Climate Technology Center Network

Final Activity Report

Substantial GHG emissions reduction in the cement industry by using waste heat recovery combined with mineral carbon capture and utilisation in South Africa

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Executive Summary

Background and Purpose of the Study

The Association of Cementitious Material Producers (ACMP), the industry body for the cement sector in RSA, has been working to achieve its own goal of "reducing emissions by 34% from the 1990 level by 2020," but it needs to implement innovative low carbon technologies for further reducing GHG emissions. Requested by ACMP for technical support and cooperation, the NDE in RSA requested the Climate Technology Centre & Network (CTCN) for technical assistance (TA) in conducting a "*feasibility study for substantial GHG emissions reduction in the cement industry by using waste heat recovery combined with mineral carbon capture and utilisation*" in December 2015.

The purpose of the TA is to conduct a technical and financial feasibility study on substantial GHG emissions reduction in the cement industry in RSA by using a hybrid low carbon technology comprising waste heat recovery (WHR) and mineral carbon capture and utilisation (MCC&U) technology. Furthermore, the TA includes determining the GHG emissions reduction potentials, assessing the cost efficiency of the technologies and marketability of recycled by-products from concrete wastes, and designing a business plan for the project implementation in RSA. This study also considers the possibility of public/international funding for the implementation.

Overview of Hybrid Low Carbon Technology for the Cement Sector

The CTCN TA focuses on a hybrid low carbon technology for the cement industry comprising WHR technology and MCC&U technology utilising specific industrial wastes whilst producing commercially useful by-products as illustrated in Fig. 1.

The WHR component generates electrical power by recovering energy from cement kiln and clinker cooler exhaust gases. It was developed in Japan in the 1980s and well-established and proven WHR technology has been deployed widely in the cement industry. Currently, the electricity price in RSA has been increasing by 2 - 15% annually, and this is expected to rise significantly with the introduction of a carbon tax. In general, when all power generated by WHR is used for cement production, indirect CO_2 emissions are reduced by approximately 30% due to the reduction of purchased power.

The MCC&U component is a system where CO_2 is chemically sequestered using alkaline earth metal components (e.g. Ca and Mg) contained in concrete sludge. Such sludges are generated from ready-mixed concrete plants or secondary concrete product manufacturing plants, and demolished concretes. Carbonates reacted with the kiln exhaust are stable and useful, resulting in safe reduction of CO_2 emissions without the addition of any chemical agents. By-products obtained from this process can also be used as neutralisation and environmental remediation agents to improve the quality of soil and water.

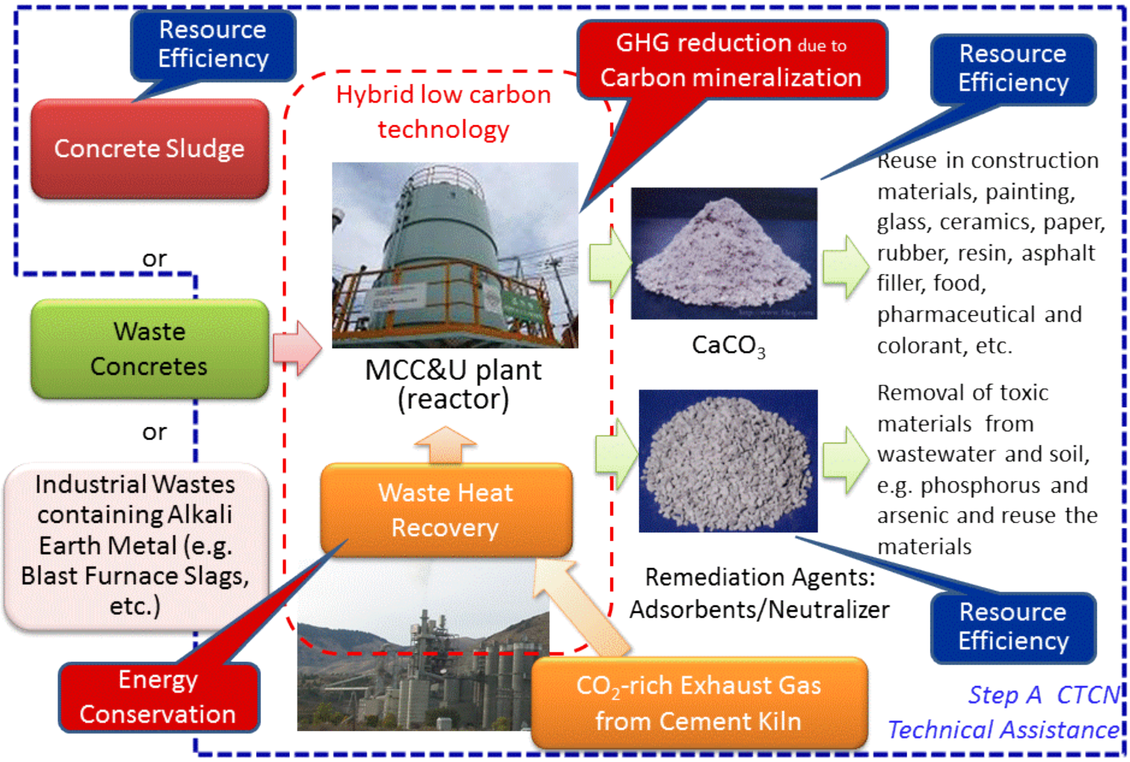

Fig. 1 Proposed hybrid low carbon technology for the cement industry

The hybrid low carbon technology that the RSA government requested to the CTCN not only substantially reduces CO_2 emissions from the cement sector but also facilitates toward achieving zero emissions in the supply chain through the effective utilisation of industrial wastes. Moreover, on-site power generation utilising waste heat can reduce the power consumption from the power grid, while the by-products from MCC reaction can improve the country's environment by applying them as environmental remediation agents, thus presenting the prospects of environmental and economic co-benefits.

Results on WHR installation

In selecting target plants to install WHR facilities in RSA, the following two types of cement plant are firstly considered:

- Full-scale cement plant (3,000 t-clinker/d or more produced by a single rotary kiln) and
- Medium-scale cement plant (nearly 3,000 t-clinker/d produced in total by multiple kilns).

Then, the following further conditions are added to estimate GHG emissions reductions at each target plant on the basis of collected data such as daily clinker production and annual operating hours for all cement plants in ACMP:

- Availability of cooling water (20t per hour or 500t/d is required)
- CO_2 emissions factor of local purchased power.

Table 1 indicates the potential annual power generation and the effective power generation for both water and air-cooled systems at target plans.

Table 1 Potential power generation and CO_2 emissions reduction at target plants

Annual Power Generation/ CO_2 emissions reduction	Cooling system	Unit	Target Plant	
			Type I (Full-scale)	Type II (Medium-scale)
		t/d	more than 3,000 (single kiln)	around 3,000 (multi-kilns)
Power to be Generated	Water	MW	5.4-7.6	3.1-5.1
Effective Power Generation		MW	4.9-6.8	2.8-4.6
Power to be Generated	Air	MW	5.3-7.4	3.0-5.0
Effective Power Generation		MW	4.7-6.7	2.7-4.5
Emission factor for electricity		t-CO_2/MWh	1	
Average annual CO_2 emissions reduction		t-CO_2/yr	37,790	26,910

Results on MCC&U installation

CO_2 is captured in the form of calcium carbonate ($CaCO_3$) by bubbling gas containing CO_2 through an aqueous calcium hydroxide solution. The amount of CO_2 that can be captured as $CaCO_3$ depends on the quantity of calcium contained in the waste.

On the basis of sample analysis of various calcium-containing wastes collected in RSA, Table 2 summarises the possibility for practical usage of input materials for the MCC process. It is measured that wastes such as concrete sludge and lime dust contain a large quantity of calcium compounds in the form (1) indicated in Table 2 which has high reactivity with CO_2. Although the quantity of the wastes is relatively small at each plant, they are identified as calcium sources for the MCC reaction. In the case of recycled fine aggregate produced from demolished concretes, it contains calcium compounds of the form (1) and (2). Although it shows rather lower reactivity, it is also identified as a calcium source.

Table 2 Effective calcium in calcium containing wastes

Industrial Wastes	Available Quantity in RSA	Chemical Component					Total Ca Content (wt%)	Effective Ca Content (wt%)	Remarks
		(1) CaO	(1) $Ca(OH)_2$	(1) CaO-SiO_2	(2) CaO-SiO_2 hydrates	(3) $CaCO_3$			
Cement sludge	None	-	++	+	+	-	-	-	- Less impurities - High reactivity - Pure $CaCO_3$
Mortar/ Concrete sludge	+	-	+	+	+	-	16	8	
Waste concrete	+++	-	+		+	-	16	8	By-product is a mixture of $CaCO_3$ with remediation materials Relatively slow MCC reaction rate
Demolished concrete	++	-	+		+	-	9.2	about 5	
Concrete Saw Dust	+	-	+		+	-	5.9	about 3	
Blast furnace slag	+	-	-	-	+++	-	23.9	≈ 0	Impurities such as heavy metals
Fly ash	++	-	-	-	++	-	2.9-5.5	≈ 0	
Cement kiln dust	++	-	-	-	-	+++	27.4	≈ 0	
Lime dust	+++	+++	-	-	-	+	37	27 - 30	High MCC reactivity
Limestone	++++	-	-	-	-	+++	30.7	≈ 0	

(1) Effective Ca : quick reactivity with CO_2 (2) Partially effective Ca (bound within silica network) : low reactivity
(3) Ineffective Ca (carbonated): less reactivity +++: Large, ++ : Medium, + : Small

Furthermore, since demolished concretes must be treated in accordance with strict environmental regulations in the regions of Johannesburg, Pretoria and West Cape, larger amounts of recycled fine aggregates and its powder containing hydrated cement can be easily collected from recycled aggregate manufacturing plants than from concrete sludges collected from ready-mixed concrete plants. In particular, the powder may be a significant input source for the MCC&U technology and, as it has been treated as a non-recyclable or non-usable material so far, the use of this waste will for the MCC&U technology will not compete with existing recycling businesses. Industrial wastes such as fly ash, blast furnace slag and cement kiln dust generated in RSA, as well as natural resources such as basic rocks (Alkali rocks), are available in significant quantities. However, it is difficult to utilise such materials for the MCC process since their effective calcium contents are extremely low as indicated in Table 2.

Based on the operational data for kiln exhaust gas from cement kilns in RSA and laboratory tests conducted using synthesized gas to estimate the potential reaction volume of CO_2, it would be considered the kiln exhaust gas as well as the boiler exhaust gas can apply to the MCC reactor.

GHG emissions reduction by WHR and MCC&U at target sites

MCC&U technology can reduce GHG emissions in the following two ways:

- Scenario (MCC): CO_2 contained in kiln exhaust gas is captured and fixed in carbonates; and
- Scenario (U): $CaCO_3$ from the MCC reaction is used as U_{mac} at the site where the $CaCO_3$ is produced.

In order to discuss GHG reduction and feasibility of the hybrid technology, Table 3 shows the categories of target site identified in this study and its CO_2 reduction measures.

Table 3 Type of target plant

<table>
<tr><th>Target Site</th><th>Scenario (MCC)</th><th>Scenario (U)</th></tr>
<tr><td>Type I</td><td>Cement plant size is full-scale (kiln capacity of over 3,000 t/d)
30% of concrete sludge from ready-mixed concretes plants and waste concretes from concrete product plants is transported an assumed distance of 200km.</td><td rowspan="4">$CaCO_3$ produced from MCC is added to portland cement as U_{mac} (replacing percentage of the cement)</td></tr>
<tr><td>Type II</td><td>Cement plant size is medium-scale (multi-kilns with the total kiln capacity of approximately 3,000 t/d)
20% of concrete sludge from ready-mixed concretes plants and waste concretes from concrete product plants is transported to the plant up to 100km.</td></tr>
<tr><td>Type II_{add}</td><td>Cement plant size is medium-scale (multi-kilns with the total kiln capacity of approximately 3,000 t/d)
Additional input material such as recycled fine aggregates from demolished concrete near the plant is included</td></tr>
<tr><td>Type III</td><td>Cement plant size is full-scale (kiln capacity of over 3,000 t/d)
Concrete sludges are not available near the plant but an alternative material such as lime dust is used. (Its transport distance is within 50km)</td></tr>
</table>

Table 4 indicates Scope I, II and III emissions of total CO_2 reduction at target sites identified in Table 3 by using the proposed hybrid low carbon technology where (-) means CO_2 reduction and (+) means increased CO_2 emissions from each boundary.

Table 4 Total CO_2 reduction by using proposed hybrid low carbon technology at target site

Emission	Emission Source + emissions - reduction		Target Site (t/yr)		
			Type I 200 Km	Type II 100 Km	Type III 50 Km
Scope I	WHR	(-)	0	0	0
	MCC	(-)	38,400-39,700	32,400-38,000	89,400-100,300
	U	(-)	Depending on volume of cement production (up to 5%)		
Scope II	WHR	(-)	37,800	26,900	37,800
	MCC	(+)	1,700-2,700	1,100-1,800	3,900
Scope III	Transport	(+)	32,600-33,700	12,200-13,100	1,128

CO_2 Emissions Reduction Potential of the Proposed Technology

Tables 5 & 6 indicate the Scope I & II CO_2 reduction potentials for the cement sector in RSA based on WHR installation at 5 potential sites and all concrete sludge and waste concretes generated by the ready-mixed concrete industry in the RSA, together with recycled fine aggregates from two demolished concrete recycling plants and lime dust from each two plants, being utilised as input materials for MCC&U. However, Scope III CO_2 emissions from transport to the plant are not included in the calculation.

Table 5 Scope I, National CO_2 emissions reduction by the hybrid facility

Technology		CO_2 Emissions Reduction Potential (t/yr)	
WHR installation		0	565,340-588,100
MCC&U installation	MCC	224,240-244,200	
	U	341,100-343,900	

Table 6 Scope II, National CO_2 emissions reduction by the hybrid facility

Technology	Power (MWh)			CO_2 Emissions Reduction Potential (t/yr)
	Generated	Consumed	Net	
WHR installations	185,800	18,600	167,200	64,300
MCC&U installation	0	102,900	-102,900	

Note: Emission factor for electricity is 1 t-CO_2/MWh

Scope I CO_2 emissions reduction potential resulting from the proposed hybrid technology is estimated to be 565,340-588,100t/yr and Scope II CO_2 emissions reduction potential to be 64,300t/yr. Assuming an annual cement production is 13 million tonnes in RSA, introducing the hybrid technology is expected to reduce CO_2 emissions from the cement industry by 629,640-652,400t/yr (approximately 7.5% to 7.7% reduction).

Marketability of by-products

By-products derived from the MCC reaction are $CaCO_3$ and environmental remediation agent (ERA). The estimated potential annual production of the by-products in RSA is 494,100 - 528,900 tonnes and 611,000 - 632,000 tonnes, respectively. Although it was firstly assumed that $CaCO_3$ would be utilised as U_{mac} to reduce CO_2 emissions in the cement industry, $CaCO_3$ can be also used as a neutralising agent. Consequently, applications of both $CaCO_3$ and ERA were studied for focused sectors such as mining and wastewater treatment. The TA team conducted a survey of the by-products from MCC on the sources and treatment of acid mine drainage (AMD) and recovery of phosphorous-bearing wastewater from industrial and urban activities in RSA together with University of Cape Town (UCT).

AMD Treatment

Both of the commercial neutralisers for AMD, $Ca(OH)_2$ and $CaCO_3$, are almost entirely domestically sourced products. The current $Ca(OH)_2$ market size for AMD treatment is approximately 69,000 t/yr, with an average market price of R1,800 - 2,500/t. The demand for $Ca(OH)_2$ as a water purification agent is increasing. However, the $Ca(OH)_2$ market size for AMD treatment seems to be limited due to cost constraints but may increase if a competitive ERA price is applied.

On the other hand, the annual market for $CaCO_3$ for AMD treatment is currently very small and is estimated at 70,000 tonnes based on the $CaCO_3$ being utilised at the AMD site with an assumed market price is R500-640/t. Lab-scale testing conducted by the Council for Geoscience suggests that ERA from MCC can be applied to AMD treatment and, furthermore, ERA can be sold in the estimated market in RSA.

Recovery of High Quality Phosphorus

Global phosphorus sources are becoming depleted. Therefore, phosphorus recovery will become increasingly important. According to the market survey by UCT, 164,000t/yr of phosphorus is discharged to the environment and lost in RSA. If ERA is economically used for sewage sludge treatment, the phosphorus can be recovered as resources. However, since the ratio of ERA required to recovered phosphorus from water is approximately 10:1, approximately 1.64 Mt-ERA will be required to completely recover all phosphorus in the county.

Furthermore, as an alternative fertilizer, UCT proposes that there is potential to produce calcium phosphate from diverted urine using the ERA since phosphorus with high concentration is contained in the urine collected at urine diversion dehydration toilets.

Other Applications

High purity $CaCO_3$ generated by the MCC reactor has a wide variety of applications, such as asphalt fillers, fillers for paper and plastic manufacturing processes and so forth. These high-end applications require precision in their specifications, their prices vary and it is difficult to estimate the market size. Since ERA contains minerals such as ettringite it can also be used to remove heavy metals and arsenic from contaminated soil and water as a substitute for $Ca(OH)_2$.

Business Plans

Based on the results of marginal abatement cost (MAC) analysis at the target site indicated in Table 6 and excluding the introduction of carbon tax, the feasibility of business plans are considered. From the viewpoint of economic feasibility, further marketing of both by-products in RSA will be a priority action to support the introduction of the MCC&U technology. On the aspect of the SDGs, the MCC technology is relatively unsophisticated so this may give a new horizon of opportunities to less skilled workers (both male and female)[1] to work in an environment surrounded by the more highly-skilled workforce of cement plants.

Business Plan (Target Site Type I)

The transportation cost of input materials to the MCC&U plant affects the results of the MAC calculation. Therefore, most of the plans could not be feasible unless all $CaCO_3$ is utilised for AMD treatment only, or other applications can be identified that will realise a higher price than for use as $U_{mac.}$ Furthermore, ERA will need to be sold at a very high price (approx. half of commercial $Ca(OH)_2$). As a constant supply of the input materials may not be secured for Target Site Type I conditions, MAC in this study is calculated with limited operation hours. However, if the plant can be operated for 24 hours, the number of reactors and new workforce required for the MCC treatment could be reduced to 16 x 60m^3 reactors and approx. 24 workers accordingly.

Business Plan (Target Site Type II)

Either $CaCO_3$ is utilised for AMD treatment instead of U_{mac} and ERA is sold with at approximately 50% of the price of commercial $Ca(OH)_2$, or both of $CaCO_3$ and ERA is sold at a high price. As with Type I, it is also conservatively assumed that securing a certain level of supply of the input materials at Target Site Type II may be difficult. If the plant can be operated for 24 hours, the number of reactors and new workforce required for the MCC treatment could be reduced to 10 x 60m^3 reactors and approx. 16 workers accordingly.

Business Plan (Target Site Type III)

$CaCO_3$ is utilised for AMD treatment instead to U_{mac} and ERA is sold with a high price (approximately half the price of commercial $Ca(OH)_2$). Unlike Type I and Type II, Target Site Type III has an abundant supply of the input materials (i.e. lime dusts) and 28 x 60m^3 reactors are expected to operate continuously for 24 hours at the plant. This will require approx. 32 workers to be newly employed for the MCC&U technology.

Post CTCN scenario

Prior to the installation of the proposed facility in a cement plant, the following steps will be considered;

- A bench-scale MCC&U reactor will be installed as soon as possible to produce $CaCO_3$ and ERA using concrete sludges and waste concretes generated in RSA and their performance assessed in

[1] South Africa has a long history introducing legislations and guidelines to empower unfairly discriminated citizens of the country including their employment. Some of the prominent legislations include Employment Equity Act of 1998 and Black Economic Empowerment Act of 2003, which protect discriminated citizens (female, black and disabled employees) and introduce systems to attract business owners to employ those employees.

comparison with commercial remediation agents. To achieve this the MCC plant should consist of two 1m^3 reactors of either a mobile type manufactured in Japan, including technical support (approximately USD 500,000), or a stationary type procured from local suppliers.

- In parallel with operator training and the development of by-product applications, R&D on the use of demolished concretes as an alternative input material will be conducted at appropriate research institutes to increase the total CO_2 emissions reduction.

On completion of the bench-scale operation and evaluation of the outcomes, the installation of a pilot hybrid plant with a commercial WHR and small-scale MCC&U plant should be considered as the next step. Other than the WHR turbine, most components for the system can be locally procured and the hybrid WHR and MCC&U plant can be installed by local contractors under supervision by (possibly Japanese) technology experts.

Financial assistance

Regarding the post-CTCN project, innovative technologies such as MCC&U needs a demonstration step in order to convince financiers or any risk takers to scale-up the project to a commercial level. Although stakeholders from the cement sector have shown their strong interest in the MCC&U technology and they agreed the need for a demonstration project, all of them appear hesitant after learning the estimated costs. Facing severe competition and the possible increase in operating costs due to the carbon tax, they commented that they would require a subsidy to move onto the next step. The cement companies may look into both national and international financial assistance. Nationally, they may consult with the Department of Trade and Industry (DTI) which provides financial support and incentives to qualifying companies in various sectors of the economy including manufacturing industries[2]. Internationally, they could approach bilateral or multilateral funds. Within the limited time available, the TA team searched for appropriate bilateral programs to match the cement sector's needs, but without success. Multilateral funds including GCF may be further limited in number, yet may be significant in supporting the deployment of new technologies with the potential for substantial GHG reductions.

The TA Team explored different options for financing the bench-scale and pilot-scale plants. Although the cost for introducing the bench-scale plant for the MCC&U is not excessive (approximately USD 20 to 40 million including training), the investment required to establish a pilot-scale hybrid plant is similar to that of establishing a commercial plant due to the inclusion of a commercial-sized WHR system. It has been identified that the RSA government has one dedicated website called "Government Investment Incentives"[3] which provides a wide range of financial incentives applicable to projects from R&D to commercial-scale plants. Furthermore, the opportunity to secure financial assistance and subsidies for the construction of a mobile bench-scale plant may be improved if the plant is a semi-shared property owned by, for instance, a public entity or research institute, and is accessible to

[2] https://www.thedti.gov.za/financial_assistance/financial_assistance.jsp
[3] http://www.investmentincentives.co.za/

all stakeholders for the benefit of the whole cement sector. In addition, there are various assistance schemes available from international organisations and donors for training.

For the pilot plant, cement companies may secure a mixture of traditional loan-equity finance together with various incentives provided by the government and international organisations. Companies in RSA may approach the Industrial Development Corporation (IDC) to access loans with low-interest rates for manufacturing industries[4]. Among various assistance schemes provided by international organisations, one notable option may be to use the Green Climate Fund (GCF)[5]. GCF is the financing arm of the UNFCCC fostering climate finance investment, including private investment. GCF requires an accredited entity (AE)[6] in order to access to their resources. The most appropriate entity for the proposed hybrid project is considered to be the IDC, which is currently applying to become an AE. The TA team has exchanged some different options with IDC, including the initiation of a new fund, to assist projects such as the one proposed under this TA.

Key Findings

- **WHR installation – drivers and barriers for implementation**

  Cement manufacturers will install a WHR plant if commercial viability proves to be attractive. However, current initial investment costs of WHR remains high and not yet competitive enough in comparison to utility supply. Renewable energy costs are also dropping drastically, and it further places WHR installation into a challenging competitive space. Thus, introducing new financial assistance and incentives (including subsidies) for WHR by the government may help cement manufacturers to choose the WHR option.

- **MCC installation – drivers and barriers for implementation**

  The MCC&U technology could deliver a "paradigm shift" by scaling up the level of the GHG emissions reduction (Goal 13 of SDGs) [7] within both RSA and other countries, while utilisation of industrial wastes containing calcium and improvement of resource efficiency contribute to attaining other SDGs (e.g. Goal 9 and Goal 12).

  However, cement sludge resulting from centrifugal molding is not available in RSA. Therefore, possible methods of generating carbonates using recycled fine aggregates from demolished concrete have been assessed, as well as a method to search for various industrial wastes containing calcium and magnesium components. It will be necessary to conduct further research on the carbonation reaction with such available industrial wastes and trial operation using the bench-scale MCC&U plant.

  Regarding waste treatment in RSA, landfilling is currently generally adopted as the preferable low cost disposal / treatment method. The distance between source sites of concrete sludges and waste concrete, and the full-scale cement plants where MCC&U plant is installed, and the associate logistics

[4] https://www.idc.co.za/

[5] http://www.greenclimate.fund/home

[6] South Africa has currently one AE (the Development Bank of Southern Africa) but it can handle only adaptation-related projects and other is limited in its target project-types (i.e. infrastructure, small and medium entities (SMEs) and municipalities). The proposed hybrid project can fit in to their requirement only if the project is in collaboration with municipalities for the time being.

[7] http://www.un.org/sustainabledevelopment/sustainable-development-goals/

can be major barriers to the increased and effective use of all input materials for the MCC reaction as it impacts the economic viability. Furthermore, a system for collecting and transporting the input materials needs to be established since concrete sludges are generated in the geographically dispersed ready-mixed concrete plants and secondary concrete product manufacturing plants.

In the future, any increase in volumes of "low carbon cement"[8] becoming utilised may lead to a decrease in the availability of effective calcium in concrete wastes for application to the MCC&U, thereby reducing the potential volume of carbon captured. For example, blended cements, where a percentage of the clinker is substituted by natural pozzolana, blast furnace slag or fly ash, is expected to reduce CO_2 emissions. Furthermore, it is recognized that geopolymeric cements[9] are being developed as binders with a significantly lower carbon footprint. Therefore, additional waste streams containing calcium or magnesium will need to be identified in order to preserve the effectiveness of the MCC&U technology.

- **Accounting and reporting for GHG emissions reduction**

Since MCC&U technology is a newly developed innovative technology, there is presently no methodology available for calculating the GHG emissions reduction. It is therefore necessary to urgently develop the methodology in line with domestic regulations, especially if the CO_2 captured by means of MCC&U is to be used to reduce the carbon tax, which will be levied in RSA. The design of a policy framework is also expected so that the methodology developed can be incorporated into the Nationally Determined Contribution (NDC).

- **By-products from MCC**

In order to reduce the GHG marginal abatement cost, it is necessary to sell the by-products. $CaCO_3$ can be utilised as a minor additional constituent for portland cement, as a neutralizing agent for acid mine drainage (AMD) treatment and for other applications. With a view toward commercialisation, environmental remediation agents produced locally using concrete sludges may require onsite assessment for treating AMD at mining sites or for recovering phosphorous at sewage treatment facilities.

Furthermore, common practice, market awareness and acceptance need to be enhanced as in some regions consumers/contractors are reluctant to use ERAs. This can be attributed primarily to a lack of awareness on the side of consumers/ contractors and to a lack of commercialisation of by-products such as environmental remediation agents on the procurement side.

