, limestone, clay and gypsum are sourced in a way which optimises environmental, social, and economic outcomes for the Blue Pacific. The Blue Concrete Initiative is the result of a partnership between the Government of Fiji and The University of Queensland's Sustainable Minerals Institute, Technology and Action for Rural Advancement in Delhi, the Pacific Community, the ACP–EU Development Minerals Programme implemented by UNDP, and the Indian Institute for Technology Delhi. The Fiji Government has requested support from its development partners to mobilise resources for the Initiative.[70]

Sugarcane ash, 'Bagasse' – promising for countries like Fiji but limited availability in other countries

Among the vegetable ashes like rice husk ash and casava peel ash, another SCM with potential application in the Pacific Islands is sugar cane ash, or 'bagasse'. Bagasse is a residual waste product from sugar mills that is often disposed of but increasingly, is burned to generate electricity.[71] The remaining ash, or bagasse ash, is a natural pozzolan that can be used as an SCM in cement production. Its use as a biofuel means associated CO_2 emissions are mitigated. Minnu et al. (2020) report that optimal concrete replacement levels are 20%, though the degree of

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[70] Fiji Ministry of Lands and Mineral Resources (2022). Fiji takes concrete steps towards a low carbon future. Press release. November. https://www.lands.gov.fj/images/images/PressReleases/2022/FijiTakesConcreteStepsTowardALowCarbonFuture.pdf

[71] Thomas et. al (2021). Sugarcane bagasse ash as supplementary cementitious material in concrete - a review. *Materials Today Sustainability*. Vol 15. https://doi.org/10.1016/j.mtsust.2021.100086

emissions reductions possible are not currently clear from the literature but would presumably be similar, not taking into account the transportation of the ash to cement plants.

For sugar producing countries like Fiji with a cement industry this may be a good option for producing low carbon cement. Even though adverse effects such as delayed initial setting and workability reduction of the concrete have been reported, researchers have found its increased strength to be better than with fly ash and slag.[72] It has also been reported that there is significant enhancement in resistance against chloride ingress and water permeability when compared to fly ash and slag blended concrete. In Fiji, a large agricultural waste storage facility has apparently been constructed not far from Suva and could be used to store bagasse ash if industry were interested and market conditions were favourable. However, the limited supply and costs and emissions associated with transportation may mean that the use of bagasse as an SCM would remain limited to countries like Fiji where there is a large, established sugar cane industry.

Insights from field consultations

Consultations with infrastructure stakeholders , provided some valuable insights. For example:

- Opportunities exist for pilots of low carbon concrete, which could be undertaken in partnership with donors and national governments.
- Cost is of high concern for most developers, therefore stakeholders highlighted that feasibility, scoping studies and business cases would be important steps as well as awareness raising of the typically lower cost of low carbon concrete, than traditional options like Portland cement.
- There is a role for tenders to request sustainable and low carbon concrete options, and allow contractors to identify the best option for the project and location, however, capacity building would be needed to assist contractors.
- There is interest in using low carbon materials.
- Export is as a way to build commercial viability of local operations.

5.2 The aggregates side

Deciding on low carbon concrete options for Pacific SIDS involves not only considering the carbon emissions performance of various cement types, but also the carbon emissions associated with aggregates and ensuring the environmental and social impacts of all the materials used to make concrete are managed responsibly. As discussed in section 4.4, current extraction and supply of aggregates in many countries is creating significant environmental damage and is also having adverse social impacts, such as contamination of rivers used for drinking water and tourist activities. Some effort has been made to address these problems, with a limited number of programs and guidelines being introduced over the past decade. In the atoll of Tarawa in Kiribati, sand mining from coastal areas has been creating major coastal erosion, involving loss of the protective shoreline and land, and flooding of businesses, houses and critical infrastructure at high tide or during large swell events. In response, the EU supported the Government of Kiribati by funding the Environmentally Safe Aggregates for Tarawa (ESAT) project.[73] The project has involved development of guidelines for sustainable extraction of sand and gravel from Tarawa Lagoon, implementation of a monitoring and evaluation system, and capacity building for government and other stakeholders to ensure sustainable extraction.

In Fiji, the concerns over environmental and social impacts recently led the Government to implement a policy of

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[72] Minnu, S.N. et al. (2020). Comparison of sugarcane bagasse ash with fly ash and slag: An approach towards industrial acceptance of sugar industry waste in cleaner production of cement. *Journal of Cleaner Production*. Vol. 285 https://doi.org/10.1016/j.jclepro.2020.124836

[73] ESAT Implementation of the Environmental Management Plan and Training Consultancy for the ESAT Project: October 14, 2014 to December 2015

gradually ending river gravel extraction by moving to a network of hard-rock quarries.[74] This is no small undertaking and will "require major changes to the business operating environment, which currently incentivises river gravel extraction".[75] As the ACP-EU Development Minerals Programme concluded, "initiatives will be needed to improve access to finance, review royalty and licensing application fees (which currently favour gravel extraction), undertake business process mapping on licensing procedures, create templates for partnerships with iTaukei landowners, and promote domestic investment through a collaboration between the Mineral Resources Department and Investment Fiji". The Mineral Resources Department of Fiji has recently drafted a new set of responsible sourcing guidelines, but these have not yet been officially approved.