- **Business plans**

Three categories of business plan, all excluding the introduction of carbon tax, are proposed in this study. It was explored that each major segment of WHR and MCC&U equipment excluding a turbine could be procured in RSA. When a pilot hybrid plant is installed at the cement plant produced more than 3,000t-clinker/d, an approximate average investment cost for WHR is estimated between

[8] https://www.wbcsdcement.org/pdf/technology/CSI_ECRA_Technology_Papers_2017.pdf_
[9] http://bze.org.au/rethinking-cement-plan/

US$14 and 20million based on information and construction experiences in several developing countries.

On the aspect of the SDGs (e.g. Goal 5 and Goal 8), the MCC technology is relatively unsophisticated so this may give a new horizon of opportunities to less skilled workers (male and female) to work in an environment surrounded by the more highly-skilled workforce of cement plants. As a result of introducing the MCC&U technology, more than 16 workers at each site will be newly employed.

On the other hand, since one unit of MCC reactors with 60 m^3 is estimated to cost US$1 million, MAC calculation suggests that the project would be feasible only when the by-products can be sold at high price in the market. From the viewpoint of economic feasibility, further marketing of both by-products in RSA will be a priority action to support the introduction of the MCC&U technology. In West Cape, demolished concrete particularly has to be treated in accordance with strict local regulations. The environmental regulations in Johannesburg and Pretoria are generally severe. Therefore, the introduction of MCC&U could be initiated in such areas to encourage appropriate disposal treatment of concrete sludges.

- **Finance assistance**

The CTCN study on the proposed hybrid technology concluded that a potential emissions reduction of approximately 7.5 to 7.7% could be realised from the cement industry in RSA. The MCC&U component is a technology that could cause a "paradigm shift" as a new means to reduce GHG emissions (Goal 13 of SDGs) while contributing to other SDGs (e.g. Goal 9 and Goal 12) and also scale-up the level of the GHG emissions reduction by diffusing the technology not only in RSA but also in other countries. The technology also holds a promising potential to apply to other sectors and further create positive impacts. However, securing finance for new, innovative technologies is always difficult as financiers often perceive them as high-risk investments.

Applying for the UN's Green Climate Fund (GCF) could be one possible solution to mobilise finance for the innovative technologies. GCF is an appropriate funding source to introduce sector-wise measures as well. The MCC&U technology needs to be added to the priority list in the government's "South Africa's Green Climate Fund Strategic Framework" if GCF is to be used for the project implementation.

Founded in 2010, GCF "*aims to catalyze a flow of climate finance to invest in low-emission and climate-resilient development, driving a paradigm shift in the global response to climate change*[10]". CTCN has already paved a linkage with GCF to assist project developers to prepare funding proposals and access to GCF funding. If CTCN can also guide the cement companies an easier pathway to securing financial support to conduct the demonstration project recommended by the TA team may be realised. Consequently, diffusion of the innovative technology will be accelerated toward contributing to meeting the 2°C target.

[10] http://www.greenclimate.fund/who-we-are/about-the-fund

1. Introduction

Background

In 2009, the government of the Republic of South Africa (RSA) pledged that it would reduce its greenhouse gas (GHG) emissions by 34% below business-as-usual levels in 2020 and 42% in 2025. The same goal was announced in both of “National Climate Change Response Policy White Paper” and "National Climate Change Response Green Paper" in 2011. Then, RSA submitted their Nationally Determined Contribution (NDC), which is aimed at reducing GHG emissions by 398 to 614 Mt CO_2 eq. between 2025 and 2030 (assuming an increase of 20 to 82% above the 1990 emissions level, excluding land use, land-use change and forestry (LULUCF)), to the Secretariat of United Nations Framework Convention on Climate Change (UNFCCC) in 2015. The Association of Cementitious Material Producers (ACMP), the industry body for the cement sector in RSA, has been working to achieve its own goal of “reducing emissions by 34% from the 1990 level by 2020,” but it needs to implement innovative low carbon technologies for further reducing GHG emissions. Requested by ACMP for technical support and cooperation, the NDE in RSA requested the Climate Technology Centre & Network (CTCN) [11] for technical assistance (TA) in conducting a “*feasibility study for substantial GHG emissions reduction in the cement industry by using waste heat recovery combined with mineral carbon capture and utilisation*” in December 2015.

A new challenge to the establishment of a low carbon society

The parties of UNFCCC agreed to the Paris Accord in 2016 as follows:

- Limit global temperatures to “well below” 2 °C above pre-industrial levels and “endeavor to limit” the temperature increase even further to 1.5 °C between 2015 and 2030.
- Restrict the amount of greenhouse gases emitted by human activity to the levels that trees, soil and oceans can naturally absorb, beginning at some point between 2050 and 2100.
- Review each country's contribution to cutting emissions every five years, enabling them to address the urgency of the challenge.

Prior to the Paris Accord, IPCC, the IEA[12], RITE and other research institutes[1] have emphasised the critical need for low carbon technologies to achieve the <2 °C target. Fig. 1.1 shows that continuing to deploy energy efficiency and renewable energy will limit the increase in temperature rise but it may end up with a 3 °C increase in 2100[13].

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[11] The CTCN was established in December 2010 within the operation of the UNFCCC for the purpose of accelerating transfer of environmentally-sound technologies for low carbon and climate resilient development.

[12] To be published (Low-carbon technology for the global cement industry)

[13] http://www.rite.or.jp/system/latestanalysis/pdf/E-GlobalCO2Emission_INDCs_20151111.pdf

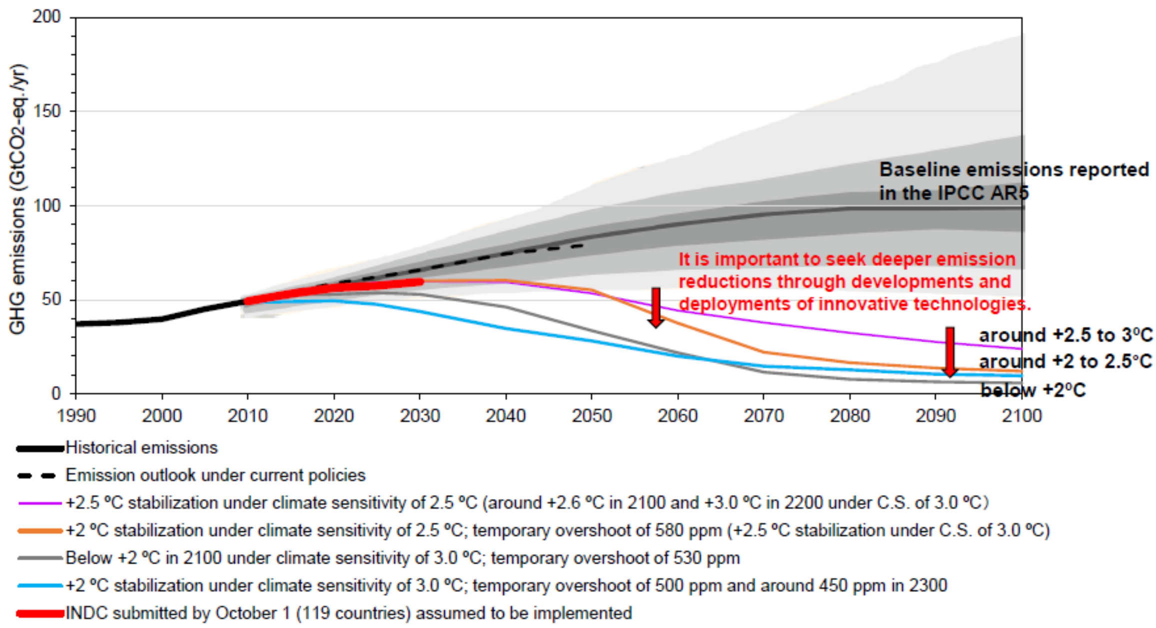

Fig. 1.1 The need for innovative technologies to limit temperature increase

It is apparent that substantial GHG emission reductions are required through development and deployment of innovative technologies. Both reforestation and afforestation are nature's CO_2 capture means, however, the reaction rates are very low. Therefore, CO_2 capture at a much faster rate presents two other options: Carbon Capture and Sequestration and Carbon Capture and Utilisation.

The 4th Innovation for Cool Earth Forum (ICEF)[14], which is an international conference where the world's leading policy makers, businesses and academia can meet and communicate with each other to address climate change through innovation, was held in Tokyo in 2017. One of the key topics discussed was CO_2 utilisation (CO_2U) technologies as shown in Fig. 1.2. The ICEF CO_2U roadmap[15] suggests that one of the near-term challenges over the next 3-10 years is the need for deeper analysis of "concrete and carbonate materials" since a carbonation reaction is thermodynamically proceeded with less Gibbs energy. This presents a market advantage due to the relatively low cost of the product.

The key CO_2U technologies in this field are "conversion to carbonates" and "infusion of CO_2 into building materials".

Currently, the following implementations are published:

- Mineral carbon capture and utilisation (MCC&U)[2]-[6]
- Concrete cured by CO_2 (CarbonCure Technologies, USA[16-17])
- CO_2 storage by concrete products (Kajima Corporation, Chugoku Electric Power Co. and Denki Kagaku Kogyo K.K., Japan[18])

[14] https://www.icef-forum.org/platform/thematic_discussion_topic13_session2.php

[15] http://www.icef-forum.org/platform/upload/CO2U_Roadmap_ICEF2017.pdf

[16] http://info.carboncure.com/white-papers/ready-mixed-technology-trial-results-white-paper

[17] https://www.netl.doe.gov/research/coal/project-information/proj?k=FE0029825r

[18] https://www.kajima.co.jp/english/csr/report/2013/pdf/csr_e_19hp.pdf

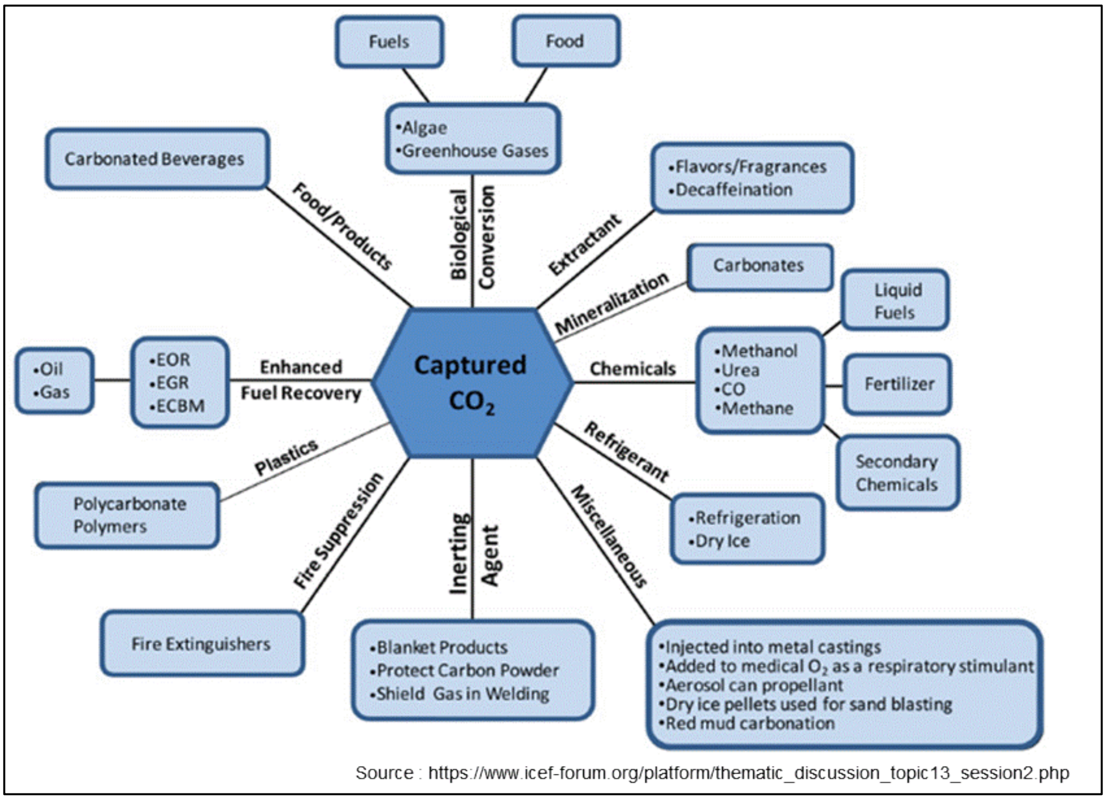

Fig. 1.2 Schematic Illustrating the Uses of CO_2 (CO_2U)[19]

Purpose of the Study

The purpose of the TA is to conduct a technical and financial feasibility study on substantial GHG emissions reduction in the cement industry in RSA by using a hybrid low carbon technology comprising waste heat recovery (WHR) and mineral carbon capture and utilisation (MCC&U) technology. Furthermore, the TA includes determining the GHG emissions reduction potentials, assessing the cost efficiency of the technologies and marketability of recycled by-products from concrete wastes, and designing of a business plan for the project implementation in RSA.

The TA team will maximise the use of previously collected information and assessment results from past and on-going studies on the topic in RSA, especially the results[20] related to WHR from the 2012 feasibility study on low carbon technologies in RSA supported by the Ministry of Economy, Trade and Industry (METI), Japan, and the on-going study with ACMP members and other relevant stakeholders. It is envisaged that some data will be collected by means of questionnaires to the selected cement plants and concrete producers via the ACMP in coordination with the TA Team.

This study also aims at examining the possibility of public/international funding for the implementation of target low carbon technologies of CTCN's TA while a team of Japanese experts cooperates with the South African government and relevant local participants, including cement and concrete companies, in order to realize these initiatives.

[19] http://www.netl.doe.gov/research/coal/carbon-storage/research-and-development/co2-utilisation

[20] http://www.meti.go.jp/meti_lib/report/2013fy/E003499.pdf “Feasibility Study Report on Bilateral Offset Credit Mechanism Project for Clean Energy Technology Diffusion in Cement Sector in the Republic of South Africa (March 2013)”

2. Overview of Hybrid Low Carbon Technology for the Cement Sector

The CTCN TA focuses on a hybrid low carbon technology for the cement industry comprising WHR technology for generating electric power by recovering energy from cement kiln and clinker cooler exhaust gases, and MCC&U technology (a safe CO_2 sequestration method) utilising specific industrial wastes containing Ca or Mg components whilst producing commercially useful by-products as illustrated in Fig. 2.1.

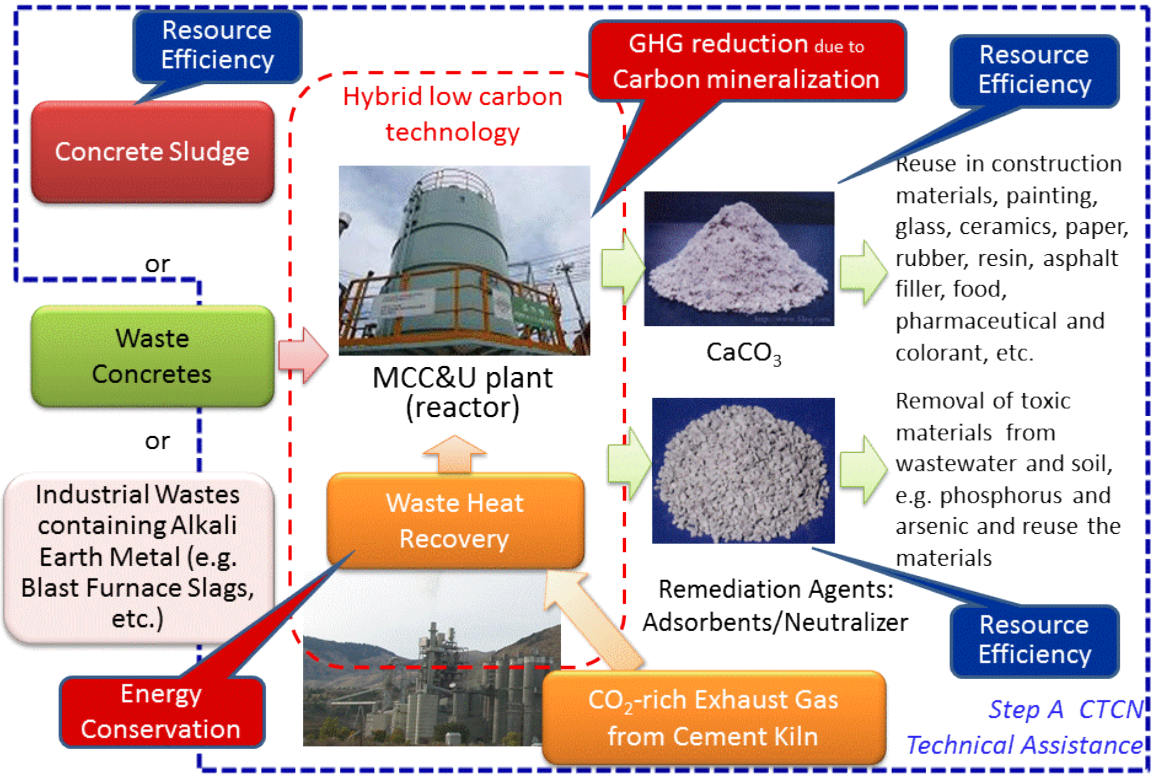

Fig. 2.1 Proposed hybrid low carbon technology for the cement industry

2.1 WHR Technology

The WHR component of the focused technology generates electrical power from waste heat. It was developed in Japan in the 1980s and the first major commercial facility with a capacity of 15 MW has been in operation since 1982. Such steam cycle WHR systems comprise an energy recovery heat exchanger that recovers heat from hot gas streams from the kiln and clinker cooler exhausts via a steam circuit, and a steam turbine to generate power. Although alternative heat transfer fluids have been introduced over recent years, most users still give preference to the conventional steam turbine system, a well established and proven WHR technology that has been deployed widely in the cement industry.

Effective utilisation of thermal energy

A typical thermal energy balance at a cement plant in Japan is illustrated in Fig. 2.2. Thermal energy is consumed for clinker burning and for drying raw materials and coal. The WHR for power generation helps improve the effective thermal energy efficiency up to 80%.

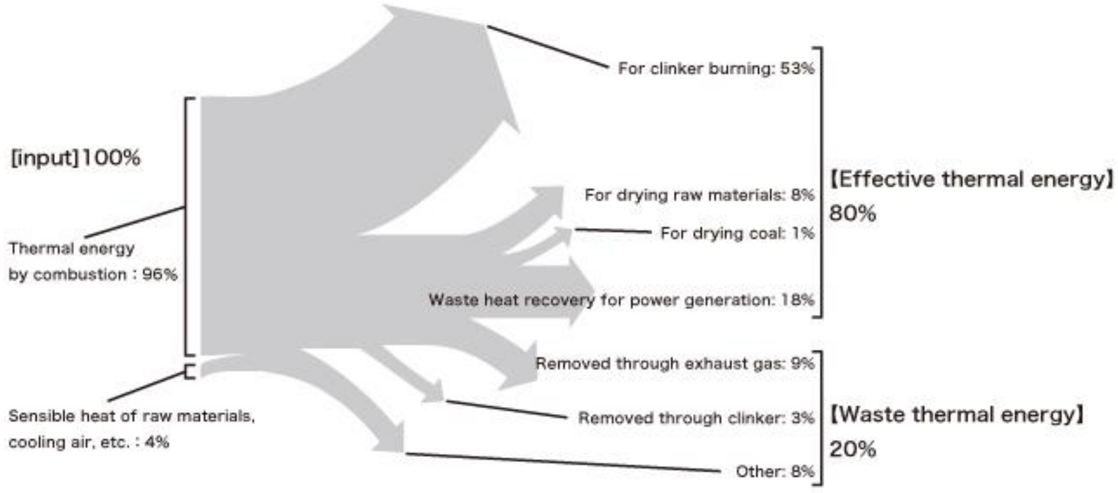

Fig. 2.2 Effective use of thermal energy at the cement plant [21]

The energy used in a cement plant consists of thermal energy and electrical energy, of which about 90% of the total is used as thermal energy in the clinker burning process. In the clinker burning process a large amount of heat is consumed for burning the raw meal at a high temperature of more than 1,450°C to produce clinker. From the thermal consumption during the burning process, around 55% is actually used for clinker burning (calcining), and the rest, 45%, is discharged as sensible heat contained in the preheater exhaust gas and the clinker cooler (Air Quenching Cooler, "AQC") exhaust gas, as well as that carried out by the product clinker and radiation. Of the 45% of heat discharged from both exhaust gases, around 10% is utilised for drying raw materials and coal, and the remainder, approximately 35%, is emitted to the atmosphere through the dust collector systems without any further utilisation of the inherent heat. To utilise the waste heat discharged to the atmosphere a WHR facility is often employed in which a WHR boiler generates steam for electric power generation, thereby recovering the waste heat as electric power as illustrated in Fig. 2.3.

[21] http://www.jcassoc.or.jp/cement/2eng/e_01a.html

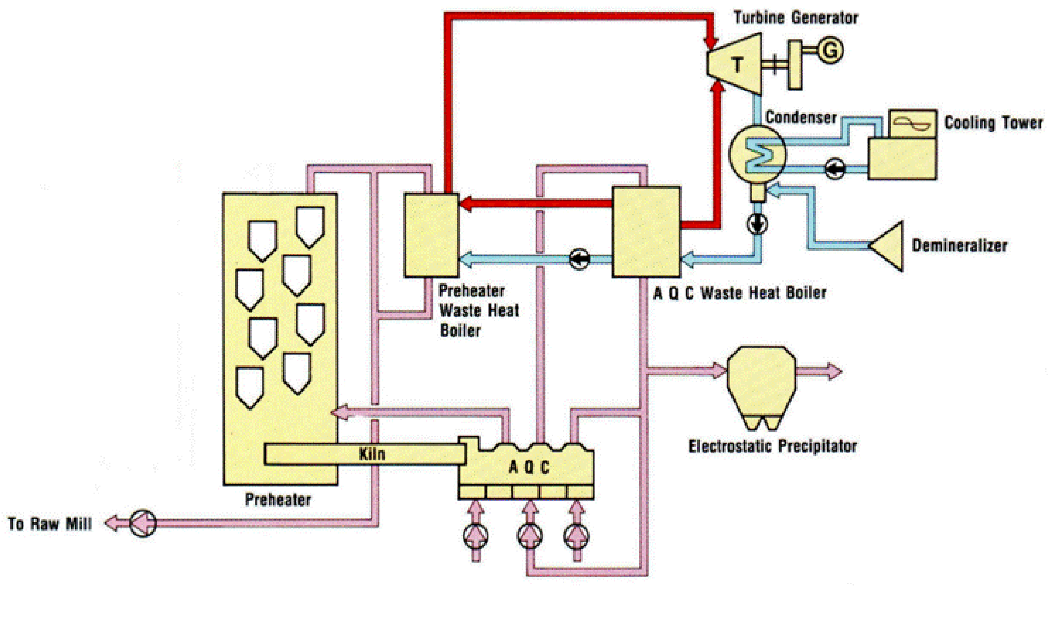

Fig. 2.3 Typical process flow for WHR

More precisely, a major portion of the heat unused in the clinker burning process is emitted to the atmosphere through the kiln pre-heater and the AQC. WHR power generation in a cement plant is a system comprising waste heat recovery boiler, steam turbine with generator, condensing unit, water feeding unit and cooling unit. This system generates electricity to realise an overall effect of recovering otherwise wasted heat energy as electric power. For smaller cement plants with a daily clinker production of generally less than 3,000 tonnes, the WHR installation may not be economically efficient due to the significant construction cost. However, for a cement plant with a sizable overall clinker production (more than 3,000 tonnes per day) such as from multiple kiln installations, it becomes more economically viable to install.

Global WHR installations

In 2014 IFC reported that there are over 850 WHR power installations in the world. In 2012 China had the most with 739 WHR installations, followed by India (26 WHR installations) and Japan (24 installations) as illustrated in Fig. 2.4 (Current installations of WHR in the cement industry[22]). WHR development in China was initially driven by incentives such as tax breaks and Clean Development Mechanism revenues (for emissions reductions from clean energy projects.) The report indicated a strong potential for WHR in selected countries including South Africa as illustrated in Fig. 2.5 (Estimated WHR installations and remaining capacity potential/investment cost[23].) A review of the status of the cement industry and prospects for WHR development in different countries was undertaken to identify emerging markets where WHR power generation may have significant growth potential and strong market drivers.

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[22] http://www.zkg.de/en/artikel/zkg_2011-05_Trends_in_power_generation_from_waste_heat_in_cement_ plants _1185560.html
[23] http://www.iipnetwork.org/62730%20WRH_Report.pdf2

WHR is currently listed in the "Technology Library" compiled by the CTCN[24]. Energy efficiency can be maximised by installing a WHR system next to a cement kiln to generate power for "in-house" consumption in the cement production process by using the recovered waste heat, which would otherwise be simply released into the atmosphere. The use of electricity generated from waste heat for cement production also enables a reduction in indirect CO_2 emissions from the cement plant.

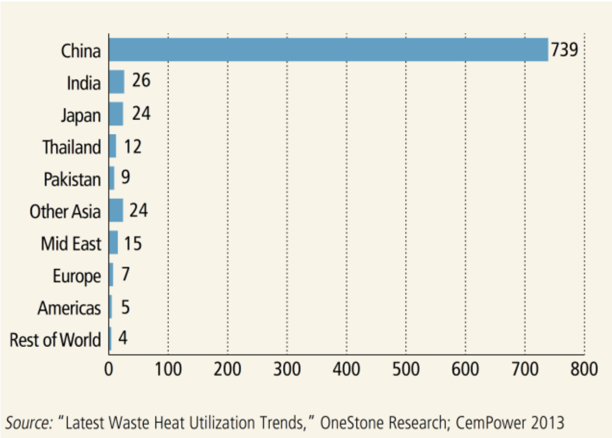

Fig. 2.4 Current installations of WHR in the cement industry

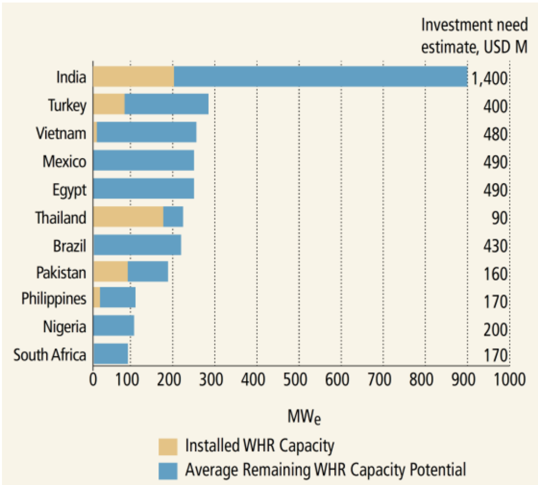

Fig. 2.5 Estimated WHR installations and remaining capacity potential/investment cost

Reduction of Indirect CO_2 emissions

In general, when all power generated by WHR is used for cement production, indirect CO_2 emissions are reduced by approximately 30% due to the reduction of purchased power. However, a detailed CO_2 reduction potential will be calculated taking into consideration the operating conditions once the target plant is identified.

2.2 MCC&U Technology

The MCC&U component of the hybrid technology is a system where CO_2 is chemically sequestered using alkaline earth metal components (e.g. Ca and Mg) contained in concrete sludge. Such sludges are generated from ready-mixed concrete plants or secondary concrete product manufacturing plants, and demolished concretes. Carbonates reacted with the kiln exhaust are stable and useful, resulting in safe reduction of CO_2 emissions without the addition of any chemical agents. By-products obtained from this process can also be used as neutralisation and environmental remediation agents to improve the quality of soil and water.

"MCC" is a technology to capture CO_2 in the form of "carbonates" by using a carbonation reaction with a calcium or magnesium compound. Such calcium/magnesium compounds must be in the form of an oxide or hydroxide. The following simplified chemical equations can be considered:

$CaO/MgO + CO_2 \rightarrow CaCO_3/MgCO_3$ (Equation 1)

or

[24] https://www.ctc-n.org/technology-library/technology-types/technologies/waste-heat-recovery-power-generation

$Ca(OH)_2/Mg(OH)_2 + CO_2 \rightarrow CaCO_3/MgCO_3 + H_2O$ (Equation 2)

However, the reaction speed is extremely slow when CO_2 gas is reacted directly with a solid surface of a calcium/magnesium compound. Therefore, the reaction will be accelerated in a solution by interposing water between CO_2 and the compound, in which case the MCC&U technology does not require pure CO_2 gas but low level CO_2 concentrations. Furthermore, since by-products of carbonates generated from the MCC reaction are industrially useful, it is possible to reduce the sequestration cost for CO_2 by widely promoting the sale and utilisation (U) of the by-products.

Applicable materials for MCC technology

The MCC&U technology requires free calcium (free lime) or free magnesium, which do not bond with silicon. Therefore, types of basic rocks (e.g. wollastonite ($CaSiO_3$) and serpentine $(Mg, Fe)_3Si_2O_5(OH)_4$), concrete wastes (e.g. concrete sludge and demolished concrete) and ferrous and non-ferrous smelting slags can be used in this technology. As concrete sludges contain high levels of $Ca(OH)_2$ they are among the most suitable of materials for use in the MCC&U technology.

- Concrete sludge

Concrete is obtained by a hydration reaction when mixing cement with coarse aggregates, fine aggregates (sand) and an appropriate ratio of water. "Concrete sludge" considered in this report includes concrete wastes generated from ready-mixed concrete plants or secondary concrete product plants, and high alkali slurry containing cement such as washing water for concrete facilities. Four types of the sludge and one used concrete are indicated in the Table 2.1.

Table 2.1 Definition of concrete sludge

Type of Concrete Waste		Compositions			
		Coarse aggregates	Fine aggregates	Cement	Water[1)]
Fresh concrete wastes generated from concrete plants	Concrete Sludge	✓	✓	✓	✓
	Mortar Sludge	-	✓	✓	✓
	Cement Sludge[2)]	-	-	✓	✓
	Waste Concretes[3)]	✓	✓	✓	-
Demolished concrete	Recycled Fine Aggregates	✓	✓	✓	-

Note: 1) Excluding hydrated water
2) Generated from centrifugal moulding
3) Non-standardized concrete products

Sources of the sludge are specified as follows:

- From ready-mixed concrete plants

The surplus concrete remaining in the agitating drum of a ready-mixed concrete vehicle and discharged at the plant is termed "Concrete Sludge".

"Concrete Sludge" after the removal/recovery of coarse aggregates is termed "Mortar Sludge".

- From secondary concrete product manufacturing plants

  Waste concretes generated in the production process or out of specification products mixed with water are termed “Concrete Sludge”.

  Sludge generated during centrifugal molding and containing water and cement (without aggregate) is termed “Cement Sludge” and it is the most appropriate material to apply to the MCC&U technology.

Although there is no precise statistical data, it is well known that a few percent of fresh concrete is wasted as concrete sludge. The concrete sludge consists of cement particles being hydrated, water and aggregates. Currently, most concrete sludges are treated by dewatering, requiring the water to be neutralised and drained into sewers, and the dewatered debris disposed of in landfill sites. Similar treatment is also done in washing water from cleaning of the agitating drum of ready-mixed concrete vehicles and ready-mixed concrete treatment facilities and concrete molds or concrete manufacturing equipment such as mixers since it contains a small amount of cement. It is generally estimated that such treatment costs are as high as 5,000 to 10,000 yen per tonne in Japan.

Since concrete sludge contains basic calcium compounds, such as calcium hydroxide or calcium silicate hydrates ($3CaO{\cdot}2SiO_2{\cdot}4H_2O$), in large quantities, it is possible to produce calcium carbonate from reaction of those calcium contents with CO_2. The reactions throughout the process are represented by the following equations.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad \text{(Equation 3)}$$

and

$$3CaO{\cdot}2SiO_2{\cdot}4H_2O + 3CO_2 \rightarrow 3CaCO_3 + 2SiO_2 + 4H_2O \quad \text{(Equation 4)}$$

Since a change of Gibbs energy is negative in both reactions, each spontaneously proceeds under ordinary environmental conditions.

Concrete sludge containing calcium or magnesium compounds is suitable for MCC&U technology through two straightforward processes: one is to extract the calcium and magnesium contents into water from the concrete sludge, and the other is to feed an exhaust gas containing CO_2 to the extracted water containing calcium and magnesium and then generate calcium and magnesium carbonate.

- Recycled Fine Aggregates

Recycled aggregate produced from the demolition of concrete is also applicable to MCC&U technology due to the relatively high reactivity of the contained calcium (See Table 2.1). Concrete with high compressive strength is the most widely used low-cost construction material and second only to water in total volume consumed annually by society globally. A large volume of concrete is generated as demolition waste during building and infrastructure rehabilitation and replacement. The recycled fine aggregates after removing coarse aggregates contain calcium hydroxide ($Ca(OH)_2$) and calcium silicate hydrates ($3CaO{\cdot}2SiO_2{\cdot}4H_2O$, etc.) which are almost the same as those of concrete sludge. However, the hydration reaction is already completed and the waste concrete solidified.

Compared to the reaction of concrete sludge, it is difficult to separate the aggregates in waste concrete which do not contribute to CO_2 capture and waste concrete also has low reactivity of calcium to CO_2 due to the low free calcium content.

"U" of by-products

- Calcium carbonate

In MCC&U, CO_2 can be mainly captured in the form of calcium carbonate. 440kg of CO_2 can be reacted per tonne of calcium carbonate produced. The calcium carbonate produced using only cement sludge has high purity and fine particle size, and therefore its properties are similar to precipitated calcium carbonate synthesised in chemical plants. The precipitated calcium carbonate is usable for multiple purposes such as paper or plastic packing materials, flue gas desulfurization agents, athletic field line paint and concrete admixtures.

According to JIS R 5210 and SANS 50197-1, up to 5wt% of blast furnace slag, siliceous admixtures, fly ash and limestone containing more than 90wt% of $CaCO_3$ and less than 1wt% of aluminum oxide can be added to portland cement as a "minor additional constituent" (U_{mac}). Since the quality of $CaCO_3$ delivered from MCC&U technology is very high with a purity over 97% and fineness of 1-20 µm as shown in Photo 2.1, calcium carbonate obtained from the MCC reaction can be utilised as U_{mac} of cement.

Photo 2.1 $CaCO_3$ produced from MCC reaction

- Environmental Remediation Agent

On the other hand, the hydrate containing concrete minerals produced from the extraction residue of the solid content of concrete sludge, can be used as an environmental remediation agent (ERA) for water and soil. ERA obtained from cement sludge in this process is called "Phosphorus Adsorbent derived from Concrete Sludge" (PAdeCS) in Japan (See Photo 2.2).

PAdeCS is a powdery granulate and consists mainly of cement hydrates such as calcium hydroxide, calcium silicate, calcium aluminate and ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12}\cdot 26H_2O$). In slurry form PAdeCS has high alkalinity, pH 11-12, and therefore acts in a similar way to industrial neutralisation agents for acid wastewater treatment currently used such as calcium hydroxide ($Ca(OH)_2$) and calcium carbonate ($CaCO_3$). On the other hand, since ettringite has anion-exchange properties, PAdeCS acts as a remediation agent for the removal of hazardous components such as iron, arsenic, lead, phosphorous, cadmium, manganese, zinc, boron and fluorine and also as an algal bloom remover, a deodoriser or decolouriser.

Photo 2.2 ERA produced from MCC reaction

Flow of the MCC&U system

Concrete sludge can be obtained from a secondary concrete product plant. Especially, the most suitable sludge for reuse in the MCC&U technology is “cement sludge” generated from the process where concrete poles, posts or pipes are manufactured using a centrifugal moulding technology. Fig. 2.6 shows a typical flow of the MCC&U system introduced by a concrete product manufacturing company in Japan, where carbon sequestration takes place within the framework of “MCC” and by-products are produced within the framework of “U”. It can be seen that the flow is not complicated and minimal facilities comprising two main reactors and incidental equipment for MCC are required.

Firstly, the calcium extraction reactor is filled with water and mortar/cement sludge and then agitated. It follows that calcium will cause a hydration reaction of unhydrated cement to proceed and calcium ions are extracted in the slurry. When calcium ions are fully extracted the composition of water solution in the reactor can be considered to be almost equal to the saturated calcium hydroxide solution (approximately 700 mg-Ca/L at 25^{o}C). The solid content of the mortar/cement sludge is separated from the slurry using a filter press for solid-liquid separation. When the solid content is naturally dried and then ground for mechanical stabilization, a multi-purpose remediation agent is produced.

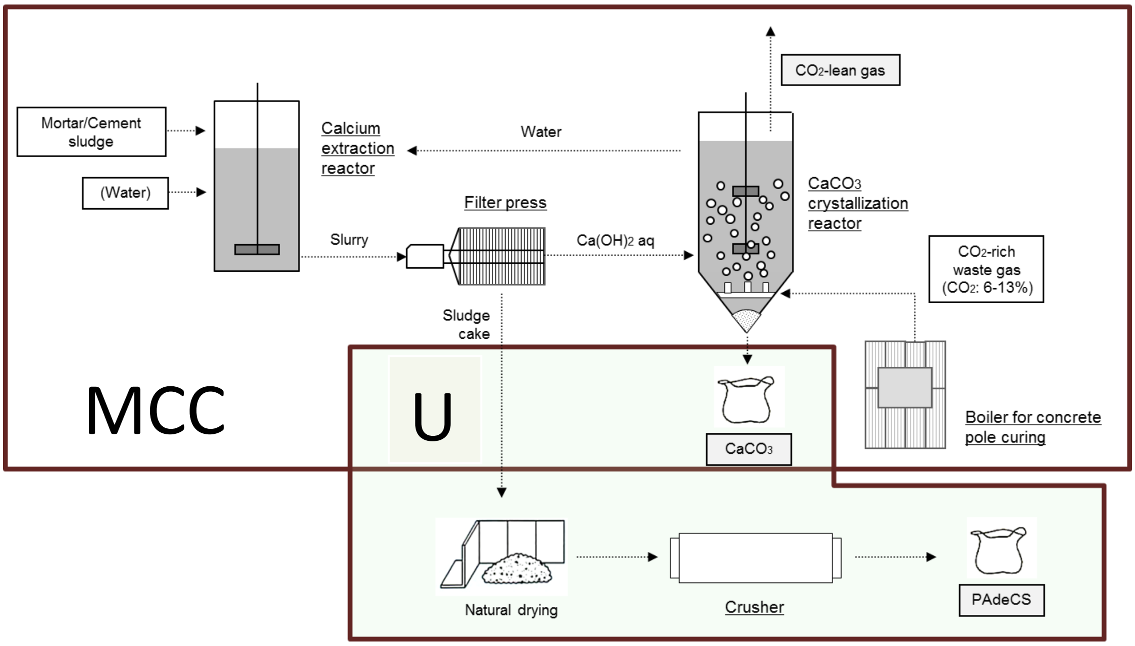

Fig. 2.6 Flow of MCC&U system

Secondly, when exhaust gas from the boiler, or kiln in the case of a cement plant, is fed into a CO_2 crystallisation reactor filled with the water solution, calcium carbonate is immediately precipitated. In the pure Ca-H_2O-CO_2 system, the saturated solubility of the calcium in equilibrium with the exhaust gas with a CO_2 concentration of 10% is approximately 130 mg-Ca/L at 25^{o}C. Since dissolved calcium ions precipitate as calcium carbonate by that difference in solubility, lower CO_2 concentration in the gas phase results in lower saturated solubility of the calcium in the water solution. Therefore, the process does not require high purity CO_2. Then, the calcium carbonate precipitated is screened out from the water solution and the calcium ion concentration of the solution in the CO_2 crystallisation reactor becomes quite low. Therefore, the water used in the CO_2 crystallisation reactor can be recycled in the calcium extraction reactor. By repeating this operation, calcium in the cement sludge can finally be extracted by capturing CO_2 in the form of calcium carbonate.

Important characteristics of this process are that all operations are carried out under room temperature and atmospheric pressure, only water is added without the need for any chemicals, and high purity of CO_2 is not required. Moreover, the calcium carbonate produced in the process is a commercially useful by-product that can be marketed as a valuable industrial chemical, where the purity is more than 97 wt%, its crystal shape is calcite and its particle size is 1 - 20 µm.

3. Results of the Study on Waste Heat Recovery (WHR)

3.1 Selection of target plants for WHR installation

Three integrated cement plants had been visited during the previous feasibility study project conducted in 2012[25]. Therefore updated operating data was obtained from ACMP members. Furthermore, visits to a medium-scale cement plant and a clinker grinding station were conducted during the CTCN TA project to obtain additional operating data and to conduct dialogue with the plant managers and staff.

The full-scale cement plants in RSA are located near either the coal production areas that provide them with their thermal energy source or lime quarries with their raw materials. Fig. 3.1 illustrates the locations of the manufacturing facilities of cement companies in RSA and indicates that integrated cement plants are mostly located far from the main city areas where large volumes of concrete is consumed. However, clinker grinding stations are mostly located near to the main city areas. In order to indentify the target plant for WHR installation, the following factors are considered:

- Size of a plant: WHR installation is commercially viable for larger plants (e.g. more than 3,000t/d clinker production capacity). However, since the WHR installation requires a significant amount of space, any space limitation may make the installation difficult and/or more expensive.
- Supply of cooling water: WHR operation requires a large volume of cooling water. If an adequate supply of water cannot be secured, an air-cooling system for boiler-turbine circle can be adopted but the efficiency of power generation is reduced.
- Purchased power cost: The payback period of the WHR investment is a function of the cost of the purchased power. The higher the cost of the purchased power, the more viable will be the WHR installation.
- Investment cost and installation works: System installation costs including design, engineering, construction, commissioning and training are functions of the installation size, complexity, suppliers and degree of locally procured content. An approximate estimated cost is in the order of US$3,000/kW in this report.

[25] http://www.meti.go.jp/meti_lib/report/2013fy/E003499.pdf "Feasibility Study Report on Bilateral Offset Credit Mechanism Project for Clean Energy Technology Diffusion in Cement Sector in the Republic of South Africa (March 2013)"

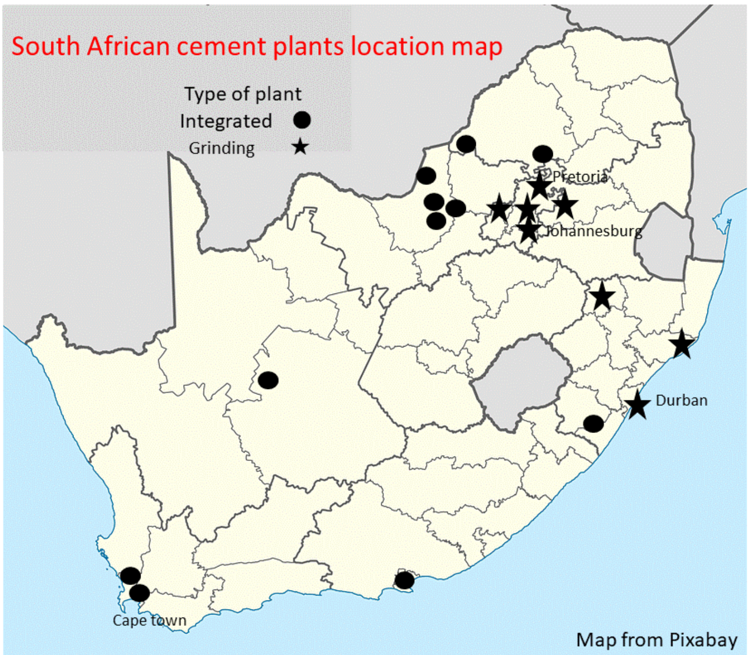

Fig. 3.1 Cement plant installation map

WHR is one of the most effective energy conservation means to reduce energy costs and CO_2 emissions. However, it requires very significant investment and the projected payback period will be a vital consideration in the investment decision making process. Unit power cost and total facility cost may vary depending on the country but, in general, the criteria for a financially feasible WHR investment would be a daily clinker production of 3,000 tonnes or more, excluding incentives.

In selecting target plants to install WHR facilities in RSA, the following two types of cement plant are firstly considered:

- Full-scale cement plant (3,000 t-clinker/d or more produced by a single rotary kiln) and
- Medium-scale cement plant (nearly 3,000 t-clinker/d produced in total by multiple kilns).

Then, the following further conditions are added to estimate GHG emissions reductions at each target plant:

- Availability of cooling water (20t per hour or 500t/d is required)
- CO_2 emissions factor of local purchased power.

3.2 Estimation of GHG reduction at target plants

Target sites for a potential hybrid system were identified as three full-scale cement plants (daily clinker production is more than 3,000 tonnes) and two medium-scale cement plants with multi-kilns (daily clinker production is around 3,000 tonnes). The average indirect CO_2 emissions reduction potential per year were then calculated for each based on collected plant operating data and using WBCSD "The Cement CO_2 and Energy Protocol" ver.3 (CSI protocol)[26].

Based on collected data such as daily clinker production and annual operating hours for all cement plants in ACMP, the estimated power generation is calculated for the two types of target plant. Any

[26] https://www.wbcsdcement.org/pdf/tf1_co2%20protocol%20v3.pdf

missing data, such as the emissions factor for electricity, are determined by referring to published data in RSA. In particular, it should be noted that all calculations assume the introduction of air cooling equipment which is 2.5% less efficient than a water cooling system since sufficient cooling water may not be available at cement plants in the RSA. Fig. 3.2 illustrates the range of temperatures from an air quench clinker cooler (AQC) and the pre-heater (PH) used to estimate the potential power generation. A temperature of between 200°C to 300°C can be expected from the AQC and between 300°C to 420°C from the pre-heater for a typical 3,000 t/d kiln.

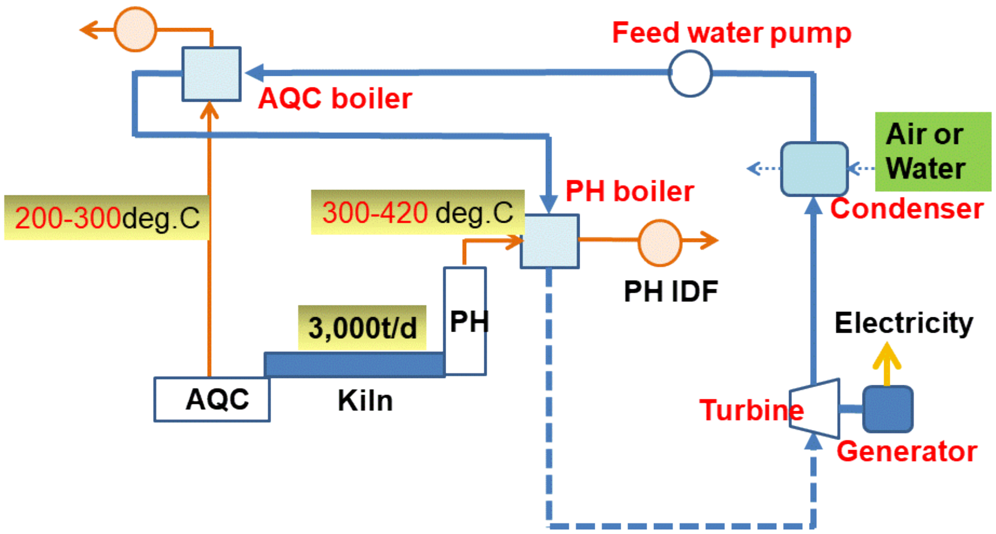

Fig. 3.2 Temperature of waste heat from AQC and PH

Assuming an emission factor of 1t-CO_2 per MWh, an average CO_2 emissions reduction per year at each target plant is calculated from the effective power generation by subtracting the power consumed within the WHR plant operation from the total power generated. The consumed power within the WHR plant is also assumed in this report to be approximately 10% of the power generation. Table 3.1 indicates the potential annual power generation and the effective power generation for both water and air-cooled systems at target plans. The average indirect CO_2 emissions reductions become:

- Type I (Full-scale plant): 37,790 t-CO_2 for air cooling system
- Type II (Medium-scale plant with multi-kilns): 26,910 t-CO_2 for air cooling system

Table 3.1 Potential power generation and CO_2 emissions reduction at target plant

Annual Power Generation/ CO_2 emissions reduction	Cooling system	Unit	Type I (Full-scale)	Type II (Medium-scale)
		t/d	more than 3,000 (single kiln)	around 3,000 (multi-kilns)
Power to be Generated	Water	MW	5.4-7.6	3.1-5.1
Effective Power Generation		MW	4.9-6.8	2.8-4.6
Power to be Generated	Air	MW	5.3-7.4	3.0-5.0
Effective Power Generation		MW	4.7-6.7	2.7-4.5
Emission factor for electricity		t-CO_2/MWh	1	
Average annual CO_2 emissions reduction		t-CO_2/yr	37,790	26,910

4. Results of the Study on Mineral Carbon Capture and Utilisation (MCC&U)

4.1 Sample analysis of various industry wastes containing Ca

As described in section 2,2, the MCC&U technology requires a large quantity of basic calcium or magnesium-containing materials. The use of wastes containing calcium would be a key target input material because there is little availability for wastes containing magnesium. Fig. 4.1 illustrates various wastes containing calcium vs. their reactivity with CO_2.

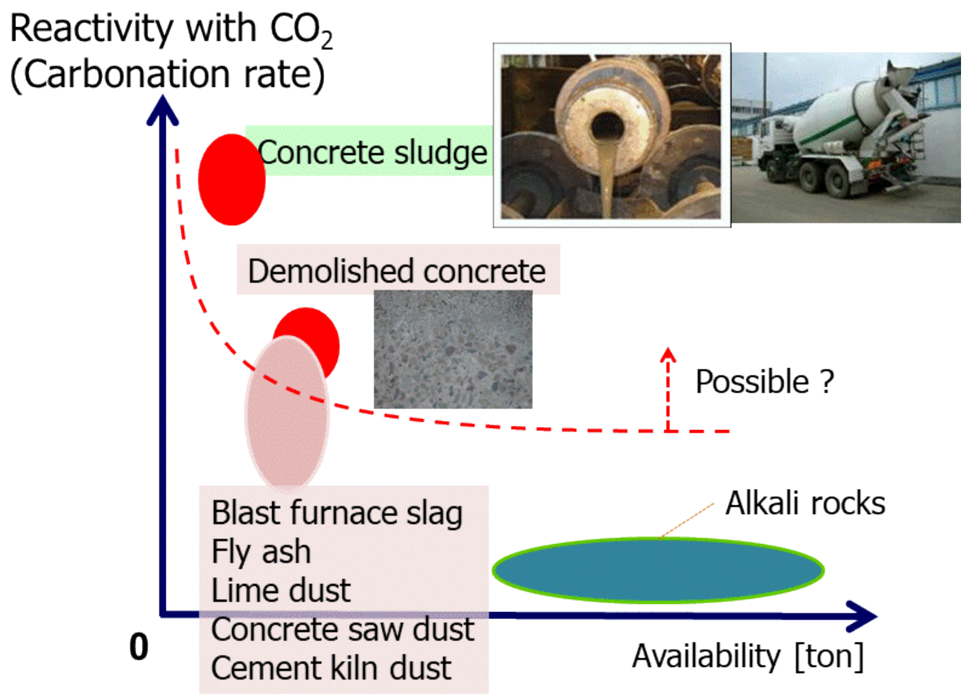

Fig. 4.1 Availability of wastes including calcium vs. Reactivity with CO_2

In the MCC reaction, the basic waste containing calcium is firstly mixed with water and an aqueous solution of calcium hydroxide is then obtained after solid-liquid separation. CO_2 is captured in the form of calcium carbonate ($CaCO_3$) by bubbling gas containing CO_2 through the aqueous calcium hydroxide solution.

The amount of CO_2 that can be captured as $CaCO_3$ depends on the quantity of calcium contained in the waste. Therefore, the waste with higher calcium content and higher available quantities is more desirable. If a large volume of the waste can be treated at one site it is expected that the economy of scale will result in improved economic efficiency of the MCC&U plant.

Since the most desirable alkali calcium compounds are easily extracted into water, the following chemical form of calcium contained is also important;

(1) Alkali calcium compounds such as CaO, $Ca(OH)_2$, CaO-SiO_2 are most suitable as a calcium source for the MCC&U technology because the calcium dissolution rate into water is very fast.

(2) CaO-SiO_2 hydrates are alkaline calcium compounds; however calcium extraction and carbonation are more difficult because the calcium contained is firmly bound in the SiO_2 network as illustrated in Fig.4.2. Therefore, the overall carbonation reaction becomes very slow and economic feasibility will be decreased. This implies that a two-step reaction process, which

produces pure $CaCO_3$ is impossible, but a single-step direct carbonation reaction can be only carried out to produce a mixture of $CaCO_3$ and ERA.

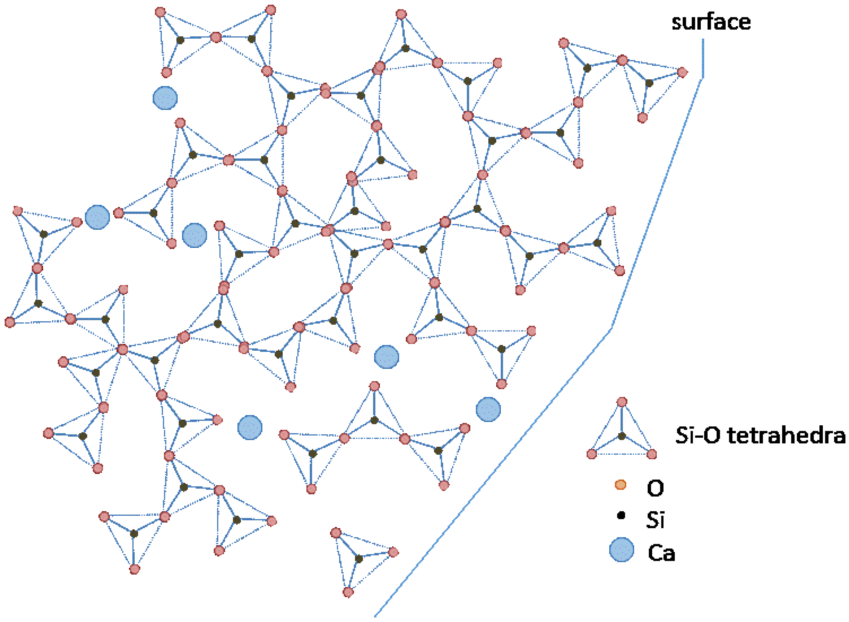

Fig. 4.2 Calcium bound in SiO_2 network in fly ash and slag

(3) In the case of $CaCO_3$, calcium is already carbonated and further reaction with CO_2 is impossible.