The production of low carbon concrete must involve the responsible sourcing of aggregates and to this end, governments and industry operating in the region must be incentivized to source from sustainable sources, within the limits of cost and quality, and carbon emissions constraints. One infrastructure developer claimed, when discussing the use of local rivers for gravel during road building operations in Vanuatu, that aggregate demand for concrete is reportedly not at a scale that is causing environmental problems, perhaps reflecting a lack of awarenss about the scale of extraction and the impacts on rivers. Sand sustainability issues are present in most Pacific Island nations, particularly those that are predominantly comprised of coral atolls, such as Tuvalu, Kiribati, Tonga, and the Marshall Islands.

Potential sources of sustainable aggregate

An understanding of the region's aggregate resources is patchy at best, which has led PRIF to recently commission The University of Queensland's Sustainable Minerals Institute to undertake the Responsible Sourcing of Aggregates in the Pacific project. While the results of study are not yet available, it is possible to identify a number of potentially significant sustainable sources of aggregate.

Fiji and PNG

Fiji has the potential to be a net exporter of sustainably sourced aggregate, providing responsible river extraction guidelines are finalised and effectively implemented, and the country takes significant steps towards developing a network of hard rock quarries, as outlined in the Mineral Resource Department's recent policy. In terms of markets, nearby countries would seem an obvious choice, such as Tuvalu (where the country already exports cement), Kiribati and Tonga. Some of Fiji's largest quarrying companies already export river gravel to nearby countries. Meanwhile, as the third largest island country in the world with diverse geology, PNG has significant potential to export all aggregate types to neighbouring countries, particularly nearby Palau and the Solomon Islands. However, much more information is first need on the location, type and quality of aggregates available.

A long-term option for countries might be to produce ore-sand byproducts from silicate-rich metal ores for both domestic and export markets.[76] Ore sand is relatively new innovation, that adds additional processing circuits to create an additional product to the primary mineral being mined. The ore sand approach offers significant benefits, including reducing the volume of mining waste and creating a valuable product. Global mining giant Vale has already begun commercially producing and selling ore sand at some of its operations in Brazil and there is potential for existing mining operations in Fiji and PNG to do the same, provided the economic and technical analysis is favourable.

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[74] Smith, Robert, Lee, Gary, Tawake, Akuila, Waqavonovono, Epeli, Chambers, Ken, Bukarau, Tevita, Prasad, Christine, Roqica, Donato, Nagata, Isireli, Nainoca, Timaima, Peltovuori, Ville, Devi, Priya, Caniogo, Josefa, Stojkoska, Mihaela, Pakoun, Lacina, Ngonze, Caroline, and Franks, Daniel M. (2018). Baseline Assessment of Development Minerals in Fiji. Development Minerals in Africa, the Caribbean, and the Pacific. Suva, Fiji: United Nations Development Programme.

[75] Ibid. p8

[76] Golev, A., Gallagher, L., Vander Velpen, A., Lynggaard, J.R., Friot, D., Stringer, M., Chuah, S., Arbelaez-Ruiz, D., Mazzinghy, D., Moura, L., Peduzzi, P., Franks, D.M. (2022). Ore-sand: A potential new solution to the mine tailings and global sand sustainability crises. Final Report. Version 1.4 (March 2022). The University of Queensland & University of Geneva; Valenta, R.K., Lèbre, É., Antonio, C., Franks, D.M., Jokovic, V., Micklethwaite, S., Parbhakar-Fox, A., Runge, K., Savinova, E., Segura-Salazar, J. and Stringer, M., (2023). Decarbonisation to drive dramatic increase in mining waste–Options for reduction. Resources, Conservation and Recycling, 190, p.106859; Segura-Salazar, J. and Franks, D.M., (2023). Ore-sand co-production from Newcrest's Cadia East HydroFloat Reject: an exploratory study. The University of Queensland

Nauru

Two other known sources of aggregate with significant reserves should also be considered. The first is Nauru, once renowned for its phosphate mining, which has large reserves of dolomite, an anhydrous carbonate mineral that can be crushed to produce strong, high-quality aggregate suitable for concrete. This dolomite is actually a waste product resulting from decades of phosphate mining and its extraction would have the benefits of creating a valuable product and rehabilitating disturbed land. The Government of Nauru, through the Nauru Rehabilitation Corporation (NRC), plans to export both aggregate and armour rock to other Pacific atoll islands, such as Majuro (Marshall Islands), Kiribati and Tuvalu. However, studies will first be required to fully assess the market potential and, assuming the findings are favourable, a suitably sized barge to transport the aggregate will need to be purchased.[77]

New Caledonia

The second source is SLN's vast stockpile of ferro-nickel slag in New Caledonia, known as 'Le Sland'. The slag is a by-product of nickel processing that can be used as an SCM and also ground into a manufactured sand that can be used as an aggregate.[78] The stockpile is from the nickel mining and processing operations of SLN, a subsidiary of French mining company Eramet. Discussions with the company indicate that there are currently 25 million tonnes of Le Sland stockpiled in New Caledonia and around a million tonnes are added each year. Le Sland has been used in New Caledonia for land reclamation, concrete blocks and other purposes for over 20 years and there is potential to use it in cement manufacture as a supplementary cementitious material. In 2018, SLN started exporting to other Pacific Island nations including Vanuatu where Le Sland was used for soil stabilization and filling geotextile bags for coastal protection. In 2019, 10,000 tonnes were also exported to NSW in Australia for trial purposes where it is currently being tested in concrete mixes blended with crusher dust. Further testing and engagement with Pacific users and standards bodies in the Pacific will be needed to build confidence in Le Sland so that its full range of environmental impacts is better understood. The company has stated that it is not seeking a profit from Le Sland and that the indicative FOB price for putting Le Sland on a barge is USD5 / tonne, while shipping costs to Vanuatu would be an additional USD18 /tonne and USD 14/tonne to Tonga.

6. Recommendations

- **Raise awareness:** There is limited understanding and practical application of sustainable, low carbon cement and concrete options across the Pacific. Engage, raise awareness, and seek feedback with national governments and the region's cement producers, major cement importers, and key infrastructure developers and contractors. This should include engagement with Japanese and other suppliers to the region to determine their ability and willingness to supply low carbon cements such as fly ash and GBFS blends. National workshops or information sessions could provide country specific options, costs and practicalities. A regional workshop would be beneficial to build regional cooperation and lessons from pilots. This could be held in one of the regional hubs such as Fiji or PNG with key stakeholders invited to attend in person or remotely.
- **Capacity building:** Develop a simple capacity building / training program for national governments and the private sector to ensure concrete is used as efficiently as possible. Research suggests that up to 30% efficiency can be lost by improper use, design, and placement of concrete.[79]
- **Short term options:**
    - Ready to go: Of all the short-term options, natural pozzolans like volcanic ash are already available to be used as a SCM in Fiji and could potentially supply a much wider market in Fiji and the Pacific. Volcanic ash is already used by Pacific Cement to produce a 20-25% blended cement, while Tengy uses around 5% at the moment, which could easily be increased with both clinker and emissions reductions benefits.

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[77] Nauru Rehabilitation Corporation (2019). Corporate Plan 2019 to 2025.

[78] Personal communication with SLN employee (10/07/2023). Le Sland is an SCM with properties similar to fly ash but it has not yet been adopted by SCM / cement manufacturers.

[79] United Nations Environment Programme (2018). 'Eco-efficient Cements: Potential Economically Viable Solutions for a Low-CO_2 Cement-based Materials Industry'. UNEP, Paris. https://wedocs.unep.org/20.500.11822/25281 Accessed 06/07/2023

    Direct engagement with both Pacific and Tengy to discuss supply capacity is recommended. In the meantime, further investigation is need to determine full emissions reduction potential, performance parameters and other considerations in the Pacific context.

  - Possible quick adoption: Fly ash and GBFS blends. Of the most suitable low carbon cement options assessed in this scoping study, fly ash and GBFS blends are proven technologies, widely produced, regulated, and sold globally, and could be imported into the Pacific SIDS market relatively quickly as a short-term option. Indeed, two of the region's companies, PNG's Taiheiyo and New Caledonia's Tokuyama, already produce fly ash and GBFS blends at their other operations in Japan and elsewhere and clearly have the expertise and access to key material inputs to supply Pacific SIDS, providing economic drivers exist. Direct engagement with these companies could determine their ability and willingness to supply the Pacific SIDS cement market. However, given the long-term uncertainty over the stocks of these materials, and the inability to source these SCMs locally this solution does not provide long-term mineral security.
  - Possible quick adoption: Limestone, which is locally abundant in at least two of the cement producing countries, Fiji and PNG, should be included in the basket of short-term low carbon cement options, along with fly ash and GBFS cements. Indeed, one of Fiji's cement companies is already taking steps to investigate the use of limestone as a filler to reduce the clinker factor and CO_2 emissions. Further analysis of the range of CO_2 emissions reduction possible should be undertaken.
  - Possible quick adoption: Limestone Calcined Clay (LC3) could be imported from producing countries like India. LC3 has excellent performance parameters and emissions reduction potential. Introducing imported LC3 to the Pacific market would help pave the way to production based on local home-grown resources.