On the basis of sample analysis of various calcium-containing wastes collected in RSA, Table 4.1 summarises the possibility for practical usage of input materials for the MCC process. It is measured that wastes such as concrete sludge and lime dust contain a large quantity of calcium compound in the form of (1) which has high reactivity with CO_2. Although the quantity of the wastes is relatively small at each plant, they are identified as calcium sources for the MCC reaction. In the case of recycled fine aggregate produced from demolished concretes, it contains calcium compounds of (1) and (2). Although it shows rather lower reactivity, it is also identified as a calcium source. Furthermore, since demolished concretes must be treated in accordance with strict environmental regulations in the regions of Johannesburg, Pretoria and West Cape, larger amounts of recycled fine aggregates and its powder containing hydrated cement can be easily collected from recycled aggregate manufacturing plants than from concrete sludges collected from ready-mixed concrete plants.

On the other hand, industrial wastes such as fly ash, blast furnace slag and cement kiln dust generated in RSA, as well as natural resources such as basic rocks (Alkali rocks), are available in significant quantities. However, it is difficult to utilise such materials for the MCC process since the calcium compounds of (2) or (3) are the main components as indicated in Table 4.1.

Table 4.1 Effective calcium in industrial wastes containing calcium

Industrial Wastes	Available Quantity in RSA	Chemical Component					Total Ca Content (wt%)	Effective Ca Content (wt%)	Remarks
		(1) CaO	(1) $Ca(OH)_2$	(1) $CaO-SiO_2$	(2) $CaO-SiO_2$ hydrates	(3) $CaCO_3$			
Cement sludge	None	-	++	+	+	-	-	-	- Less impurities - High reactivity - Pure $CaCO_3$
Mortar/ Concrete sludge	+	-	+	+	+	-	16	8	
Waste concrete	+++	-	+		+	-	16	8	By-product is a mixture of $CaCO_3$ with remediation materials Relatively slow MCC reaction rate
Demolished concrete	++	-	+		+	-	9.2	about 5	
Concrete Saw Dust	+	-	+		+	-	5.9	about 3	
Blast furnace slag	+	-	-	-	+++	-	23.9	≈ 0	Impurities such as heavy metals
Fly ash	++	-	-	-	++	-	2.9-5.5	≈ 0	
Cement kiln dust	++	-	-	-	-	+++	27.4	≈ 0	
Lime dust	+++	+++	-	-	-	+	37	27 - 30	High MCC reactivity
Limestone	++++	-	-	-	-	+++	30.7	≈ 0	

(1) Effective Ca : quick reactivity with CO_2 (2) Partially effective Ca (bound within silica network) : low reactivity
(3) Ineffective Ca (carbonated): less reactivity +++: Large, ++ : Medium, + : Small

Photos 4.1 - 4.5 show typical potential input materials for MCC&U in RSA.

- Concrete sludge generated from ready-mixed concrete plant

Photo 4.1 Solid portion of the concrete sludge in the storage pond

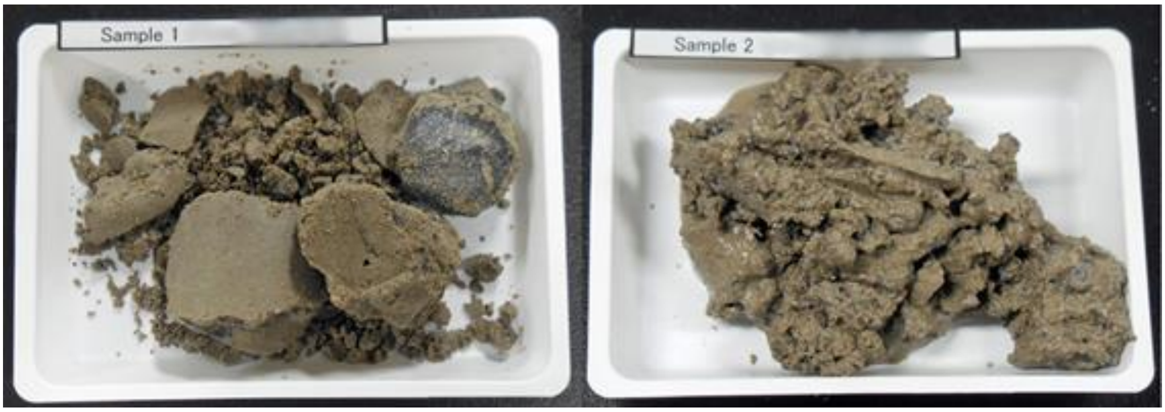

Photo 4.2 Collected solid samples

The Ca content in the concrete sludge samples collected at two plants was measured and found to be approximately 16.0%. The concrete sludge contains a large amount of effective calcium for the MCC&U because it contains unreacted cement compounds. Therefore, the concrete sludge is considered to be a promising calcium source for the MCC&U technology. In the collected liquid samples, calcium was also contained at high concentration. Although this liquid can be used to capture CO_2, the total amount of calcium contained is much lower compared to calcium in the solid waste. Therefore, solid waste utilisation is preferable to capture a large amount of CO_2.

- Waste concrete generated from secondary concrete product plant

Photo 4.3 Scrap material deposition and sampling site

Since RSA is the 30th driest country in the world, secondary concrete products are mostly moulded with a low water-cement ratio. This results in difficulties in obtaining cement sludges compared to the centrifugal moulding processes used in Japan. The Ca contents of the waste concrete samples collected at one plant were measured and found to be 10.9 - 21.0wt%. The chemical forms of the contained calcium are hydrated cement compounds, such as $Ca(OH)_2$ and calcium silicate-hydrates etc. Although the reactivity of the contained calcium is lower than that of concrete sludge, the waste concrete also would be a promising calcium source for MCC&U technology.

- Recycled fine aggregates produced from demolished concretes

Photo 4.4 Crushed fragments of demolished concrete

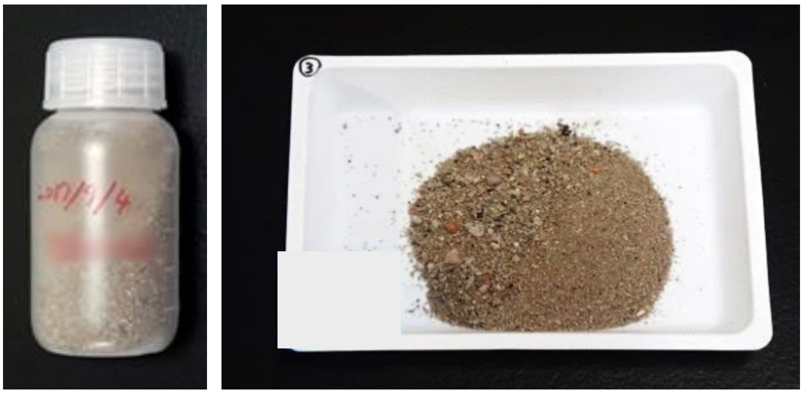

Photo 4.5 Recycled fine aggregates

Alternative waste samples containing calcium indicated in Table 4.1 were also analysed. The analyses showed both the recycled fine aggregates produced from demolished concrete and lime dust generated from a lime plant to contain a high content of effective calcium and are therefore considered to be potential input materials for the MCC reaction.

The strict environmental regulations in the West Cape area require demolished concrete to be properly treated and aggregates contained in the concrete recycled. However, the availability of demolished concrete from other regions should be considered. Since demolished concrete contains impurities such as crushed bricks and natural stones, further R&D is required to assess its suitability for utilisation in the MCC&U technology.

In summary, TA study confirmed that cement sludge utilised in Japan is not available in RSA.

However, potential input materials for MCC&U in RSA are concrete sludges generated from ready-mixed concrete plants and waste concrete generated from secondary concrete product plants. Furthermore, it is found that alternative industrial wastes containing calcium are available from other sectors in the vicinity of the potential hybrid system site. These are recycled fine aggregate and lime dust.

4.2 Material flow of potential input materials

Based on the outcome described in section 4.1, it is concluded that concrete sludges, waste concretes, recycled fine aggregates and lime dust are considered as high potential input materials for the MCC&U plant. A material flow for MCC&U at each concrete plant was calculated and the volume of CO_2 capture in the MCC reactor estimated. The CO_2 reduction by MCC reaction is estimated from the annual carbon captured quantity illustrated in Figs. 4.3 - 4.6.

The production volume of by-products from the industrial wastes containing calcium is illustrated. Although there are many uses of $CaCO_3$ in other sectors, U_{mac} for cement production is focused upon since CO_2 emissions from the cement industry can be reduced as a result of the addition of up to 5wt% of $CaCO_3$ to portland cement as a "minor additional constituent".

- Concrete sludge from ready-mixed concrete plants

Fig. 4.3 illustrates a schematic mass flow for CO_2 reduction due to the generation of $CaCO_3$ and other by-products at a ready-mixed cement plant with 100,000 m^3 annual production. Between 1,500 and 2,350 tonnes of concrete sludge will be generated at the plant annually based on a concrete density of 2.35t/m^3 and mean waste concrete generation of 0.64 - 1% of ready-mixed concrete production. The quantity of carbon captured annually and generation of by-products are calculated based on 16wt% of calcium measured in the sludge and assuming the following conditions:

1) Annual operation of 300 days
2) Approximately half of the contained calcium (8wt%) is utilised in the MCC reaction and the effective calcium for the MCC reaction is estimated at 120 to 188 t/yr
3) Weight ratio of aggregates contained in the concrete sludge is 0.5 and
4) Coarse aggregates can be reused for appropriate applications or sold.

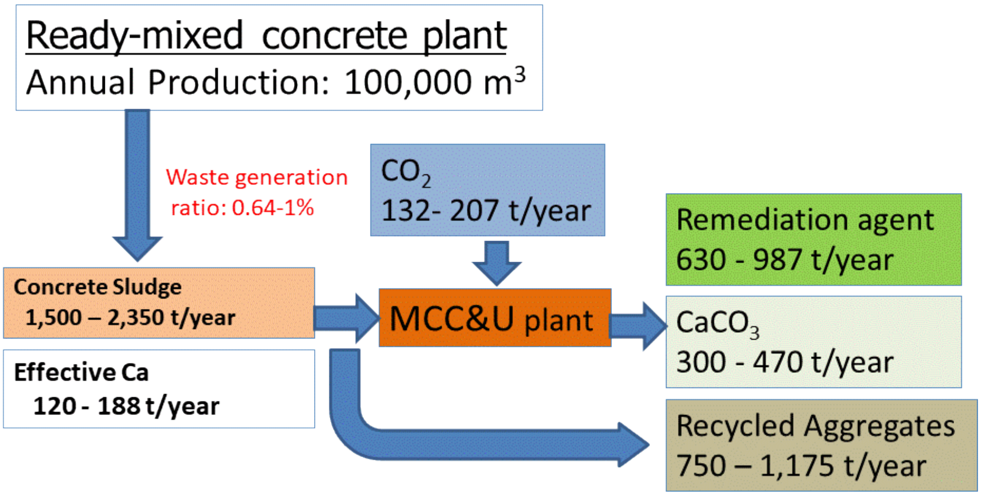

Fig. 4.3 CO_2 captured by MCC&U at a typical ready-mixed concrete plant

- Wastes concrete from concrete product manufacturing plant

Fig. 4.4 illustrates a schematic mass flow for CO_2 reduction due to generation of $CaCO_3$ and other by-products at a concrete product manufacturing plant with 100,000m^3 annual production and using similar assumptions to those for the ready-mixed concrete plant.

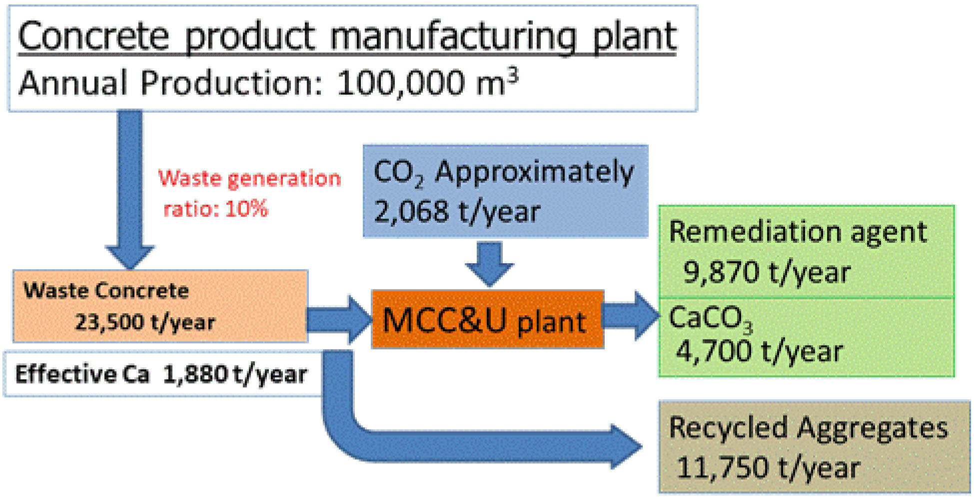

Fig. 4.4 CO_2 captured by MCC&U at a typical concrete product plant

- Recycled aggregate manufacturing plants

It is assumed that the average ratio of concrete to bricks and natural stone in concrete demolition waste is roughly 50:50. Based on a sample analysis of the fine aggregates, the calcium content is measured as 3.0 wt% and of this it is assumed that approximately half can be considered effective calcium. Therefore, the annual available quantity of effective calcium can be calculated.

Fig.4.5 illustrates a material flow of recycled coarse and fine aggregates at recycling plant handling an estimated 100,000 t/yr demolished concrete and the estimated CO_2 that can be captured by MCC&U.

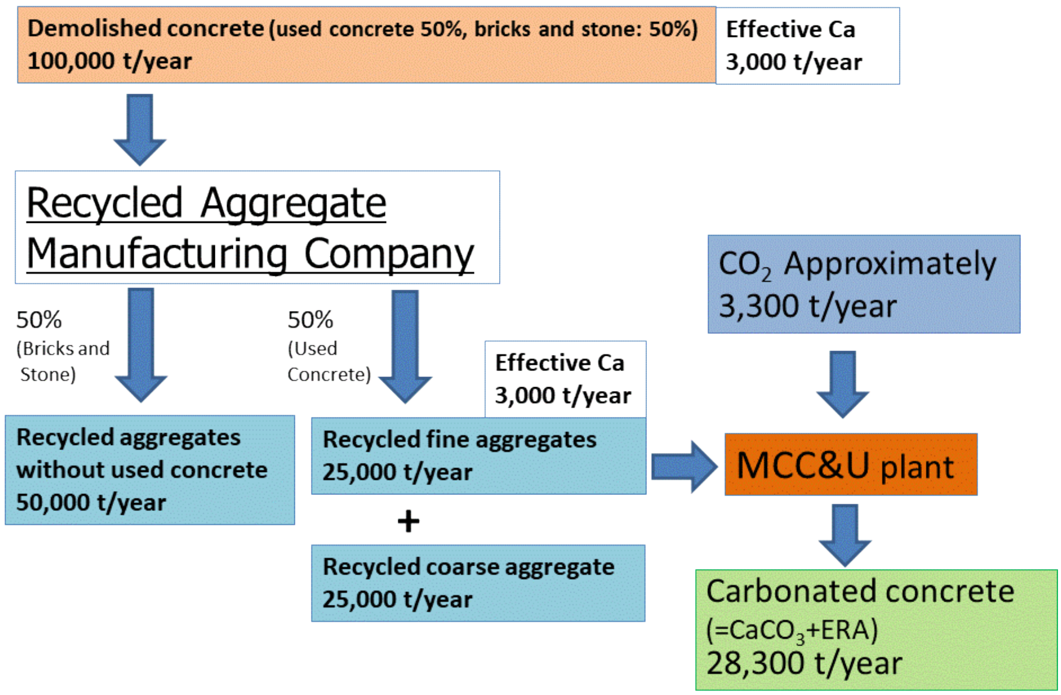

Fig. 4.5 CO_2 captured by MCC&U at the recycled aggregate manufacturing plant

- Lime dust from Lime Plant

Laboratory analysis of collected samples showed the effective calcium content in lime dust to be between 26.9 and 30.2 wt%. Therefore the potential quantity of CO_2 to be reacted with the effective calcium can be calculated and the high purity $CaCO_3$ produced can be estimated. In parallel with carbonation, residuals after solid-liquid separation process generate low purity (around 50wt%) $CaCO_3$. This by-product is dissolution residue of lime dust, and mainly derived from impurities and unreacted $CaCO_3$ in limestone used in the lime plant. Fig. 4.6 illustrates a schematic mass flow for lime dust and CO_2 captured by MCC&U at the lime plant from which annual generation of lime dust is estimated to be 151,000 t.

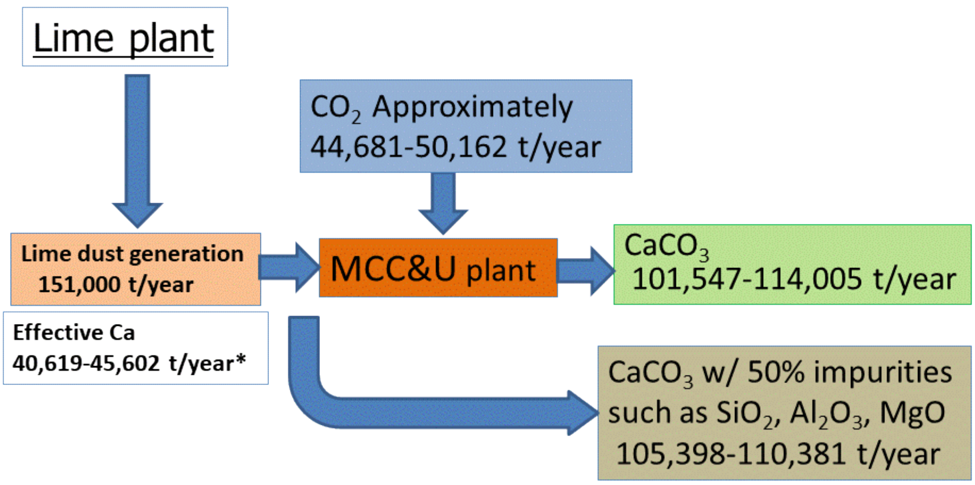

Fig. 4.6 CO_2 captured by MCC&U at the lime plant

4.3 MCC reaction with cement kiln exhaust gas

Based on updated data collected from cement companies of ACMP, Table 4.2 shows the operational data for kiln exhaust gas from cement kilns in RSA. Under the following technical conditions and without CO_2 concentration of the exhaust gas, it can be considered that both the kiln exhaust gas and the boiler exhaust gas can be applied to the MCC reactor. Therefore, laboratory tests were conducted using synthesized gas to estimate the potential reaction volume of CO_2.

Table 4.2 Properties of exhaust gas from cement kiln in RSA

Properties		Measured value	Remarks
Temperatures of exhaust gas at the inlet of a stack		70-190°C	Raw mill - ON
		105-200°C	Raw mill - OFF
Composition of kiln exhaust gas	CO_2	16-24%	Normally less than 20% at stack but depending on the operation control.
	O_2	6 - 11%	Depends on the operation control.
	NO_x	180 - 750ppm	Depends on the combustion condition.
	SO_x	less than 80ppm	SO_x from cement kiln exhaust gas is generally low because desulfurization takes place in the NSP process but depends on the Sulphur in raw materials and fuel.
Gas volume of exhaust gas at the outlet		153,200-206,200 Nm^3/h	Generally proportional to clinker production quantity.

- Temperature of exhaust gas

When feeding the exhaust gas from the target cement kiln through the WHR facility to the MCC&U plant, it is necessary that the exhaust gas is at an optimum and sufficiently low temperature to prevent boiling of the water in the reactor. Although the temperature of the exhaust gas from the cement kiln stack is quite low, it is technically difficult to feed the gas to the MCC&U plant directly from the stack without additional power consumption.

However, all cement plants are generally equipped with either an electrostatic precipitator (EP) or a bagfilter system to remove dust from the gas, and the temperature of the gas leaving the EP and the bagfilter is expected to be around 100°C illustrated in Fig. 4.7. Therefore, it is recommended that such equipment is operated to ensure that the kiln exhaust gas fed to MCC&U plant is at the appropriate low temperature.

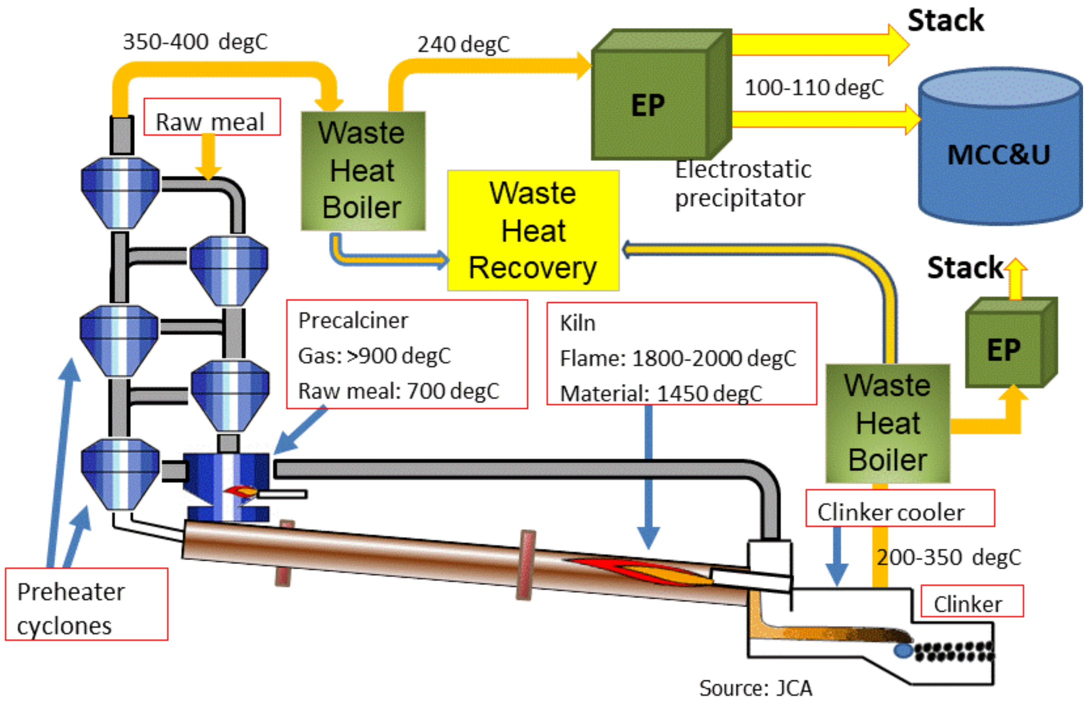

Fig. 4.7 Kiln exhaust gas flow temperature

- Effect of CO_2 Concentration on MCC Reaction

CO_2 concentration in the kiln exhaust gas is between 16 and 24%, roughly two times higher than that in the exhaust gas fed from the waste heat boiler at the MCC&U plant in Japan. The CO_2 concentration affects the dissolution rate of gaseous CO_2 into the basic solution obtained by calcium extraction from wastes and the solubility of calcium in the solution. Since a high CO_2 concentration makes a rapid MCC reaction possible, it is very important to obtain a high CO_2 concentration within the exhaust gas. Therefore, the following laboratory study was conducted to confirm the carbonation reaction with CO_2. Firstly, a saturated $Ca(OH)_2$ solution was prepared as a reference solution for concrete sludge. Then, CO_2 gas with different concentrations from 10% to 30% was introduced into the solution.

The pH variation of the solution over time with different CO_2 concentration is illustrated in Fig. 4.8. The higher CO_2 concentration in the gas phase accelerated the dissolution rate of CO_2 into solution, and resulted in a faster decrease in solution pH. The pH decreases along with the calcium removal from the solution by $CaCO_3$ precipitation (MCC reaction). Thus, this result indicated that the MCC reaction could be completed within a shorter period of time using the CO_2 rich-exhaust gas.

The calcium concentration in solution over time before and after CO_2 gas bubbling is illustrated in Fig. 4.9. Dissolved calcium was removed from the solution by $CaCO_3$ precipitation. This result indicated that the final calcium concentration in the solution was not so affected by the CO_2 concentration in the studied range.

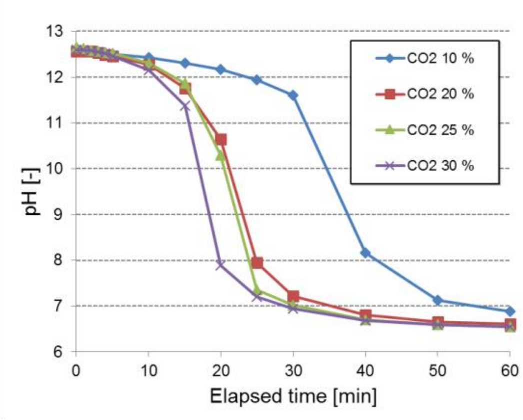

Fig. 4.8 pH variation over time

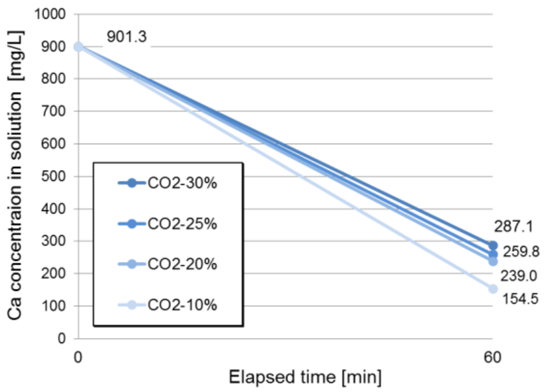

Fig. 4.9 Calcium concentration over time

These results indicate that exhaust gases with different CO_2 concentrations could be utilised for the MCC reaction (recovery of $CaCO_3$). However, a higher CO_2 gas concentration in the exhaust gas is preferable for MCC reaction rate acceleration. Furthermore, total feed volume of the exhaust gas can be reduced with higher CO_2 concentration.

- Effect of NO_x in exhaust gas on MCC Reaction

180-750 ppm of NO_x in the cement kiln exhaust gas is dissolved in the solution during the procedure. However, since it cannot be removed as a solid due to high solubility of nitrates, the concentration of NO_x when reusing water in the reactor could become a technical issue.

- Effect of SO_x in exhaust gas on MCC Reaction

It is well known that SO_x produces $CaSO_4{\cdot}2H_2O$ as an impurity in $CaCO_3$. However, since its concentration is much lower than CO_2 in the cement kiln exhaust gas, it does not significantly affect the purity of $CaCO_3$.

4.4 Estimation of CO_2 emissions reduction by MCC&U Technology

- Estimation of Concrete Production in RSA

The TA team searched for statistical data on concrete production in order to estimate CO_2 reduction potential by MCC&U technology. However, it is found that whilst there is data published for 2013[27], no updated data is available due to restrictions of the Competition Act of RSA. Therefore, the 2013 data only was referred to in this report where 18.9 million m^3 of concrete (45.4 Mt) was produced annually in RSA for the period 2005-2008. These figures are expected to have increased due to investment by both the government and the private industry for new and replacement construction with rapid urbanisation and the growth of population. It was also reported that an average of 8.69 million m^3 of ready-mixed concrete was produced annually and 8.17 million m^3 of concrete was used in the production of concrete products such as paving blocks, roof tiles, masonry, floor slabs, retaining blocks and infrastructure products as illustrated in Fig. 4.10.

[27] http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S1021-20192013000200001

However, since annual cement production has recently decreased to 13 Mt, total concrete production volume is calculated at 29.1 million m^3 of concrete, corresponding to 68.4 Mt based on 13Mt cement divided by 0.19. Through many conversations with cement and concrete experts, it was estimated that the ready-mixed concrete industry and the concrete products industry each account for 20% of total demand, corresponding to 5.82 million m^3 of concrete for each industry. This is higher than the 17% and 16% reported in the 2008 data and as illustrated in Fig. 4.10.

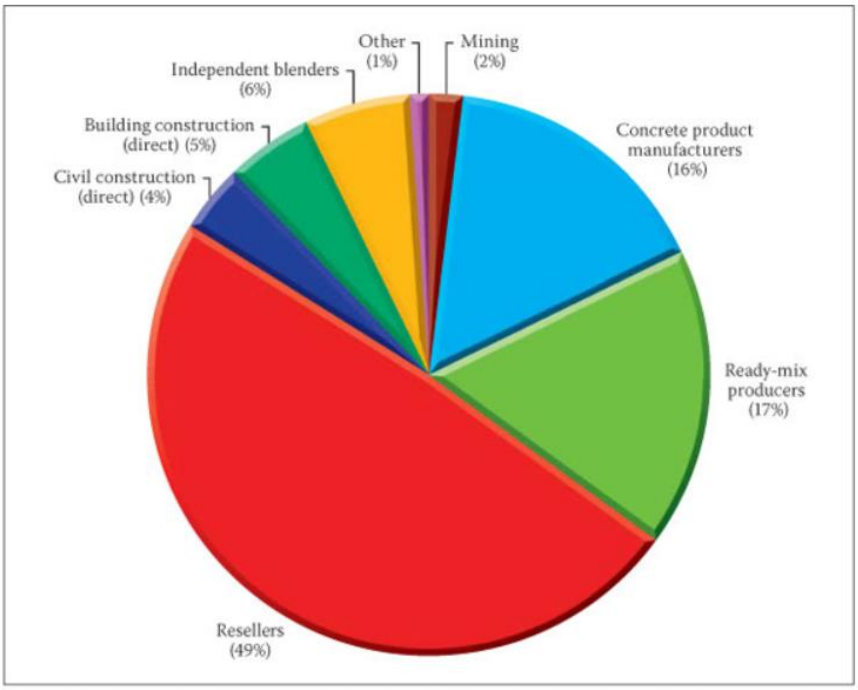

Fig. 4.10 Four-year (2005-2008) average of cement consumption by application in RSA (C&CI 2008)

➢ Calculation of national CO_2 reduction by MCC

In Section 4.2, material flows of concrete sludge and waste concrete are illustrated for a 100,000 m^3/yr concrete production plant. Based on estimated recent concrete production in RSA, national CO_2 reduction potential by MCC is simply calculated to be between 128,000 and 132,000 t/yr by estimating national production in proportion to material flow data at one plant where CO_2 captured for both 100,000 m^3 ready-mixed plant (132 -207 t/yr) and concrete product plant (2,068 t/yr) indicated in Table 4.3.

The potential quantity of $CaCO_3$ generated by MCC&U is also calculated to be between 291,000 and 300,900 t/yr. This is based on estimating national production in proportion to material flow data where CO_2 is captured at a 100,000 m^3 ready-mixed plant (300- 470 t/yr) and a concrete product plant (4,700 t/yr) as indicated in Table 4.3.

Table 4.3 Annual carbon captured volume and generation quantity of $CaCO_3$

Concrete Plant	Estimated National Production (m^3/yr)	Volume of Carbon Captured (t-CO_2/yr)	Generation of $CaCO_3$ (t/yr)
Ready-mixed concrete	5,820,000	7,680-12,040	17,460-27,350
Secondary concrete product	5,820,000	120,360	273,540

➢ Estimation of Concrete Production by Region

The TA team investigated the concrete market in RSA to estimate an available quantity of concrete sludge and waste concrete around the cement plant through dialogues with concrete experts. Fig. 4.11 illustrates a very approximate estimation of relative concrete consumption in Johannesburg region, West Cape region and other region of 60%, 20% and 20%, respectively.

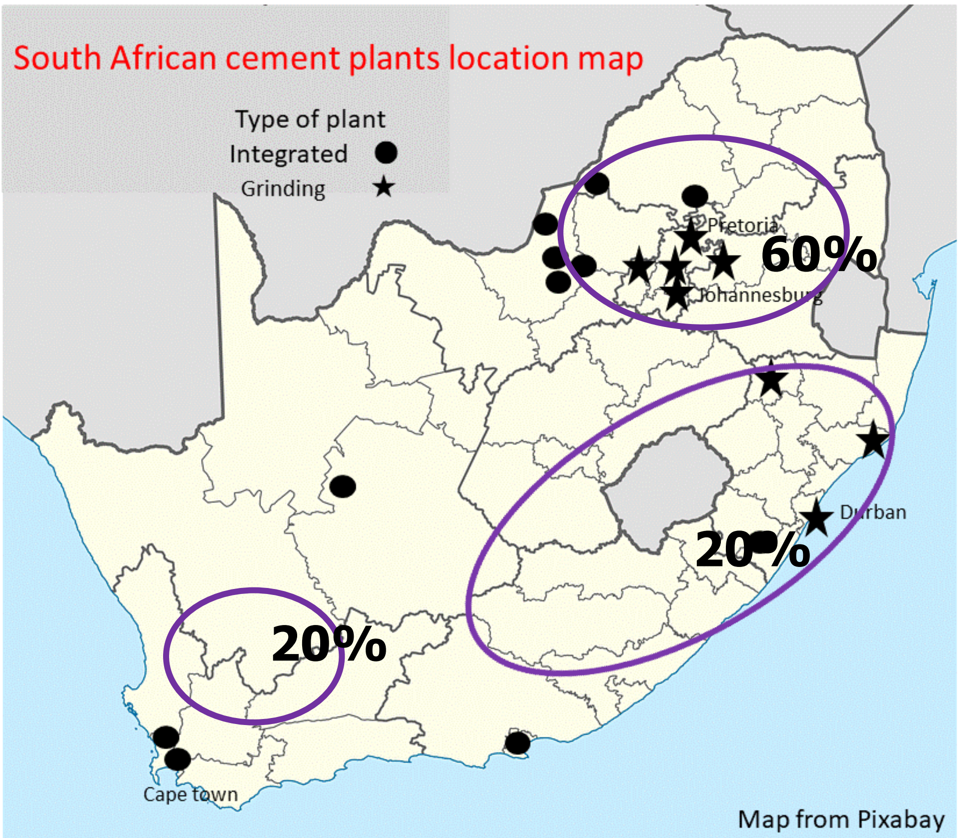

Fig. 4.11 Assumed ratio of concrete consumption for 3 regions in RSA

4.5 Determination of target sites for GHG reduction

➢ Selection of target sites for MCC&U installation

As described in section 3.2, target plants for WHR installation are 1) full-scale cement plant (3,000 t-clinker/d or more produced by a single rotary kiln) and 2) medium-scale cement plant (nearly 3,000 t-clinker/d produced by multiple kilns). Then, the further criteria for MCC&U installation are considered to estimate GHG emissions reductions at each target site:

- Large quantities of concrete sludge, waste concretes and other industry wastes containing calcium or magnesium are generated near the plant or transported to the plant without any difficulty.

- By-products are consumed in cement production at the plant or sold to a plant nearby.
- A recycling system for used water in the MCC reactor is required since water shortage is one of the urgent issues in RSA.

It is strongly recommended that a full-scale plant for cement production around which many concrete sludge or waste concretes are generated is identified as a target site. However, it is observed that many ready-mixed concrete plants are located in urban areas between Johannesburg and Pretoria and many concrete product plants are located along the southern region of Johannesburg. On the other hand, full-scale clinker manufacturing plants near coal mining sites or lime quarries are located more than 200 km from such concrete consuming area. One exceptional case may be West Cape where strict local regulations are enforced for demolished concrete disposal. The distance between the cement plants and recycled aggregate manufacturing plants is relatively short compared to the case of Johannesburg and Pretoria, and introducing the MCC&U technology near recycled aggregate manufacturing plants may further encourage appropriate disposal treatment of demolition concretes in the country.

Regarding the second requirement, Fig. 4.12 provided by CGS indicates that most cement plants are located near areas where AMD is a concern and where by-products can easily be delivered from the MCC&U plant. This suggests that an MCC&U facility can be installed at any cement plant in RSA.

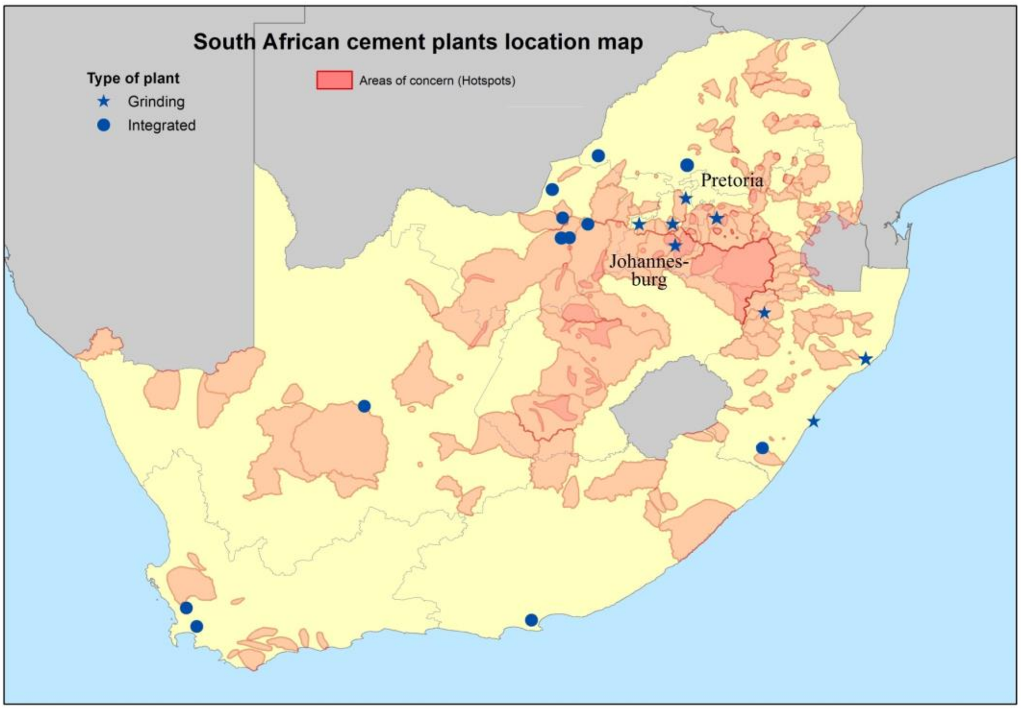

Fig. 4.12 Cement plants map vs. AMD concern area[28]

[28] Provided by Council for Geoscience

As sufficient cooling water for WHR is not available in RSA, a used water recycling system will be designed for the MCC&U plant. However, the plant requires only an amount of water for initial operation of two reactors. In order to prevent precipitation of gypsum, the quality of the water used in the reactors should have a low sulfate ion (SO_4^{++}) concentration.

➢ Determination of Target Site

The pros and cons are summarised for each cement plant (Type I and II) and clinker grinding station to determine the target site for the hybrid low carbon technology as illustrated in Table 4.4.

Table 4.4 Cement plant size vs. pros and cons

Cement Plant		Pro	Con	Remark
Type I	Full-scale (more than 3,000 t-clinker/d)	Large volume of waste heat from cement kiln	Too far to collect concrete wastes	Need to consider how to transport concrete wastes to the plant from the sites
Type II	Medium-scale (multi-kilns, around 3,000 t-clinker/d)		Economically inefficient due to the significant WHR construction cost and Lower WHR power generation due to less volume of kiln exhaust gas	Economically viable WHR installation if multiple kilns or higher temperature of kiln exhaust gas are available
Clinker grinding station in a concrete consuming region		Easy to collect concrete wastes from various sites	Other exhaust gas containing CO_2 is required since no kiln exists	If exhaust gas from fossil fuels is available, MCC&U installation should be separated from WHR installed at full-scale plant.

MCC&U technology can reduce GHG emissions in the following two ways:

- Scenario (MCC): CO_2 contained in an exhaust gas is captured and fixed in carbonates; and
- Scenario (U): $CaCO_3$ from MCC reaction is used as U_{mac} at the site where $CaCO_3$ are produced.

In order to discuss GHG reduction and feasibility of the hybrid technology, categories of target sites are identified in Table 4.5. However, clinker grinding stations are excluded as the target site in this study since annual volume of CO_2 emissions from fossil fuels is very small according to recent plant environment data provided by ACMP members.

Table 4.5 Type of target plant

<table>
<tr><th>Target Site</th><th>Scenario MCC</th><th>Scenario U</th></tr>
<tr><td>Type I</td><td>Cement plant size is full-scale (the kiln size of over 3,000 t/d)
30% of concrete sludge from ready-mixed concretes plants and waste concretes from concrete product plants is transported to the plant by 200km.</td><td rowspan="4">$CaCO_3$ produced from MCC is added to portland Cement as U_{mac} (replacing a percentage of the cement)</td></tr>
<tr><td>Type II</td><td>Cement plant size is medium-scale (multi-kilns with the total kiln size of approximately 3,000 t/d)
20% of concrete sludge from ready-mixed concretes plants and waste concretes from concrete product plants is transported to the plant by 100km.</td></tr>
<tr><td>Type II_{add}</td><td>Cement plant size is medium-scale (multi-kilns with the total kiln size of approximately 3,000 t/d)
Additional input material such as recycled fine aggregates from demolished concrete near the plant is included</td></tr>
<tr><td>Type III</td><td>Cement plant size is full-scale (the kiln size of over 3,000 t/d)
Concrete sludges are not available near the plant but an alternative material such as lime dust is only used. Transport distance is 50 km.</td></tr>
</table>

4.6 Proposal on transport of potential input materials to the MCC&U plant

How to collect and transport concrete sludges generated at each concrete plant to the MCC&U plant are considered. Methods of sludge and waste collection are suggested by taking into consideration pre-treatment at the plant to reduce transport cost and CO_2 emissions arising from transportation. The most economical means is to transport only the effective calcium for MCC reaction to the plant by 18 tonne loading dump truck with the coarse aggregate removed from concrete sludge or waste concrete using mechanical separation at the concrete plant. Details are described as follows.

➢ Concrete Sludge from Ready-mixed Concrete Plant

In general, concrete is delivered to site from the ready-mixed concrete plant by agitator vehicle which returns to the plant after placing the fresh concrete at the construction site. The average distance between the construction site and the ready-mixed concrete plant is assumed to be 50 km one way. Water is used to clean the inner drum of the agitator truck at the plant. Aggregates are then removed from the diluted concrete sludge using mechanical separator at the ready-mixed concrete plant. The aggregates are reused for pavements or other appropriate applications, and mortar and cement sludge are transported to the cement plant by dump truck as illustrated in Fig. 4.13. The sludge is then diluted with water and mechanically divided into liquid and solid portion.

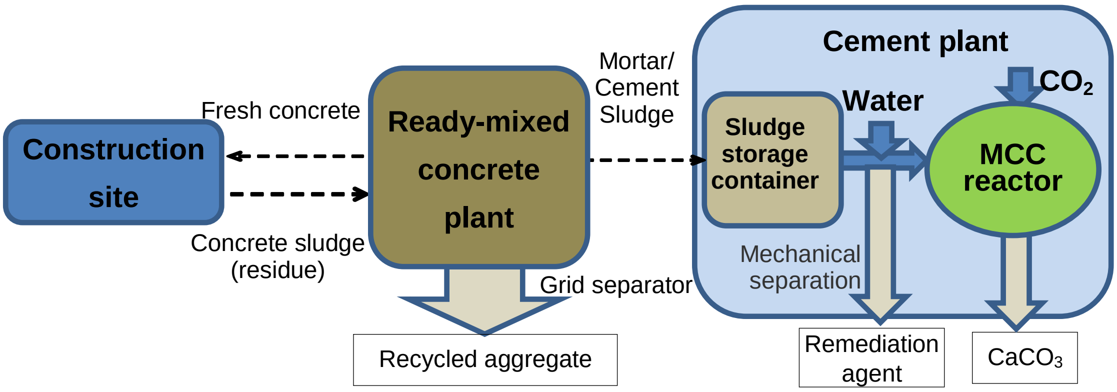

Fig. 4.13 Proposed transport of sludge from ready-mixed concrete plant to cement plant

The liquid portion is used for the MCC reaction and the solid is dried and ground for utilisation as a remediation material.

- Waste Concrete from Concrete Product Manufacturing Plant

It is very difficult to collect cement sludge generated from concrete product plants since a very low water-cement ratio is used for concrete molding in RSA. However, it was found that waste concretes such as non-standardised concrete products or used concrete are readily available.

Fig 4.14 suggests the following treatment of waste concretes or demolished concretes. Coarse aggregates are firstly removed from the waste concrete at the concrete product manufacturing plant or demolished concrete at the recycled aggregate manufacturing plant by using a mechanical crusher (see Photos 4.6 & 4.7). Then, waste concretes are pre-treated and recycled fine aggregates from demolished concretes are transported to the cement plant by 18 tonne loading dump truck if economically available. At the cement plant, such concretes are diluted with water and mechanically divided into liquid and solid portion. The liquid portion only is used for the MCC reaction and the remediation material is produced by mechanical separation of the sludges.

Photo 4.6 Concrete crusher

Photo 4.7 Mobile crushers at a recycled aggregate manufacturing plant

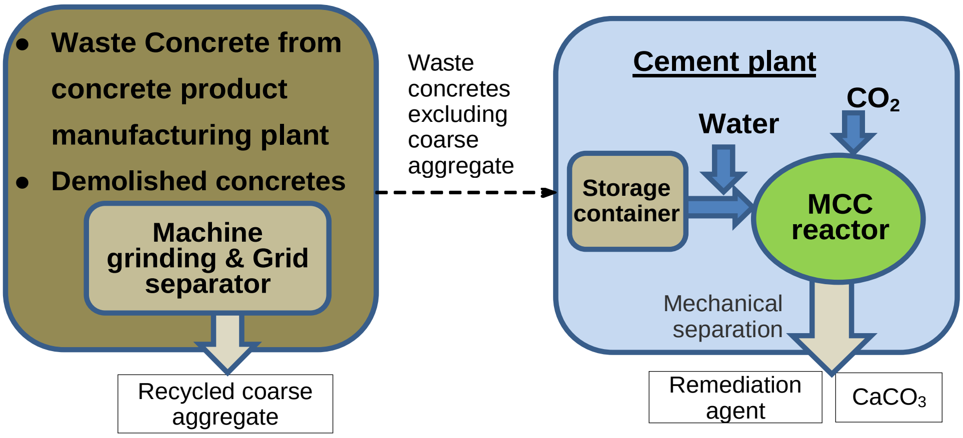

Fig. 4.14 Proposed transport of waste concrete and demolished concrete

- Collection Network

Basically, transport of concrete sludge and waste concrete is conducted by 10-18 tonne dump trucks. Therefore, the pre-treatment of such concrete wastes as illustrated in Fig. 4.13 & 4.14 is required for economical operation of an MCC&U plant.

Fig. 4.15 illustrates the collection of various wastes containing calcium around the target cement plant. It is assumed that concrete sludge is transported either to the MCC&U plant installed in the concrete consuming region using ready-mixed concrete vehicles (A1), or to the cement plant far from the region by 18 tonne dump trucks (A2), and other possible input materials for MCC&U are transported to the cement plant (B, C and D). Especially, recycled fine aggregates including fine particles of hydrated cement mortar will be utilised for MCC&U by transporting from recycled aggregate manufacturing plant (C) to the cement plant where demolished concretes have to be treated in accordance with strict local regulations in West Cape, Johannesburg and Pretoria. Further details of all input materials for MCC&U are summarised in Table 4.6.

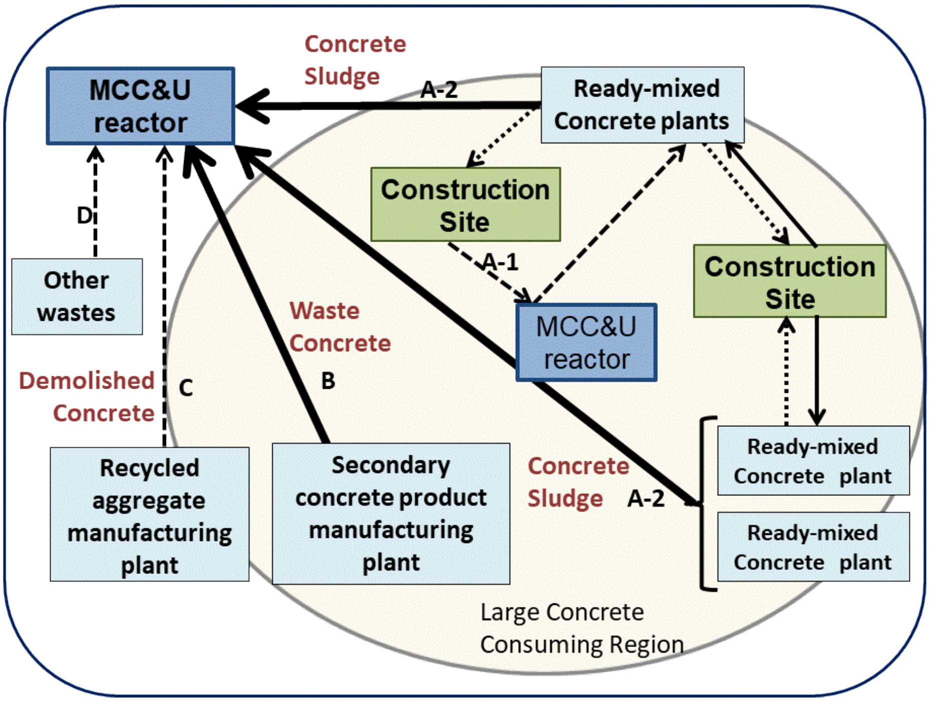

Fig. 4.15 Schematic collection network of various input materials for MCC&U operation

Table 4.6 Collection details of each calcium source

Option	Ca Source	MCC&U Installation	Outline of Collection Measure
A-1	Concrete sludge from ready-mixed concrete plant	Within concrete consuming region	Concrete vehicle returns to the plant from a construction site through the MCC&U plant where excessive waste concrete in the agitating drum is washed away.
A-2	Concrete sludge from ready-mixed concrete plant		Excessive waste concrete in an agitating drum is washed away and collected as mortar sludge which coarse aggregates are removed the concrete plant. Then the sludge is periodically transported to the MCC&U plant.
B	Waste concrete from secondary concrete product manufacturing	Far from concrete consuming region	Coarse aggregates are removed from waste concretes by using mechanical grinder at the concrete plant and fine aggregates are periodically transported to the MCC&U plant by dump truck.
C	Recycled fine aggregate from demolished concrete		Demolished waste concretes are milled or grinded at recycled aggregate manufacturing plant. Recycled fine aggregate is only transported to the MCC&U plant
D	Alternative feedstocks such as blast furnace slag or fry ash		Wastes or natural resources containing Ca & Mg compounds are transported to the MCC&U plant by dump truck

4.7 CO_2 Accounting Methodology of MCC&U technology

➢ Project boundary and accountable emission sources

Identifying the project boundary is important for the GHG emission accounting. South African government has currently considering two measures to achieve its national GHG emissions: carbon tax and carbon budget. Both are still under discussion; however, carbon tax is mandatory while carbon budget is proposed to become mandatory only from 2020 and until then kept voluntary. Both measures target only "Scope I emissions," that is, direct emissions caused by fuel combustion or gasification and utilisation by facilities at sites that are owned or controlled by a company. In addition, the proposed carbon tax bill allows the use of carbon offsets with a ceiling of 5% to 10% of the total emissions during the taxed period[29]. Although outside of the scope for both carbon tax and carbon budget, the government also encourages to reduce "Scope II emissions" or indirect emissions from using purchased power, steam and heat from a third party by providing separate measures and incentive schemes[30]. It is important to note that neither the carbon tax nor carbon budget includes transportation fuel consumption. This exceptional treatment also applies to direct emissions from transportation fuel consumption by company-owned vehicles, which are considered as Scope I emission[31].

Considering the current situation in the development of these two measures, this study focuses on Scope I emissions and its emissions reduction, and excludes emissions arising from transportation fuel consumption. However, emissions from power consumption (Scope II) and transportation of input materials (Scope I or III) are estimated for future reference.

As mentioned in Table 4.5, there are two types of key target plant for the introduction of the MCC system:

- Target site (Type I): A MCC&U facility is installed at a "full-scale" cement plant”
-Target site (Type II): A MCC&U facility is installed at a "medium-scale" cement plant”

At both plant types, concrete sludge from ready-mixed plants and wastes from secondary concrete manufacturing plants are used as input materials. Project boundaries for target site Type I and II are shown in Fig.4.16. Scope I emissions include the CO2 emissions from the cement plant captured and mineralised by the MCC system and any direct fuel consumption within the site.

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[29] Carbon offset allowances is mentioned in the Article 13 of the draft bill, where "(2) The reduction of the liability for the carbon tax allowed in terms of subsection (1) [utilising carbon offsets] may not exceed so much of the percentage of the total greenhouse gas emissions of a taxpayer in respect of a tax period as is determined by matching the line in the column "Sector" with the percentage in the corresponding line of the column “Offsets allowance %” in Schedule 2." The maximum percentage of offset allowances allowed to the cement production is 5%.