- **Best overall option:** LC3 appears to be the most promising low carbon cement option for Pacific SIDS in the medium term and, indeed, many other countries. Immediate actions should be taken, such as resource assessment to commence necessary implementation steps for producing LC3 in the region, particularly in Fiji where both cement companies have expressed interest in producing it. Of all the low carbon cement options currently proven or under development LC3 has:
  - the greatest potential to reduce emissions at large scale (by up to 40% relative to OPC)
  - excellent performance parameters relative to OPC including strength and durability and as a General Purpose Cement is suitable for all types of infrastructure
  - produces concrete with qualities that make it particularly suitable for marine environments, including having low porosity and reduced chloride ingress (this makes it a good choice for building coastal infrastructure in the Pacific given their increasing exposure to climate change related extreme weather events such as cyclones, flooding and coastal wave inundation)
  - the potential to be produced locally in the region – LC3 can provide resilience in regional cement supply chains, which is particularly important when countries and regions are recovering from natural disasters and imported construction materials are in short supply
  - lower transport related emissions and costs when produced locally (e.g., associated with clinker imports) and creates local quarry and cement manufacturing jobs

  The development of LC3 could occur via support for the Fiji Government's Blue Concrete Initiative, including detailed evaluation of mineral resource reserves, technology transfer, capacity building for government, local industry and universities, and development of new policies and standards.

- **Pilots and trials:** Deeper market analysis and pilot studies can be used to trial production in the Pacific SIDS market as short term options for making low carbon cements and concrete. There are opportunities for partnerships between donors, national governments and the private sector to pilot and trial options. Pilot studies could involve analysis of different blends produced or imported to the Pacific, including their strength and other properties in different environments, embodied and released carbon, economic factors, and others. Trialing the use of alternate aggregates, such as ore-sand, dolomite from Nauru and Le Sland could be undertaken, including undertaking detailed carbon emissions, and environmental, market and supply chain analysis. SLN could be engaged as a partner and co-funder of any program of work investigating the feasibility of widespread uptake of Le Sland. Country-level initiatives like Fiji's Blue Concrete Initiative should be encouraged and supported.

- **Incentives:** Infrastructure programs or governments could specify the use of low carbon concrete in infrastructure tenders or require options to be proposed that meet this objective. Prior to this, however, a period of capacity building would assist so that government, infrastructure program staff, and infrastructure contractors fully understand the advantages and disadvantages of using different types of low carbon cements and concretes and are able to choose the best option for them. This would reduce any potential resistance to new products given poor commercial or technical understanding.[80]
- **Regional guidelines:** Support the development of a region-wide set of sourcing guidelines on aggregate, cement and concrete building on the PRIF-funded Responsible Sourcing of Aggregates study that considers the full range of circumstances and geological conditions of Pacific SIDS.
- **Recycling:** Develop a set of guidelines that can help Pacific SIDS effectively and cheaply recycle concrete from demolished roads, buildings etc. for use as aggregates.
- **Regional partnerships:** Explore partnerships with key actors such as the Pacific Community, The University of Queensland's Sustainable Minerals Institute, Fiji National University and the ACP-EU Development Minerals Programme, implemented by UNDP, who have been working together on sustainable construction materials in the Pacific since 2015; PRIF; the Pacific Resilience Partnership, Resilient Infrastructure Working Group; the Coalition for Disaster Resilient Infrastructure and Accelerating Resilient Infrastructure in SIDS, among others.

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[80] United Nations Environment Programme (2017). 'Eco-efficient Cements: Potential Economically Viable Solutions for a Low-CO_2 Cement-based Materials Industry'. UNEP, Paris. https://wedocs.unep.org/20.500.11822/25281 Accessed 06/07/2023.

ANNEXES

Annex 1. Price of OPC in Select PSIDS

Country	Price in local currency (40kg bag)	Price in US$*
Fiji	FJ$ 18-20	$8-9
Timor-Leste	US$ 5-6	$5-6
Solomon Islands	SI$ 68-74 (low quality from China) SI$119 (from PNG)	$8-8.75 $14
Vanuatu	VUV 1500	$12

* Exchange rates s at 22/08/2023

About us

The Climate Partnership is supporting the Australian Government to integrate climate and disaster resilience in Australia’s aid program in the Pacific.

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