[30] According to the *Draft Explanatory Memorandum for the Carbon Tax Bill, 2015 [2 November 2015]*, "Complementary measures and incentives (such as the energy efficiency savings tax incentive) have been introduced to encourage businesses to reduce their Scope 2 emissions; i.e. indirect emissions resulting from a firm’s use of purchased electricity, heat or steam."

[31] According to the *Draft Explanatory Memorandum for the Carbon Tax Bill, 2015 [2 November 2015]*, "Carbon taxes imposed on transport fuels at the pump are excluded from the analysis because emissions from transport fuels do not fall within the scope of carbon budgets." This is due to avoid double taxation with liquid fuels producers apart from the continuation of current fuel taxation system. According to *Integration of the Carbon Tax and Carbon Budgets in South Africa (March 2017)*, carbon budget does not include transport fuels, either.

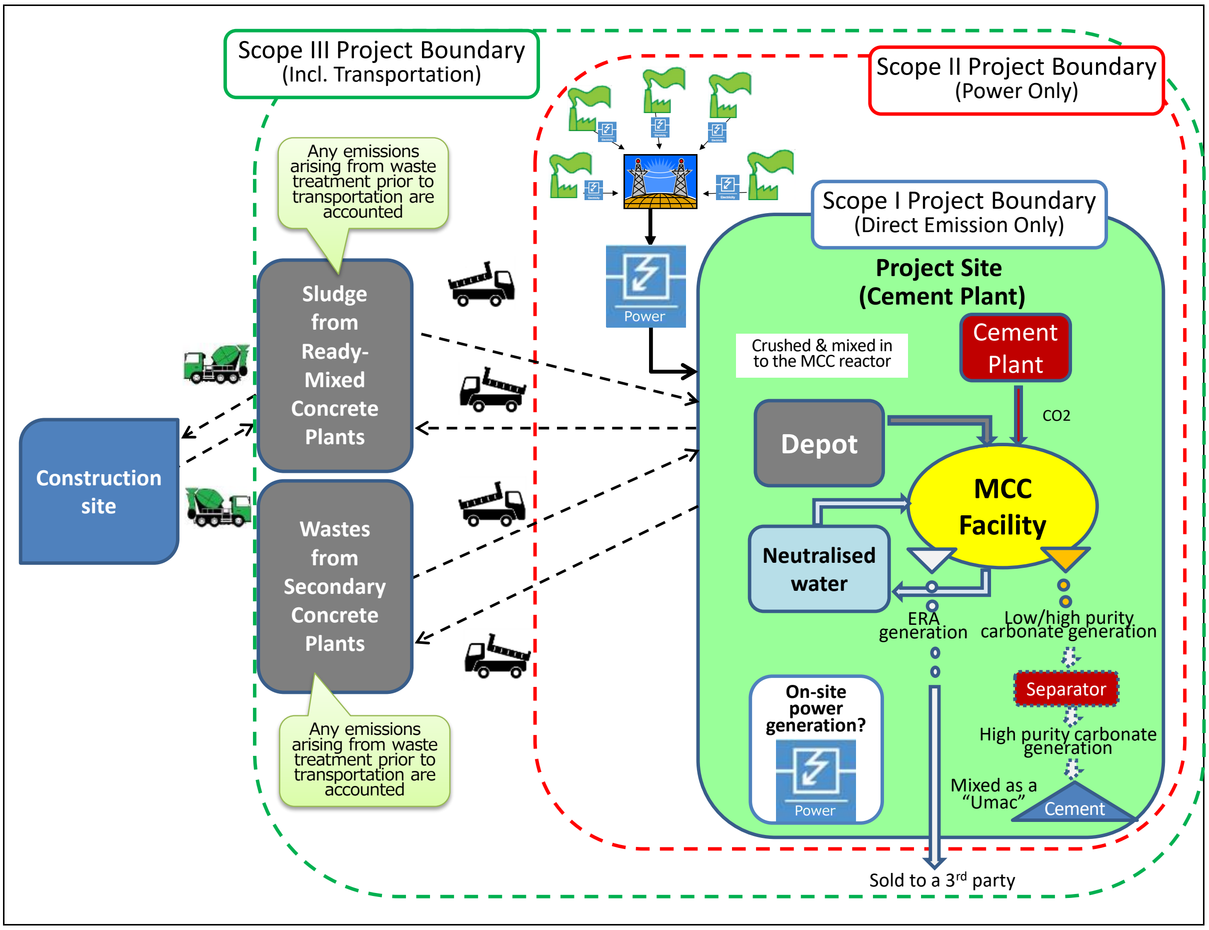

Fig. 4.16 Project boundaries of target site type I and II

MCC operation requires power (Scope II emissions) and input materials transported from outside the project site (Scope III emissions). Based on the TA Team's site visits and interviews with relevant stakeholders, power consumed by the cement plants is mostly purchased from the grid supplied by a company called Eskom. Although the methodology for GHG emissions reduction includes the option of on-site power generation in its formula, this study assumes that all the power consumed by the MCC operation is from the grid. In addition, as shown in Fig. 4.16, the Scope I project boundary includes the addition of $CaCO_3$ into portland cement as U_{mac}.

➢ Direct emission sources for baseline emissions calculation

Both scenarios of MCC and U can be considered as direct emissions reduction at the target sites if the MCC reactor is installed at the cement plant and by-product $CaCO_3$ is mixed with the cement onsite. However, in accordance with the detailed analysis mentioned in the marginal abatement cost (MAC) calculation and business plan section, it is also possible to have a third scenario, that is, the carbonates are sold to other cement plants to use them as U_{mac}. In addition, ERA is assumed to be sold to a third company.

Baseline emissions for each scenario can be calculated based on the information provided in Table 4.7.

Table 4.7 Sources of baseline emissions and calculation methods

Scenarios	Baseline Emission Sources	Calculation Methods
(MCC)	• Exhaust gas (from cement kiln through WHR) containing CO_2 released to the air	Formula: (a) x (b) x (c), where: (a) Quantity of by-product carbonates produced (metric tonnes) (b) CO_2 contained in the carbonates (e.g. 44 g-CO_2/100 g/mol for calcium carbonates and 44 g-CO_2/84 g/mol for magnesium carbonates) (b) Purity of carbonates
(U)	• Combustion of fossil fuels used to produce clinker	Formula: (d) x (e), where: (d) Quantity of by-product $CaCO_3$ added to cement as Umac (e) Benchmark emissions of cement—(i.e. 0.65 t-CO_2/t-cement)*

*Note: The benchmark is used based on communications with ACMP and other experts.

It is important to note that the quantity of by-product $CaCO_3$ used as a raw material for calcination in kiln must be excluded from the baseline emission calculation for Scenario I. If not, the amount of CO_2 locked in the carbonates that is re-released back to the air through calcination will be wrongly accounted in the emission reduction calculation.

➢ Issue with the purity of by-product carbonates

As shown in Fig. 4.17, the purity of carbonates is significant in calculating the baseline emissions. Based on a series of interviews with various stakeholders in RSA, the TA Team learnt that there are limited ready-mixed concrete sludges available in RSA. In addition, the laboratory analysis of samples showed that waste concretes from secondary concrete product manufacturing plants may generate $CaCO_3$ together with ERA. For this reason, the TA Team assumes to introduce a separator to recover $CaCO_3$ from amalgamate. The amount of $CaCO_3$ used for the calculation of the baseline emissions of (U) (parameter (d) in the above formula) should be weighted after the separator.

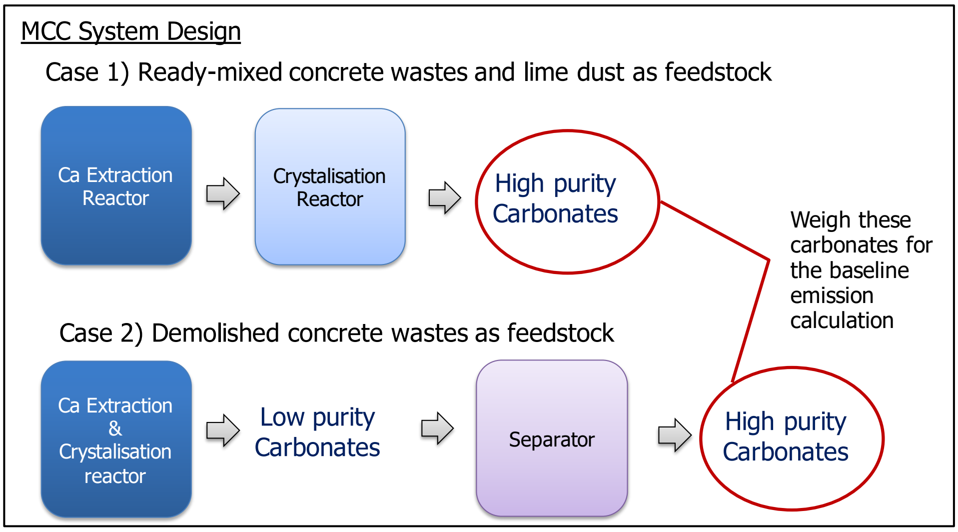

Fig. 4.17 Purity of carbonates

➢ Direct and indirect emission sources for project emissions calculation

Direct (Scope I) and indirect (Scope II) emission sources for the project emissions are as follows:

< Direct emission sources >

- Fuel used for on-site power generation that are consumed by the MCC operation (see below indirect emission sources)

< Indirect emission sources >

- Purchased power consumed by crushers, if any
- Purchased power consumed by reactors and water pumps
- Purchased power consumed by separators, if any

Table 4.8 summarises the calculation methods for each project emission source. For future reference, emissions from the consumption of transportation fuels (Scope III) can be calculated. Table 4.9 summarises the calculation methods for each project emission source.

Table 4.8 Sources of project emissions and calculation methods

Emission sources	Project Emission Sources	Calculation Methods
Power	[Scope I] • In-house power consumed by crushers, if any • In-house power consumed by reactors and water pumps • In-house power consumed by separators, if any	Formula: [(a) + (b) + (c)] x (d)], where: (a) Quantity of the in-house power consumed by crusher (Mwh) (b) Quantity of the in-house power consumed by reactors and water pumps (Mwh) (c) Quantity of the in-house power consumed by separators (Mwh) (d) Emission factor of the power calculated from on-site power generation
	[Scope II] • Purchased power consumed by crushers, if any • Purchased power consumed by reactors and water pumps • Purchased power consumed by separators, if any	Formula: [(a)' + (b)' + (c)'] x (d)'], where: (a)' Quantity of the purchased power consumed by crusher (Mwh) (b)' Quantity of the purchased power consumed by reactors and water pumps (Mwh) (c)' Quantity of the purchased power consumed by separators (Mwh) (d)' Emission factor of the power calculated from the purchased sources

Table 4.9 Project emissions and calculation methods for the transportation

Emission sources	Project Emission Sources	Calculation Methods
Transportation fuel	Fossil fuel consumed by transportation of input materials	Formula: [(e) x (f)], where: (e) Quantity of fossil fuel consumed (tonne) (f) Default emission factor of fossil fuel used (diesel)

4.8 Estimation of GHG reduction at target sites

➢ **CO_2 emissions reduction by MCC&U at target sites**

CO_2 reduction by MCC and U application is dependent on the production quantity of $CaCO_3$. Assuming sufficient input materials such as concrete sludge are available for collection and transportation to the target sites, both CO_2 emissions reduction (MCC) and (U) can be calculated from the volume of $CaCO_3$ generated and its purity at each site according to the accounting methodology described in section 4.7.

Table 4.10 indicates the carbon capture volume at each target site, where Type II_{add} will use recycle aggregates from two demolition companies as an additional input material, and generation of $CaCO_3$ used as U_{mac} in accordance with the cement standard.

Table 4.10 CO_2 reduction by MCC&U at each target sites

Target Site	Input Material for MCC&U	Transport Distance (km)	Volume of Carbon Captured (t-CO_2/yr)	Generation of $CaCO_3$ (t/yr)
Type I	Concrete Sludge	200	2,300-3,600	5,200-8,200
	Waste concretes		36,100	82,100
Type II	Concrete Sludge	100	1,500-2,400	3,500-5,500
	Waste concretes		24,100	54,700
Type II_{add}	Recycled fine aggregates (from 2 plants)		6,800-11,500	-
Type III	Lime dust (from 2 plants)	50	89,400-100,300	203,100-228,000

➢ **GHG emissions reduction by WHR and MCC&U at target sites**

Table 4.11 indicates the impact on Scope I, II and III CO_2 emissions at the target sites identified in Table 4.10 by using the proposed hybrid low carbon technology where (-) means CO_2 reduction and (+) means CO_2 emissions.

Table 4.11 Total CO_2 reduction by using proposed hybrid low carbon technology at target site

Emission	Emission Source + emissions - reduction		Target Site (t-CO_2/yr)		
			Type I 200 Km	Type II and II_{add} 100 Km	Type III 50 Km
Scope I	WHR	(-)	0	0	0
	MCC	(-)	38,400-39,700	32,400-38,000	89,400-100,300
	U	(-)	Depending on volume of cement production (up to 5%)		
Scope II	WHR	(-)	37,800	26,900	37,800
	MCC	(+)	1,700-2,700	1,100-1,800	3,900
Scope III	Transport	(+)	32,600-33,700	12,200-13,100	1,128

4.9 Marketability of environmental remediation agent

Sample analysis of various wastewaters

- Acid mine drainage (AMD)

TA team visited AMD treatment sites at closed coal mines located east of Pretoria to take samples of the water and gain an understanding of on-site circumstances. Mine wastewater polluted by AMD was collected at three coal mining sites shown in Photos 4.8 - 4.10.

The mine wastewater showed between pH2.66 to 2.92 which is very high acidity. In addition, it contained high concentrations of Fe, Mg, Al and Mn. It is well-known that AMD treated with $Ca(OH)_2$ and $CaCO_3$ can be efficiently neutralized[7]-[8] and, therefore, the possibility of applying ERAs delivered from MCC&U using industrial waste at low cost as an alternative neutralizer was explored.

Photo 4.8 AMD from coal mine (site 1)

Photo 4.9 AMD from coal mine (site 2)

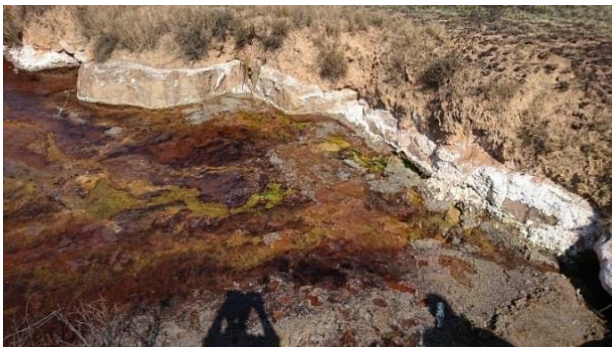

Photo 4.10 AMD from coal mine (site 3)

The Counsel of Geoscience (CGS) conducted lab-scale experiments to assess the performance of powder samples of ERA produced in Japan (PAdeCS) to treat the collected AMD samples in comparison with treatment using commercial $CaCO_3$. Since ERA contains $Ca(OH)_2$, $CaCO_3$ and ettringite as mineral phase, the Ca content was measured at almost same value as that of the $CaCO_3$ (calcium carbonate). On the other hand, the commercial calcium carbonate sample contained gypsum and dolomite.

Tests were conducted using additions of the neutralising agent at 45, 75, and 100 g/L. Although these ratios are excessive dosages for neutralisation, the removal of sulfate (SO_4^{2-}) was also measured. The results of the neutralisation experiment showed that the pH value of the treated AMD to be approximately 7 using the commercial $CaCO_3$, but higher than 12 for the ERA. This indicates that the ERA has a very high neutralisation performance compared with the commercial $CaCO_3$. In addition, although the removal effect of sulfate ions (SO_4^{2-}) in the AMD was very low for $CaCO_3$, the ions were reduced by approximately 60% when ERA was used. This implies that the performance of ERA on the removal of sulfate is also very high.

The preliminary tests showed that the ERA could be used to replace commercial $CaCO_3$ for AMD neutralisation and sulfate (SO_4^{2-}) removal. However, further studies are required.

- Sewage treatment facility

Samples of wastewater were collected from sewage treatment facilities as shown in Photos 4.11 - 4.13. Analysis of the collected samples showed that all samples contained a high phosphorus concentration. This suggests that phosphorus resources could potentially be recovered from the wastewater as HAP (Hydroxylapatite, $Ca_{10}(PO_4)_6(OH)_2$) using inexpensive ERA derived from concrete wastes.

Photo 4.11 Sedimentation concrete tank (site 4)

Photo 4.12 Reaction facility (site 4)

Photo 4.13 Sampling site (site 5)

Through conversations with experts and observation on site, the TA team realised that a large volume of AMD was generated and that the treatment of AMD did not appear to be being conducted appropriately due to economic barriers.

With regard to the wastewater from two sewage sludge treatment facilities, analysis of the collected samples and interviews with staff at the facilities confirmed that although the phosphorus concentration in the final effluent from the facilities is low, higher phosphorus concentrations are present in some of the treatment steps. This indicates that phosphorus contained in the sewage is usually removed within the conventional sewage treatment process. By adding ERA derived from the MCC&U process to the water with high phosphorus concentration, it is expected that phosphorus resources can be recovered as HAP (Hydroxyapatite, $Ca_{10}(PO_4)_6(OH)_2$). However, support of local governments will be necessary at the early stage of R&D to facilitate the introduction to RSA of the phosphorus recovery process by ERA.

Market survey

The by-products derived from the MCC reaction are $CaCO_3$ and ERA. Table 4.12 shows the estimated potential annual production of $CaCO_3$ and ERA in RSA to be 494,100 - 528,900 tonnes and 611,000 - 632,000 tonnes, respectively.

Table 4.12 Estimation of national production of $CaCO_3$ and ERA from MCC&U

Plant	Annual generation of by-products derived from MCC	
	$CaCO_3$ (t/yr)	ERA (t/yr)
Ready-mixed Concrete	17,460 - 27,350	36,700-57,400
Concrete Product	273,540	574,400
Two Lime Plants	203,100 - 228,000	-
Total	494,100-528,900	611,000-632,000

Although it was firstly assumed that $CaCO_3$ would be utilised as U_{mac} to reduce CO_2 emissions in the cement industry, $CaCO_3$ can also be used as a neutralising agent. Consequently, applications of both $CaCO_3$ and ERA were studied for focused sectors such as mining and wastewater treatment. The TA team made a survey of the by-products from MCC on the sources and treatment of acid mine drainage (AMD) and recovery of phosphorous-bearing wastewater from industrial and urban activities in RSA together with University of Cape Town (UCT). A preliminary review of existing literature in the public domain was conducted by UCT and the results were discussed with CGS.

- Typical AMD treatments in RSA

The main sources of AMD pollution in RSA are the Witwatersrand Goldfields and the Mpumalanga Coalfields, both of which have been identified as priority areas requiring immediate action. Currently the state-owned Trans-Caledon Tunnel Authority (TCTA), under the auspices of the Department of

Water and Sanitation (DWS), is operating three AMD treatment plants on the Western (approximately 34 ML/d), Central (75-84 ML/day) and Eastern (84-110 ML/d) limbs of the Witwatersrand Goldfields illustrated in Fig. 4.18.

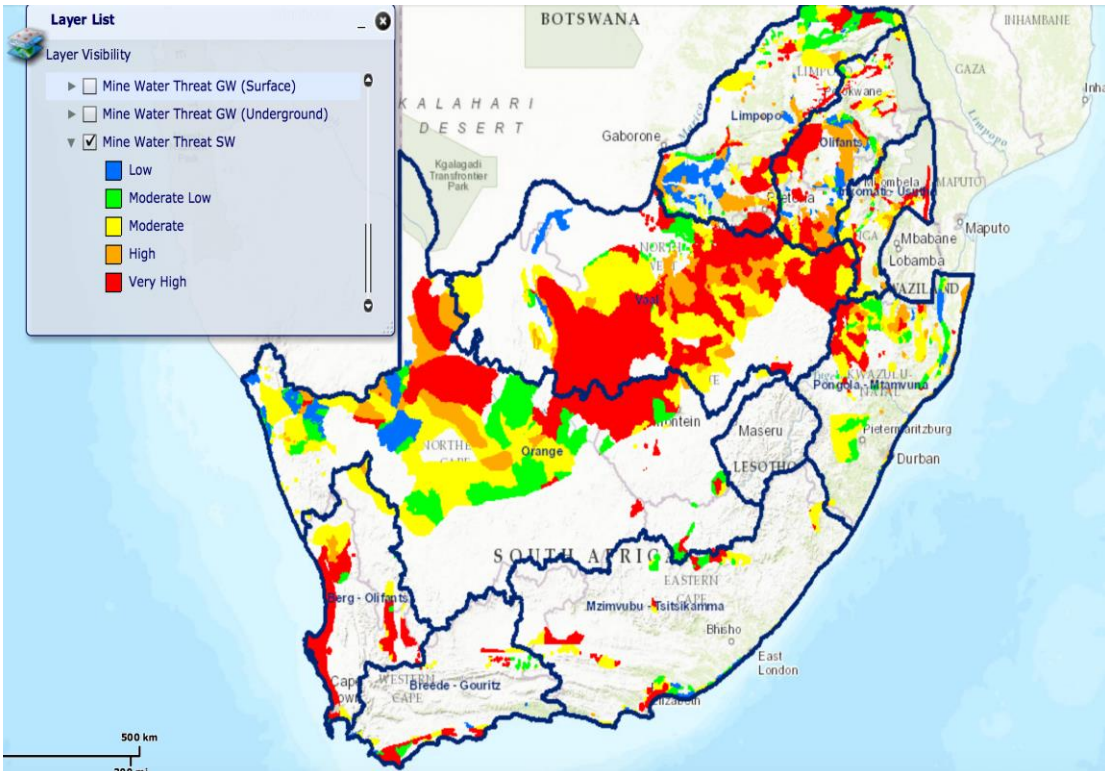

Fig. 4.18 Mine water threat SW (WRC, 2016)[32]

These plants use the High Density Sludge (HDS) Process, with lime as neutralising agent. Currently the Central and Eastern basin plants are consuming a total of 3,983 tonnes/month high-grade (95%) lime, at a cost of R1850/ton. Residual soluble salts remain a serious concern because of the need to reduce the salt loads currently entering river systems. Various desalination - the removal of salts from water - methods are currently under investigation. Also of concern is the land disposal of relatively large quantities of gypsum sludge from the HDS process.

Tables 4.13 & 4.14 indicate commercial prices of neutralization agents for AMD treatment based on the average mine water volume.

Table 4.13 TCTA treatment plants

Neutralization agent	Price (R/t)	Annual Volume (t/yr)	Consumption rate
Lime 95% purity (received as CaO)	1,850	12,700 (Eastern Basin) 35,100 (Central Basin)	420 kg/ML(Eastern Basin) 1300 kg/ML (Central Basin)

Note: Polymer priced at R48.5/kg on average is also used.

[32] WRC (Water Research Commission)
"South African Mine Water Atlas", Available on-line http://www.wrc.org.za/pages/minewateratlas.aspx) (2017)

Photo 4.14 shows limestone/lime neutralisation and gypsum crystallisation (High Density Sludge (HDS) Process) for discharge into river system. [9].

Photo 4.14 TCTA AMD treatment plant at Central Basin

Table 4.14 EWRP in the Mpumalanga coalfields

Neutralization agent	Price (R/t)	Annual Volume (t/yr)	Remarks
Limestone	640	2,300	Adopted two stage neutralisation with limestone only recently
Lime	2,520	14,000	

Note: An anionic polymer is dosed to agglomerate the floc which settles in the clarifier.

In the Mpumalanga Coalfields, the eMalahleni Water Reclamation Plant (EWRP) shown in Photo 4.15 has been generating approximately 30 ML/day potable water for the past 10 years, and has been recently upgraded to generate 50 ML/day potable water. This plant uses a combination of HDS, ultrafiltration and reverse osmosis (HiPRO process). The HDS circuit typically uses 1,163 t/month high purity lime (R2,520/t) and 190 t/month limestone (86% purity at a cost of R640/t). Gypsum sludge is currently recovered and sold to the construction industry to make ceiling boards, while the fine fraction is also used in agricultural and building applications. Not all the mine effluent in the Mpumalanga coalfields is acidic, however. A second mine water treatment plant at Glencore's Tweefontein mine uses ultrafiltration and reverse osmosis to generate approximately 15 ML/day potable water from the circum-neutral saline mine water. The world's first full-scale eutectic freeze crystallisation plant has recently been commissioned for the further treatment of the brines generated in the reverse osmosis process. [10]

Photo 4.15 eMalahleni water reclamation plant (EWRP)

The EWRP process is illustrated in Fig. 4.19 and comprises three stages : 1) green sand filtration to remove residual manganese, 2) ultrafiltration to remove any microorganisms and suspended solids and 3) high recovery precipitating reverse osmosis process to remove dissolved salts.

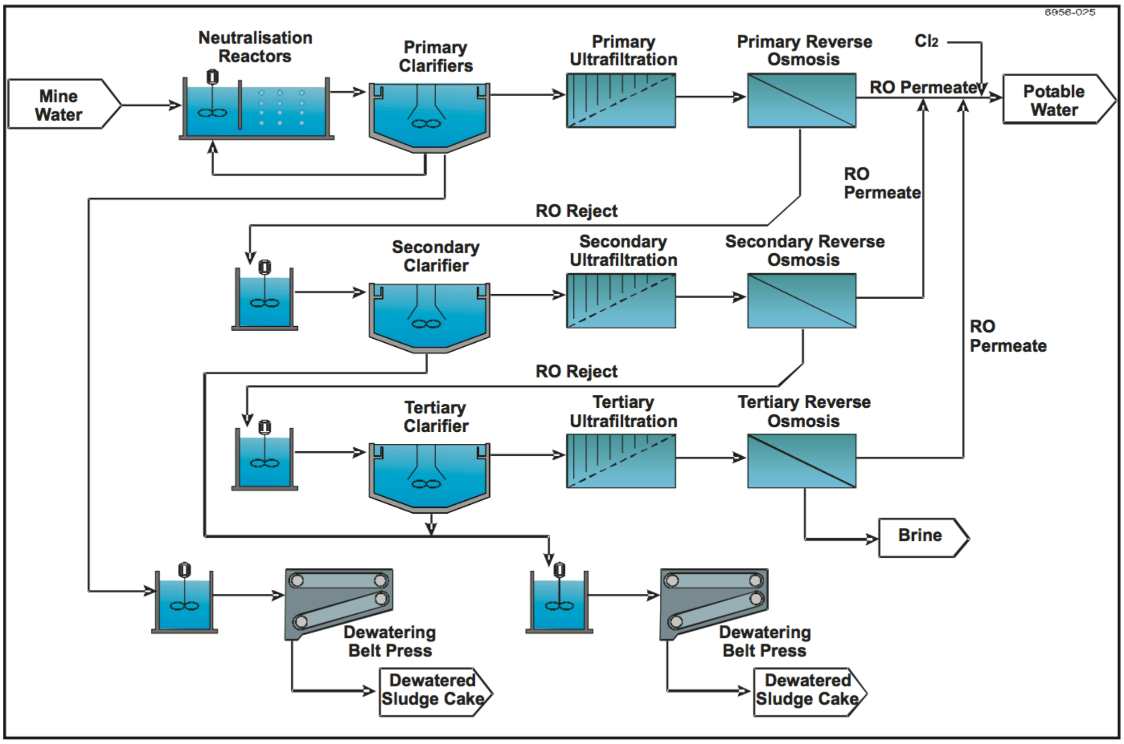

Fig. 4.19 Process flow diagram of the EWRP [11]

- Phosphorus

Table 4.15 indicates 164,000 tonnes of phosphorus is estimated to enter the environment in RSA annually (surface water, arable and non-arable soils) mainly as manure, human waste and as a result of soil erosion. Detergent is another notable phosphorous source entering the environment in RSA contributing approximately 30–35% of the phosphorus present in wastewater entering treatment works.[12] There are currently approximately 824 wastewater treatment works (WWTWs) in RSA, treating in excess of 6,400 ML/day. Many of these treatment plants are inefficient and operating beyond their designed capacity. In RSA, beneficiation of sewage sludge generated at wastewater treatment plants is limited and most wastewater treatment plants dispose sewage sludge either by direct land application or by stockpiling.

Table 4.15 Phosphorous entering the environment in RSA

Sources of Phosphorus released into environment	Estimated Flow (t/yr)	Potential recycling option
Manure	87,000	Chemical processing, direct application to arable soils
Burning and wild animal consumption	12,000	Direct application to arable soils
Post-harvest losses	3,500	Subsistence or de-centralised farming to reduce travel distance
Food distribution losses	4,000	Subsistence or de-centralised farming to reduce travel distance
Human waste	27,000	Chemical processing, direct application
Erosion losses from arable soil	31,000	Efficient application to arable soils
Total phosphorous entering environment	**164,000**	

Primary phosphate production from igneous phosphate rock occurs in Phalaborwa, whilst a sedimentary phosphate plant has recently been commissioned by Kropz at Elandsfontein in the Western Cape. The most widely used source of secondary phosphates in RSA is animal manure. Many farmers either use animal manure on-site or sell it as an organic fertiliser. Significant research conducted in South Africa has indicated phosphates may be recovered from wastewater or directly from urine as a fertiliser. A particularly promising initiative is the urine diversion dehydration toilets (UDDT) provided to households in unserved rural and peri-urban areas. There is potential to produce calcium phosphate from the diverted urine by using ERA. This could be a viable alternative fertiliser.

- **Marketability of By-products**

AMD Treatment

Table 4.16 suggests that both commercial products, $Ca(OH)_2$and $CaCO_3$, are almost entirely domestically sourced products and that the annual $Ca(OH)_2$ market size is approximately 69,000 tonnes, with an average market price is R1,800 - 2,500/t. On the other hand, the annual market for $CaCO_3$ for AMD treatment is currently very small but is estimated at 70,000 tonnes if $CaCO_3$ is utilised at the AMD site with an assumed market price of R500 - 640/t.

Lab-scale tests conducted by CGS suggests that ERA from MCC can be applied to AMD treatment and, furthermore, approximately 610,000 t/yr of ERA can be sold in the estimated market of $CaCO_3$ & $Ca(OH)_2$ in RSA. However, the $Ca(OH)_2$ market for AMD treatment seems to be limited due to cost constraint and would increase if a competitive ERA price is applied. Further study on ERA replacing $Ca(OH)_2$ is required.

Table 4.16 Commercial neutralisers for AMD

Commercial product	Ratio of Domestic -Imported	Market Price (R/t)	Annual Sales Volume (t/yr)	Remarks
Calcium hydroxide – slaked lime $Ca(OH)_2$)	3% imported	1,800-2,520	69,000	Currently applied. Increasing demand for water purification
Calcium carbonate - limestone ($CaCO_3$)	0% imported	500-640	Estimation 70,000	Increasing demand as neutraliser substitute for AMD treatment due to high $Ca(OH)_2$ price

Recovery of High Quality of Phosphorus

Global phosphorus sources are becoming depleted. Therefore, phosphorus recovery will be become increasingly important. According to the market survey by UCT, 164,000t/yr of phosphorus is discharged to the environment and lost in RSA. If ERA is economically used for sewage sludge treatment, the high quality of phosphorus can be recovered as a resource. However, since the ratio of ERA required to recover phosphorus from water is approximately 10:1, around 1.64 Mt-ERA will be required to completely recover all phosphorus.

Furthermore, as an alternative fertiliser, UCT proposes that there is potential to produce calcium phosphate from the diverted urine by using ERA since phosphorus with high concentration is contained in the urine collected at urine diversion dehydration toilets (UDDT).

Other applications

High purity $CaCO_3$ generated by the MCC reactor has a wide variety of applications, such as asphalt fillers, fillers for paper and plastic manufacturing processes, and so forth. These high-end applications require precision in their specifications (e.g. purity, particle diameter, color, etc.), their prices vary and it is difficult to estimate the market size. Since ERA contains minerals such as ettringite, it can also be used to remove heavy materials and arsenic from contaminated soil and water as a substitute for $Ca(OH)_2$.

5. GHG Reduction Potentials for the Cement Sector

CO_2 reduction by WHR

The TA team searched for all cement plants where daily clinker production is more than 3,000 tonnes and there is availability of cooling water in order to estimate CO_2 reduction potential by WHR installation. Based on all collected data, including published data, there are 3 full-scale plants and 2 medium-scale plants in RSA, but all plants have only limited cooling water available.

Therefore, assuming an air cooling system is equipped to all WHR plant, annual CO_2 emissions reduction of three full-scale plants is 113,370 t-CO_2/yr and that of two medium plants is 53,820 t-CO_2/yr, based on data shown in Table 3.1.

CO_2 Reduction by MCC&U

Potential input materials for MCC&U are concrete sludges, waste concrete and industrial wastes such as recycled fine aggregates and lime dust in RSA. Based on sample analysis, the material flow of input materials is illustrated in section 4.2 and then the nationally available quantity of such potential wastes was calculated using data from published literature and recommendations from cement and concrete experts.

Table 5.1 indicates the potential annual volume of carbon captured and annual generation of $CaCO_3$ to estimate direct CO_2 emissions reduction potential by MCC and U. The potential national CO_2 emissions reduction by MCC is 224,240-244,200 tonnes and the potential generation quantity of $CaCO_3$ delivered from MCC&U is calculated to be 494,100-528,900 tonnes. Based on an annual cement production by ACMP of 13 million tonnes and CO_2 emission intensity of 650Kg per tonne cement, the maximum allowable addition of $CaCO_3$ (up to 5wt%) is 650,000 tonnes. However, since the potential quantity of $CaCO_3$ generated is estimated at 494,100-528,900 tonnes, the carbon intensity of cement production is reduced by 3.8-4.1wt%.

Table 5.1 Carbon captured volume and generation quantity of by-products

Facility		[Scenario MCC] Volume of Carbon Captured (t/yr)	[Scenario U] Generation of $CaCO_3$ (t/yr)
Ready-mixed concrete plant	All plants (Estimated annual production $820,000m^3$)	7,680-12,040	17,460-27,350
Secondary concrete product plant		120,360	273,540
Recycled aggregate plant	Two plants in Type II region	6,800-11,500	-
Lime plant	Two plants in Type III region	89,400-100,300	203,100-228,000
Total		224,240-244,200	494,100-528,900

CO_2 Emissions Reduction Potential by the Proposed Technology

Tables 5.2 & 5.3 indicate the estimated Scope I & II CO_2 emissions reduction potential for the cement sector in RSA based on WHR installation at 5 potential sites and assuming that all concrete sludges and waste concretes generated by the ready mixed concrete industry in the RSA, together with recycled fine aggregates from two demolished concrete recycling plants, and lime dust from two lime plants are utilised as input materials for MCC&U. However, Scope III CO_2 emissions from transportation to the plant are not included in the calculation.

Table 5.2 Scope I, National CO_2 emissions reduction resulting from the hybrid facility

Technology		CO_2 Emissions Reduction Potential (t-CO_2/yr)	
WHR installation		0	565,340-588,100
MCC&U installation	MCC	224,240-244,200	
	U	341,100-343,900	

Table 5.3 Scope II, National CO_2 emissions reduction resulting from the hybrid facility

Technology	Power (MWh)			CO_2 Emissions Reduction Potential (t-CO_2/yr)
	Generated	Consumed	Net	
WHR installations	185,800	18,600	167,200	64,300
MCC&U installation	0	102,900	-102,900	

Scope I CO_2 emissions reduction potential resulting from the proposed hybrid technology is estimated to be 565,340-588,100t/yr and Scope II CO_2 emissions reduction potential to be 64,300t-CO_2 /yr where an emission factor for electricity is 1 t-CO_2/MWh in RSA. Asssssuming an annual cement production of 13 million tonnes in RSA, the introduction of the hybrid technology is expected to reduce CO_2 emissions from the cement industry by 629,640-652,400t/yr (approximately 7.5% to 7.7% reduction).

6. Feasibility Analysis

MAC analysis for WHR installation

It is considered feasible to install WHR at the cement plants in South Africa equipped with a single rotary kiln or multiple medium-scale kilns of 3,000 t-clinker/d or more.

Marginal abatement cost (MAC) is, according to *Mitigation Report: South Africa's Greenhouse Gas Mitigation Potential Analysis* published in 2014 by the Department of Environmental Affairs of the country, "an indicator of the cost required to implement a given technical measure to abate a unit of CO_2e ....[and] "the MAC describes the net cost of implementing a measure by comparing the capital and operational costs against potential energy cost savings (or additional energy overheads) per tonne of abatement." MAC is a powerful tool to determine what would be the least costly option to reduce one tonne of GHG per technology or project. Together with a potential GHG emissions reduction analysis, it creates a marginal abatement cost curve (MACC) to demonstrate which technology has the least costly option to reduce a significant amount of GHG emissions. The lower the MAC, the higher amount of CO_2 reduction can be expected from the investment in deploying a specific technology.

MAC can be calculated with basic parameters used for investment analysis[33] and GHG emissions reduction over the lifetime of the equipment or the project. The RSA government has already calculated MAC for various technology options for mitigation measures and published their results including the cement sector in 2014[34]. Table 6.1 and 6.2 are the data used in the 2014 report. Most of the energy price forecasts come from South African Times Model (SATIM) Version 2.1 by Energy Research Centre (ERC)[35]. Electricity price is from Department of Energy (DOE)'s *Integrated Resource Plan (IRP) for Electrify 2010-2030*[36].

Table 6.1 Relevant energy price* for 2010 base year and projected prices used in the 2014 mitigation report

Parameters	Units	Source	Note	2010	2020	2030	2040	2050
Motor gasoline	R/GJ	(ERC, 2013)	Imports of oil gasoline	124	153	188	211	234
Gas diesel oil	R/GJ	(ERC, 2013)	Imports of oil diesel	117	145	180	203	226
Heavy fuel oil (HFO)	R/GJ	(ERC, 2013)	Imports of oil HFO	97	121	150	168	187
Biodiesel	R/GJ	(ERC, 2013)	Imports of biodiesel	123	152	189	213	237
Electricity	R/GJ	(DOE, 2011)	IRP** projection Breakdown of anticipated average electricity price path	117	264	264	264	264
	R/MWh			421.17	950.33	950.33	950.33	950.33

*Prices are net prices and do not include tax or additional local distribution charges.
**Integrated Resource Plan
Source: Department of Environmental Affairs (DEA) (2014)

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33 Only exception is the parameter for tax rates. MAC does not usually include taxes in its calculation.

34 The 2014 study calculated the MACC using the net annual cost (NAC), that is, equivalent annual cost (EAC)/year plus annual O&M cost/year - energy cost saving/year. In this study, EAC was defined as the "capital investment cost (Capex) of the technical measures annualised over the measure's lifetime, applying a discount rate". The discount rate used by the study was 11.3% by the Technical Working Report.

35 SATIM Version 3.1 is now available.

36 DoE released the revised version of IRP was released in 2016. However, the table with specific electricity price forecast data was not available in the revised version.

For the financial analysis, energy prices should be adjusted using forecast inflation rates. The ERC provides net prices inclusive of inflation rates. The same applies with DEA's electricity price forecast. However, the 2014 DEA report kept the electricity price constant after 2020.

Table 6.2 Other parameters used in the 2014 mitigation report

Parameters	Units	Source	Note	2010	2020	2030	2040	2050
Capital discount rate	%	National Treasury	Guidelines provided by South African National Treasury	11.3				
Exchange rate	R/USD	Unknown	-	-	-	-	-	-
Grid electricity emission factor	t-CO_2/MWh	Unknown	Not reported	-	-	-	-	-
Transportation	Weight-t/km	Unknown	Not reported	-	-	-	-	-

The TA team has also learned from interviews that the DEA is currently revising the 2014 report; however, the new sets of data are yet to be made available to the public. In order that this study result is comparable to the 2014 report, the TA team decided to use the basic parameters used in the 2014 report to the extent possible and fill in the gaps, if any, with reasonable assumptions. Table 6.3 summarises the parameters applied in this study.

Table 6.3 Common parameters and assumptions and their reference sources used for MAC calculation

Common Parameters	Values	Units	Sources	Note and Assumptions
Electricity emission factor	1.00	CO_2/MWh	Eskom (2017)	
Electricity price	950.33	R/MWh	DEA (2013)	-Using 2010 price as a base year price.
Internal costs saved by $CaCO_3$	10 100 700	R/t	Market survey and interviews	- Three different prices based on different wastes (blast furnace slags, fry ashes, etc) that are currently used as minor additional constituents in the cement mix
Price of environmental remediation agent (ERA)	500 925 1260	R/t	Market survey and interviews	- Three different prices based on current prices available for the ERP used for treatment of acid mine drainage
Inflation rate(CPI)	5.1	%	South Africa Reserve Bank (September 2017)	- Released in October 2017
Discount rate	11.3	%	DEA (2014)	-Discount rate applied by DEA (2014) was, according to the report, based on the guidelines by National Treasury, and not a societal discount rate. National Treasury advised to use

				government bond yield as the discount rate. -The current 10-year bond yield is approx. 8.8% (Oct. 2017), whose average yield of the past 10 years was 8.269%. -While the country's prime lending rate during the same period is about 10%, it is uncertain whether the rate provided by DEA (2014) includes both risk premium and inflation.
Exchange rate	14	R/USD	Oanda interbank rate (2017 average)	

Source: DEA (2014), National Treasury (2017)[37], ERC (SATIM Methodology Appendices Version 3.2)[38], Oanda (https://www.oanda.com/currency/average)

< MAC calculation formula >

This study applies the MAC formula using net annualised cost (NAC) found in the DEA's 2014 report, where:

$$\mathrm{MAC\ (R/t-CO_2)} = \frac{\text{net annual cost (NAC)(R/yr)}}{\text{annual emission saving (t}-\text{CO}_2\text{/yr)}} \quad \text{(Equation 5)}$$

$$\begin{aligned}\text{Net Annual Cost (R/yr)} \\ &= \text{equivalent annual cost (EAC)(R/yr)} + \text{annual OPEX (R/yr)} \\ &- \text{cost savings (R/yr)} - \text{cash inflow (R/yr)}\end{aligned} \quad \text{(Equation 6)}$$

$$\text{EAC(R/yr)} = \text{initial investment} * \frac{\text{discount rate}}{1-(1+\text{discount rate})^{-period}} \quad \text{(Equation 7)}$$

This study follows the usual practice of excluding taxes, interest payments, land leasing, insurance, etc. when calculating MAC.

< MAC for waste heat recovery >

Table 6.4 shows additional parameters specific to waste heat recovery and MAC calculation results for Target plant Type I, II and III.

[37] http://www.treasury.gov.za/publications/guidelines/Capital%20Planning%20Guidelines%202017%20MTEF.pdf
[38] http://www.erc.uct.ac.za/groups/esap/satim

Table 6.4 WHR-specific parameters used for MAC calculation and the calculation results

<table>
<tr><th colspan="2"></th><th>Unit</th><th>Type I</th><th>Type II</th><th>Type III</th><th>Source/Notes</th></tr>
<tr><td colspan="2">CAPEX</td><td>Million R</td><td>208</td><td>167</td><td>208</td><td>CTCN Team</td></tr>
<tr><td colspan="2">OPEX</td><td>Million R</td><td>6.2</td><td>5</td><td>6.2</td><td>CTCN Team</td></tr>
<tr><td colspan="2">Equipment life</td><td>yr</td><td colspan="3">25 years</td><td>DEA (2014)</td></tr>
<tr><td colspan="2">Effective power generation</td><td>MWh/yr</td><td>37,785</td><td>26,874</td><td>37,785</td><td>CTCN Team</td></tr>
<tr><td colspan="2">Power consumed by MCC</td><td>MWh/yr</td><td>2,185</td><td>1,460</td><td>3,925</td><td>CTCN Team</td></tr>
<tr><td colspan="2">Grid Power replaced (Cost saving)</td><td>MWh/yr</td><td>35,600</td><td>25,400</td><td>33,860</td><td>CTCN Team</td></tr>
<tr><td rowspan="2">CO_2 emissions reduction</td><td>With MCC*</td><td>t-CO_2/yr</td><td>35,600</td><td>25,400</td><td>33,860</td><td rowspan="2">Using 1t-CO_2/MWh (Eskom 2017)</td></tr>
<tr><td>Without MCC*</td><td>t-CO_2/yr</td><td>37,785</td><td>26,874</td><td>37,785</td></tr>
<tr><td rowspan="2">MAC</td><td>With MCC*</td><td>R/t-CO_2</td><td>-234</td><td>-145</td><td>-198</td><td>CTCN Team</td></tr>
<tr><td>Without MCC*</td><td>R/t-CO_2</td><td>-276</td><td>-189</td><td>-276</td><td>CTCN Team</td></tr>
</table>

* "With MCC" includes MCC's power consumption while "without MCC" excludes it.

WHR alone can reduce as much as 37,785 t-CO_2/yr, which can result in negative MAC over a long equipment lifespan, despite the power price kept constant. Table 6.5 shows the effect of the power price.

Table 6.5 WHR: sensitivity analysis for MAC

<table>
<tr><th colspan="3"></th><th>Unit</th><th>Base</th><th>Scenario 2</th><th>Scenario 3</th><th>Scenario 4</th></tr>
<tr><td colspan="3">Electricity price</td><td>R/MWh</td><td>950.33</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td colspan="3">Inflation</td><td>%</td><td>--</td><td>5.1 (CPI)</td><td>10</td><td>15% up in 2020 + 5.1%</td></tr>
<tr><td rowspan="3">Type I</td><td colspan="2">Cost savings (w/MCC)</td><td>Million R/yr</td><td>33.8</td><td>51.5</td><td>78.8</td><td>56.4</td></tr>
<tr><td rowspan="2">MAC</td><td>With MCC</td><td>R/t-CO_2</td><td>-234</td><td>-732</td><td>-1,498</td><td>-868</td></tr>
<tr><td>Without MCC</td><td>R/t-CO_2</td><td>-276</td><td>-773</td><td>-1,540</td><td>-910</td></tr>
<tr><td rowspan="3">Type II</td><td colspan="2">Cost savings (w/MCC)</td><td>Million R/yr</td><td>24.1</td><td>36.8</td><td>56.2</td><td>40.2</td></tr>
<tr><td rowspan="2">MAC</td><td>With MCC</td><td>R/t-CO_2</td><td>-145</td><td>-642</td><td>-1,409</td><td>-778</td></tr>
<tr><td>Without MCC</td><td>R/t-CO_2</td><td>-189</td><td>-686</td><td>-1,453</td><td>-823</td></tr>
<tr><td rowspan="3">Type III</td><td colspan="2">Cost savings (w/MCC)</td><td>Million R/yr</td><td>32.1</td><td>49.0</td><td>75.0</td><td>53.5</td></tr>
<tr><td rowspan="2">MAC</td><td>With MCC</td><td>R/t-CO_2</td><td>-198</td><td>-695</td><td>-1,461</td><td>-830</td></tr>
<tr><td>Without MCC</td><td>R/t-CO_2</td><td>-276</td><td>-733</td><td>-1,540</td><td>-910</td></tr>
</table>

Scenarios 2 and 3 show the impact of inflation on MAC while Scenario 4 envisages a sharp increase in the price after the introduction of the carbon tax and the price increase with a moderate inflation rate thereafter. Regardless, these assumptions suggest that the inflation alone can improve MAC two to three times more than the base year.

From the cement companies, Scenario 4 is particularly important with the expected rise in the power price with carbon tax. From that perspective, WHR can be an attractive solution to reduce the operation costs.

MAC analysis for MCC installation

For the MAC calculation, it is important to identify the emissions boundary. As the draft carbon tax bill defines the taxable boundary to Scope I (direct emissions), the reasonable choice for calculating CO2 emissions reduction by MCC&U is to limit it to Scope I as well. However, indirect emissions accrued from using power (Scope II) and transporting raw materials (Scope III) are usually accounted in carbon offset credit calculations. Therefore, this study will include all scopes for the MAC calculation.

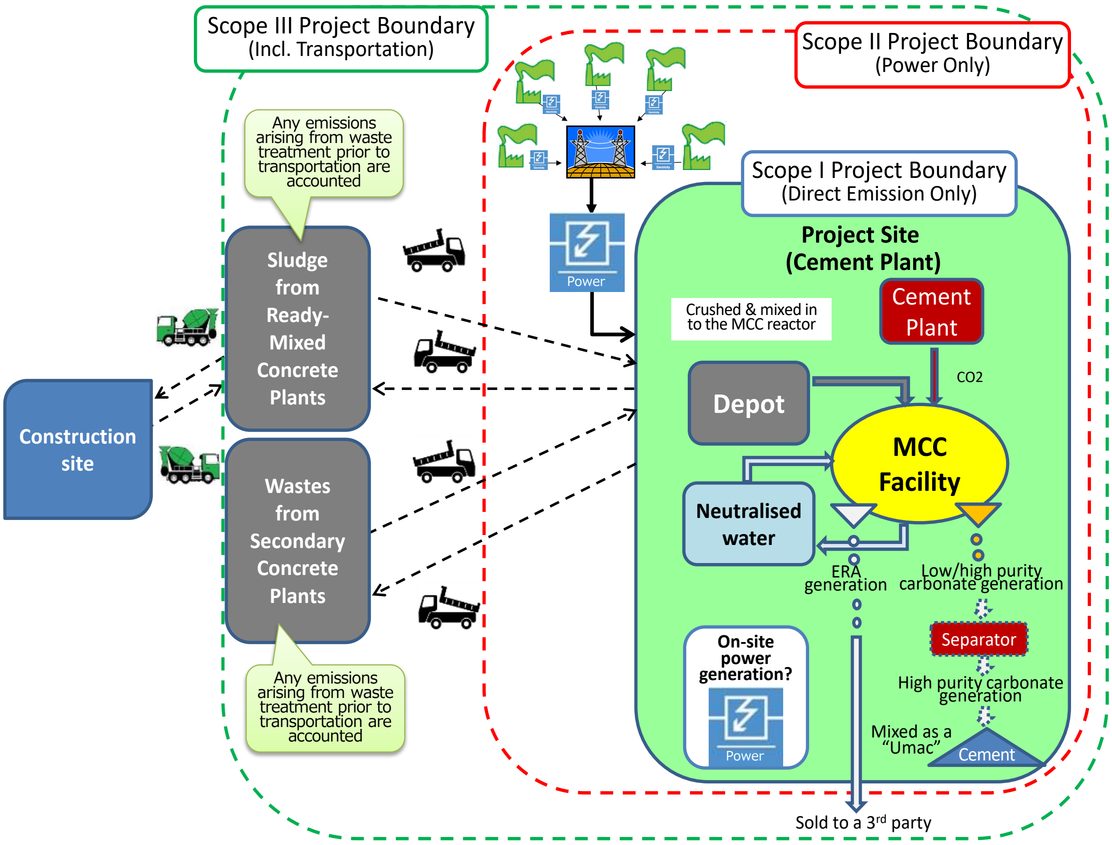

Fig. 6.1 Boundary for the CO_2 emissions accounting

In addition to common parameters mentioned in Table 6.6, site specific parameters used for MAC calculation are summarised in Table 6.6.

Table 6.6 MCC&U-specific parameters used for MAC calculation

		Unit	Type I	Type II	Type III	Source/Notes
CAPEX		Million R	448.6	295.9	267.3	CTCN Team
OPEX* (transportation diesel)		Million R/yr	164	55	74	CTCN Team,
Discount rate		%	11.3%			DEA (2014)
Inflation		%	5.1%			Reserve Bank, 2017
Equipment life		yr	15 years			CTCN Team
Power required		MWh/yr	0 (using the power from WHR)			CTCN Team
Sludge treated		t/yr	168,000	112,000	302,000	CTCN Team
By-products	$CaCO_3$	t/yr	67,230	44,900	215,000	CTCN Team
	ERA**	t/yr	100,950	67,300	0	CTCN Team
Cost saved by $CaCO_3$		R/t	10/100/700 (all inflated @5.1%)			CTCN Team
ERA? price		R/t	500/925/1260 (all inflated @5.1%)			CTCN Team
CO_2 emissions reduction	MCC	t-CO_2/yr	26,800	17,900	86,000	CTCN Team
	$CaCO_3$	t-CO_2/yr	43,600	29,100	139,700	0.65 t-CO_2/t-cement
	Total	t-CO_2/yr	70,400	47,000	225,700	--

*OPEX does not include the cost for water used to fill in a first batch. Water is recycled then after.
** ERA stands for environmental remediation agent.

CAPEX is calculated based on the annual amount of sludge to be treated. Although Type III has nearly twice as much sludge as Type I, economies of scale and adjustment in operating hours contribute to the significant cut in the initial investment. Type I may also reduce CAPEX further if the operation hours can be adjusted. Power required for the operation of the MCC system is provided by WHR. However, if grid power is used, this will be added into OPEX. CO_2 emissions reduction by $CaCO_3$ results from its use as a minor additional constituent in the cement mix. This will also reduce operation costs by substituting currently used materials (blast furnace slags, fly ashes, etc.) purchased from outside.

For the diesel consumed in transportation, RSA data is not readily available to the public. Thus, Japanese, IPCC and International Energy Agency (IEA) data are used to derive the conservative figures (i.e. 2.619 L/t-km and 7.65×10^{-5} tCO_2/t-km for 100% loaded to calculate the high project emissions) for the MAC calculation.

Table 6.7 Transportation diesel consumption

Parameters	Units	Japanese data	IPCC/IEA
Density	kg/L	--	0.843
Heating value	GJ/kL	38.20	36.25
	GJ/t	--	43.00
Emission factors	t-C/GJ	0.019	0.020

		$t\text{-}CO_2/kL$	2.619	2.685
Weight index for 12-17 tonne trucks	t-km (100% loaded)	L/t-km	2.619	--
	t-km(10% loaded)	L/t-km	0.0285	--
	t-km (100% loaded)	$t\text{-}CO_2/t\text{-}km$	7.46E-05	7.65×10^{-5}
	t-km(10% loaded)	$t\text{-}CO_2/t\text{-}km$	4.85E-04	4.97×10^{-4}

MAC for MCC&U is highly affected by (i) the unit cost of the substitution materials for minor additional constituents and (iii) profits accrued from sales the ERA. As both costs and price figures each have three variations, 9 different combinations are examined in Table 6.8.

Table 6.8 MCC&U: Sensitivity analysis for MAC (case of 9 combinations)

Cost Savings by $CaCO_3$(R/t)			**Price for ERA (R/t)**			**MAC (R/t-CO_2)**		
H	M	L	H	M	L	**Type I (transport D =200km)**	**Type II (transport D =100km)**	**Type III (transport D =50km)**
700	100	10	1260	925	500			
H			H			**-356**	**-1,022**	**-1,515**
H				M		340	**-558**	
H					L	1,224	31	
	M		H			474	**-467**	1,141
	M			M		1,171	**-3**	
	M				L	2,054	586	
		L	H			599	**-384**	1,540
		L		M		1,295	80	
		L			L	2,179	669	

The sensitively analysis shows that the impact created by $CaCO_3$ from cost savings is relatively less than the impact created by the price of ERA. This is due to a difference in the generated volume. The breakeven price for ERA in the case of Type II, for instance, is approximately 923 t if $CaCO_3$ results in 100 R/t of cost savings. If the transportation costs can be reduced by using reverse logistics, MCC&U's MAC will further improve.

This study does not take into account any costs related to collecting sludges. Some of the waste materials, especially aggregates, are used as roadbeds. Some companies give them away for free to whoever would like to collect, while for others they are saleable commodities. MCC&U can be designed to collect "real wastes" that have no markets for secondary use in order to avoid competition with existing markets.

7. Business Plans

7.1 Feasible scenarios

The TA team considered the installation of WHR in RSA at a cement plant producing more than 3,000t-clinker/d. It was established that each major component of WHR and MCC&U equipment, other than the WHR turbine, as indicated in Table 7.1 and Table 7.2, could be procured in RSA. An approximate average investment cost, including the importation of a turbine, is estimated at between US$14 and 20million based on information and construction experience in several developing countries.

On the other hand, since a single MCC reactor unit with a volume of 60 m^3 is estimated at US$1 million based on data from Japan, the MAC calculation suggests that the project would be feasible only when the by-products can be sold at a high price in the market. Therefore, further study will be necessary to reduce the investment cost of the MCC reactor units, develop a more efficient MCC process, including expansion of MCC reactor size, and develop a new application or market for the by-products in RSA.

Table 7.1 List of WHR equipment details

Segments	Specification	Number
Preheater boiler	Waste heat boiler (PH exhaust gas, dust laden 200g/m^3N) Horizontal type, (vertical boiler tubes) with circulation pump, with de-dusting facility (soot blow and hammering device) Inlet gas temp. 400 °C, Outlet gas temp. 230 °C Gas volume 285,000 m^3N/hr Generated steam 37 t/h Steam pressure 17.5 kg/cm^2 Steam temperature 370 °C Heat transfer area boiler 7,674 m^2 Super heater 1,322 m^2	2
AQC boiler	Waste heat boiler (AQC exhaust air, dust laden 50g/m^3N) with pre-dusting facility Vertical type, for hot water supply Inlet gas temp 255 °C, Outlet gas temp 110 °C Gas volume 198,000 m^3N/hr Generated hot water 110t/h Steam pressure 45 kg/cm^2	1
Turbine imported	8,000kW	1
Generator	8,000kW 3,3kV, 1,500rpm	1
Condenser	To fit this boiler-turbine circle	1

Electric panel, switchgear, controlling equipment	Same as that of coal fired power station of same power output	1 set
Feed water pump	Horizontal single stage volute pump, Capacity 390t/h Pressure 22kg/cm^3 Feed water temperature 210 ^oC Motor power 75kW	2
Cooling tower	To fit the boiler-turbine circle	1
Connecting duct	Preheater–Boiler, Boiler–Preheater exhaust fan, AQC–Boiler Boiler–Dust collector, To be inserted to existing gas ducts	1 set
Civil and structure		1 set

Table 7.2 List of MCC unit equipment details

Segments	Specification	Number
Ca extraction reactor	Vertical vessel with agitator Capacity 60 m^3 Temperature Ambient Pressure Ambient	1
CaCO3 crystallisation reactor	Vertical vessel with agitator and CO_2 feeding nozzle Capacity 60 m^3 Temperature Ambient Pressure Ambient	1
Slurry pump	Centrifugal pump Capacity 30 kW	1
Recycle water pump	Centrifugal pump Capacity 30 kW Feed water temperature Ambient Pressure Ambient	1
Solid-liquid separator	Slurry feed volume 10 t/hour Solid portion after separation 5 t/hour (water content 50％) Liquid portion after separation 5 t/hour	1
Feeding crane	Capacity 1 tonne	1
Electric panel, controlling equipment	Same as that of water treatment facility	1 set

Based on the results of MAC analysis, excluding consideration of carbon tax, the feasibility of business plans are considered as the following negative costs indicated in Table 6.8. From the viewpoint of economic feasibility, further marketing of both by-products in RSA will be a priority action to support the introduction of the MCC&U technology. On the aspect of the SDGs(e.g. Goal 5 and Goal 8)[39], the MCC technology is relatively unsophisticated so this may give a new horizon of opportunities to less skilled workers (both male and female)[40] to work in an environment surrounded by the more highly-skilled workforce of cement plants.

Business Plan (Target Site Type I)

The kiln capacity of a cement plant is full-scale (over 3,000 t-clinker /d) and 30% of concrete sludge generated from ready-mixed concretes plants together with waste concretes from concrete product plants are transported to the plant over a distance of 200km. It is found that the transportation cost of input materials to the MCC&U plant affects results of the MAC calculation. Therefore, most of the plans could not be feasible unless all $CaCO_3$ is utilised for AMD treatment only or other applications can be identified that will realise a higher price than for use as $U_{mac.}$ Furthermore, ERA will need to be sold at a very high price (approx. half of commercial $Ca(OH)_2$). If rail transportation could be applied from the site to the plant, other options at Target Site Type I would become feasible.

As a constant supply of the input materials may not be secured for Target Site Type I conditions, MAC in this study is calculated with limited operation hours. However, if the plant can be operated for 24 hours, the number of reactors and new workforce required for the MCC treatment could be reduced to 16 x 60m^3 reactors and approx. 24 newly employed workers accordingly.

Business Plan (Target Site Type II)

The total kiln capacity of a cement plant with multi-kilns is approximately 3000 t-clinker/d and 20% of concrete sludge generated from ready-mixed concretes plants together with waste concretes from concrete product plants are transported to the plant over a distance of 100km. The following cases would be feasible plans;

- $CaCO_3$ is utilised for AMD treatment instead of U_{mac} and ERA is sold at approximately 50% of the price of commercial $Ca(OH)_2$ (between 925 and 1,260(R/t) or
- Both of $CaCO_3$ and ERA is sold at a high price.

As with Type I, Target Site Type II it is also conservatively assumed that securing a certain level of supply of the input materials may be difficult. If the plant can be operated for 24 hours, the number of reactors and new workforce required for the MCC treatment could be reduced to 10 x 60m^3 reactors and approx. 16 newly employed workers accordingly.

Business Plan (Target Site Type III)

The kiln capacity of a cement plant is full-scale (over 3,000 t-clinker/d). Concrete sludges are not

[39] http://www.un.org/sustainabledevelopment/sustainable-development-goals/

[40] South Africa has a long history introducing legislations and guidelines to empower unfairly discriminated citizens of the country including their employment. Some of the prominent legislations include Employment Equity Act of 1998 and Black Economic Empowerment Act of 2003, which protect discriminated citizens (female, black and disabled employees) and introduce systems to attract business owners to employ those employees.

available near the plant but an alternative material such as lime dust is used. Transportation distance of lime dust is 50 km. Although Type III is estimated to reduce CO_2 greatly, it is much more difficult to demonstrate its financial feasibility. $CaCO_3$ is utilised for AMD treatment instead to U_{mac} and ERA is sold with a high price (approximately half the price of commercial $Ca(OH)_2$).

Unlike Type I and Type II, Target Site Type III has an abundant supply of the input materials (i.e. lime dusts), 28 x 60m^3 reactors are expected to operate continuously for 24 hours at the plant. This will require approx. 32 newly employed workers to be newly employed for the MCC&U technology.

7.2 Post CTCN scenario

Prior to the installation of the proposed facility in a cement plant, the following steps should be considered;

- A bench-scale MCC&U reactor should be installed as soon as possible to produce $CaCO_3$ and ERA using concrete sludges and waste concretes generated in RSA and their performance assessed in comparison with commercial remediation agents. The MCC plant for the bench-scale reactor would consist of two 1 m^3 reactors of either mobile (option A) or stationary type (option B).
- In parallel with operator training and development of applications for the by-products, R&D on the use of demolished concretes as an alternative input material will be conducted at appropriate research institutes to increase the potential CO_2 emissions reduction.
- Private company has to either spend their own budget or find any financial aid including international funds to install the MCC&U reactor.

Option A comprises a mobile bench-scale MCC&U reactor (US$ 500,000) manufactured in Japan as illustrated in Fig. 7.1 and the operator training with an additional charge as follows:

1) Engineers from RSA would be invited to undertake training in MCC&U reactor operation for one month in Japan
2) The MCC&U reactor will be shipped from Japan and installed on a trailer in RSA
3) MCC&U experts will provide operational technical assistance at least for one week

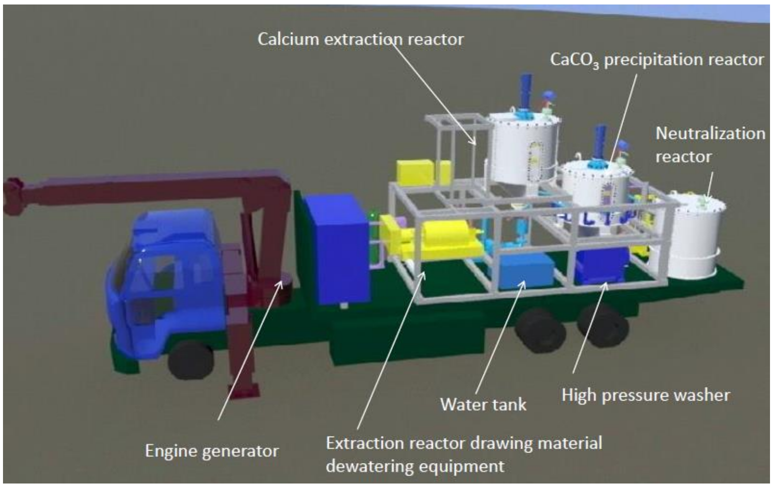

Fig. 7.1 An image of the mobile bench-scale plant[41]

[41] Provided by Nippon Concrete Industries Co., Ltd., Japan

Option B comprises a stationary MCC&U reactor manufactured in RSA under supervision of technology experts. Although the cost would be less than that of option A, an operational training for engineers for MCC&U reactor should be considered until the reactor is well operated.

After understanding the results of the bench-scale operation and experience, the installation of a pilot hybrid plant (or a hybrid plant with a combination of a commercial-scale WHR and a small-scale commercial plant of MCC&U) is proposed as the next step. Many components of the system, except for the WHR turbine, can be locally procured and the hybrid facility of WHR and MCC&U installed by local contractors under supervision of (possibly Japanese) technology experts.

7.3 Financial assistance

The CTCN study on the proposed hybrid technology identified a potential emissions reduction of approximately 7.5 to 7.7% from the cement industry in RSA. Furthermore, the MCC&U technology could deliver a "paradigm shift" to achieve sustainable development goals (SGDs) as follows:

- Easy operation (Goal 5, 8 & 9)

  Unlike conventional CCS technologies, MCC can capture and mineralise CO_2 in cement kiln gas without using any chemicals and in ambient temperature and pressure conditions. All MCC&U components could be procured in the country and it is possible for both male and female to operate it.

- Utilisation of industrial wastes (Goal 9, 12 & 13)

  Two types of marketable by-products delivered from the industrial wastes contribute to conserving resources as well as CO_2 emissions control and further reducing its operating costs providing “Negative” marginal abatement costs.

- Improvement of resource efficiency (Goal 6, 9 &12)

  The environmental remediation agent delivered from concrete wastes can be applied to recover mineral resources such as phosphorus.

Therefore, the MCC&U component provides a new means to reduce GHG emissions (Goal 13) while contributing to other SDGs (e.g. Goal 9 and Goal 12) and also scale-up the level of the GHG emissions reduction by diffusing the technology not only in RSA but also in other countries. The technology also holds a promising potential to apply to other sectors and further create positive impacts. However, innovative technologies such as MCC&U need a demonstration step in order to convince financiers or any risk takers to scale-up the project to the commercial level. Although stakeholders from the cement sector have shown their strong interest in the MCC&U technology and they agreed the need for a demonstration project, all of them appear hesitant after learning the estimated costs. Facing severe competition and the possible increase in operating costs due to the carbon tax, they commented that they would require a subsidy to move onto the next step. The cement companies may look into both national and international financial assistance. Nationally, they may consult with the Department of Trade and Industry (DTI) which provides financial support and incentives to qualifying companies in various sectors of the economy including manufacturing industries[42]. Internationally, they could

[42] Details of the DTI's assistance can be found at https://www.thedti.gov.za/financial_assistance/financial_assistance.jsp

approach bilateral or multilateral funds. Within the limited time available, the TA team searched for appropriate bilateral programs to match the cement sector's needs, but without success. Multilateral funds including GCF may be further limited in number, yet may be significant in supporting the deployment of new technologies with a potential of substantial GHG reductions.

The TA Team explored different options for financing the bench-scale and pilot-scale plants. Although the cost for introducing the bench-scale plant for the MCC&U is not excessive (approximately USD 14 to 20 million including the aforementioned training), the investment required for introducing the pilot-scale hybrid plant is similar to that of establishing a commercial plant due to the inclusion of a commercial-sized WHR system. According to interviews with South African government representatives, the government has one dedicated website called "Government Investment Incentives"[43] which provides a wide range of financial incentives applicable to projects from R&D to commercial-scale plants. Furthermore, the opportunity to secure financial assistance and subsidies for the construction of a mobile bench-scale plant may be improved if the plant is semi-shared property owned by, for instance, a public entity or research institute, and is accessible to everyone for the benefit of the whole cement sector. In addition, various assistance schemes from international organisations and are available for training.

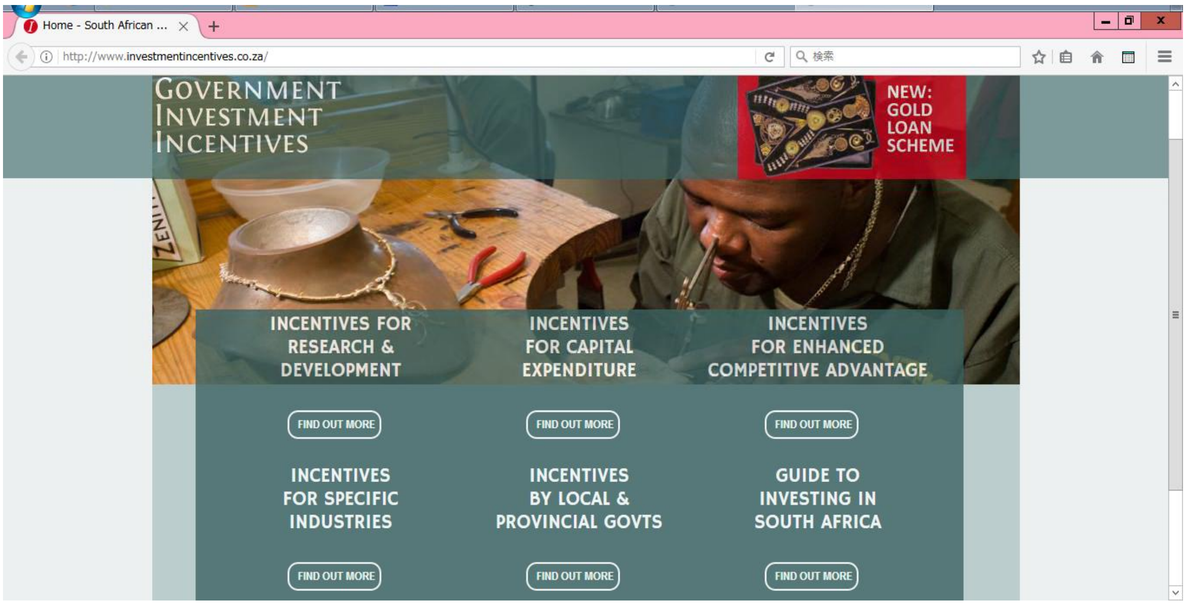

Fig. 7.2 "Government investment incentives" site

For the pilot plant, cement companies may secure a mixture of traditional loan-equity finance together with various incentives provided by the government and international organizations. Companies in RSA approach Industrial Development Corporation (IDC) to access loans with low-interest rates for manufacturing industries[44]. Among various assistance schemes provided by international organisations, one notable option may be to use the Green Climate Fund (GCF)[45]. GCF is the financing

[43] http://www.investmentincentives.co.za/
[44] https://www.idc.co.za/
[45] http://www.greenclimate.fund/home

arm of the UNFCCC fostering climate finance investment, including private investment. GCF requires an accredited entity (AE) in order to access to their resources. South Africa has one existing AE, the DBSA, and one potential new AE, the IDA. However, the IDC can handle only adaptation-related projects and the DBSA is limited in its target project-types[41]. The most suitable entity for the proposed hybrid project is the IDC. South Africa has one existing AE, the DBSA, and one potential new AE, the IDA. However, the IDC can handle only adaptation-related projects and the DBSA is limited in its target project-types[41]. The most suitable entity for the proposed hybrid project is the IDC. The TA team has exchanged some different options with the IDC, including the initiation of a new fund to assist projects such as the one proposed under this TA.

7.4 Barriers for implementation

WHR Installation

The RSA cement sector has been facing severe competition with more and more new market players coming into the domestic market. Furthermore, there is a constant threat from cheap, imported cement. Under such circumstances RSA cement manufacturers are sensitive to new large-scale investments such as WHR. The payback period of WHR may be around 5 years but this is entirely affected by the price of electricity. It is likely that the decision to invest in WHR will be supported by rising electricity prices but will also depend on the availability of financial incentives and the effects of the introduction of carbon tax.

Under the draft carbon tax bill, only Scope 1 emissions are taxable. Thus, any CO_2 emissions reduction by WHR will not directly contribute in alleviating cement companies from taxation of CO_2 emissions.

It is possible that indirect emissions reduction such as those realised by WHR may be registered as carbon offset credits[46] and used to reduce the tax. However, RSA has not yet established its domestic offset credit scheme yet and, in the interim period, the government is expected to allow only internationally recognised offset credits (Clean Development Mechanism, Voluntary Carbon Standards, Gold Standard, etc). This would be an additional burden for cement manufacturers —both time and resources.

In short, the cement manufacturers may install WHR if the rise in the electricity price is significant and affects its operation costs. Carbon tax and offsets may not be strong enough to motivate them to invest in WHR unless there are additional, effective incentive schemes provided along with the implementation of the carbon tax.

MCC Installation

Regarding MCC&U technology, the followings are especially major barriers related to collection and transportation of the concrete wastes as its logistics impacts the economic viability. Simultaneously, local regulations on the MCC operation should be checked.

<u>Technical Barriers</u>

In RSA cement sludge resulting from centrifugal molding is not available. Alternative input materials to the MCC reactor are therefore required such as other industrial wastes containing calcium sources suitable for the carbonation reaction. Blast furnace slag and fly ash available but these are expected to be difficult to apply to the MCC reaction. In order to select appropriate input materials for MCC&U it will be necessary to conduct further research on the carbonation reaction with the available wastes and trial operation using a bench-scale MCC&U plant. Then, the physical property of each by-product can be analyzed and the potential volumes generated estimated. Furthermore, in order to assess the effectiveness of ERA obtained through the MCC reaction on AMD treatment, on-site field testing should be conducted to compare performance with commercial agents.

[46] There are on-going discussions on what could be claimed as "carbon offsets" in the context of the carbon tax bill, and depending on the outcome, WHR may or may not be applicable to become a carbon offset.

The region where concrete is consumed in the greatest volumes is far away from the cement plants. Therefore, concrete sludge generated in concrete product plants must be transported to the cement plant where the MCC&U facility is to be installed. This is a distance of approximately 200 km. Regional availability of concrete sludges remains critical in term of quantity and its impact on transport costs. However, since the transportation network is not well developed, transportation of the waste steams needs to be firstly considered.

Economic Barriers

Regarding waste treatment, low cost disposal methods are generally adopted. Landfilling is currently used as the preferable treatment in RSA.

The transportation cost of input materials, such as concrete sludge and waste concretes, depends on the distance between the sites where such wastes are generated and the location of the MCC&U plant. Therefore, cost effective measure should be considered to reduce the cost and CO_2 emissions from haulage vehicles. It will therefore be important to only transport the effective calcium in the wastes to the MCC&U plant, for instance by introducing pre-treatments such as the removal of coarse aggregates from the concretes at the concrete plant.

Common practice, market awareness and acceptance need to be enhanced as in some regions consumers/contractors are reluctant to use ERAs. This can be attributed primarily to a lack of awareness on the side of consumers/ contractors and to a lack of commercialization of by-products such as environmental remediation agents on the procurement side

Legal Barriers

MCC&U technology needs to be added to the priority list in the government's "South Africa's Green Climate Fund Strategic Framework" if this fund is used for the project implementation.

It is recognised that demolished concrete in West Cape has to be treated in accordance with strict local regulations and the environmental regulations in Johannesburg and Pretoria are generally severe. However, incentives for disposal treatment of concrete sludges and demolished concrete are not usually available and low cost landfilling is the most acceptable option in RSA. Therefore, the cost and value of waste treatment should be considered in order to introduce MCC&U technology in RSA.

Other future concerns on low carbon cement[47]

Blended cements, where a percentage of the clinker is substituted by natural pozzolana or industrial wastes such as blast furnace slag and fly ash, is expected to reduce CO_2 emissions from the cement sector. However, if the clinker-to-cement ratio is reduced in this way, the effective calcium content of the cement will also decrease. Therefore, the available effective calcium content of concrete based wastes to be used in the MCC reactor will decrease, thereby reducing the potential volume of carbon captured.

[47] https://www.wbcsdcement.org/pdf/technology/CSI_ECRA_Technology_Papers_2017.pdf

Furthermore, it is recognized that geopolymer cement[48], produced by the reaction of an aluminosilicate precursor material such as metakaolin or fly ash with an alkaline reagent (e.g. sodium or potassium soluble silicates) and water, is a binding system that hardens at room temperature as well as ordinary cement. It relies on minimally processed natural materials or industrial wastes to realise a significantly lower carbon footprint than portland cement. However, it is unclear how much effective calcium is contained in concrete produced with geopolymeric cement. Furthermore, the global market for geoploymers remains limited since such new types of cement are presently only used in non-structural applications. In the future, any increase in volumes of “low carbon” cement becoming utilised may lead to a decrease in the availability of effective calcium in concrete wastes for application to the MCC&U technology. Therefore, additional waste streams containing calcium or magnesium will need to be identified in order to preserve the effectiveness of the MCC&U technology.

[48] http://bze.org.au/rethinking-cement-plan/

8. Conclusion

The following key findings including drivers, barriers and recommendations are identified through the CTCN TA project:

Key Findings

- **WHR installation – drivers and barriers for implementation**

Cement manufacturers will install a WHR plant if commercial viability proves to be attractive. However, the current initial investment cost of WHR remains high and not yet competitive enough in comparison to utility supply costs. Renewable energy costs are also dropping drastically, and it further places WHR installation into a challenging competitive space. Thus, introducing new financial assistance and incentives (including subsidies) for WHR by the government may help cement manufacturers to choose the WHR option.

- **MCC installation – drivers and barriers for implementation**

The MCC&U technology could deliver a "paradigm shift" by scaling up the level of the GHG emissions reduction (Goal 13 of SDGs) [49] within both RSA and other countries, while utilisation of industrial wastes containing calcium and improvement of resource efficiency contribute to attaining other SDGs (e.g. Goal 9 and Goal 12).

However, cement sludge resulting from centrifugal molding is not available in RSA. Therefore, possible methods of generating carbonates using recycled fine aggregates from demolished concrete have been assessed, as well as a method to search for various industrial wastes containing calcium and magnesium components. However, it would be necessary to conduct further research on the carbonation reaction with such available industrial wastes and trial operation using the bench-scale MCC&U plant.

Regarding waste treatment in RSA, landfilling is currently generally adopted as the preferable low cost disposal / treatment method. The distance between source sites of concrete sludges and waste concrete, and the full-scale cement plants where MCC&U plant is installed, and the associate logistics can be major barriers to the increased and effective use of all input materials for the MCC reaction as it impacts the economic viability. Furthermore, a system for collecting and transporting the input materials needs to be established since concrete sludges are generated in the geographically dispersed ready-mixed concrete plants and secondary concrete product manufacturing plants.

In the future, any increase in volumes of "low carbon cement"[50] becoming utilised may lead to a decrease in the availability of effective calcium in concrete wastes for application to the MCC&U, thereby reducing the potential volume of carbon captured. For example, blended cements, where a percentage of the clinker is substituted by natural pozzolana, blast furnace slag or fly ash, is expected to reduce CO_2 emissions. Furthermore, it is recognized that geopolymeric cements[51] are being developed as binders with a significantly lower carbon footprint. Therefore, additional waste streams

[49] http://www.un.org/sustainabledevelopment/sustainable-development-goals/
[50] https://www.wbcsdcement.org/pdf/technology/CSI_ECRA_Technology_Papers_2017.pdf
[51] http://bze.org.au/rethinking-cement-plan/

containing calcium or magnesium will need to be identified in order to preserve the effectiveness of the MCC&U technology.

- **Accounting and reporting for GHG emissions reduction**

Since MCC&U technology is a newly developed innovative technology, there is presently no methodology available for calculating the GHG emissions reduction. It is therefore necessary to urgently develop the methodology in line with domestic regulations, especially if the CO_2 captured by means of MCC&U is to be used to reduce the carbon tax, which will be levied in RSA. The design of a policy framework is also expected so that the methodology developed can be incorporated into the NDC.

- **By-products from MCC**

In order to reduce the GHG marginal abatement cost, it is necessary to sell the by-products. $CaCO_3$ can be utilised as a minor additional constituent for portland cement, as a neutralizing agent for acid mine drainage (AMD) treatment and for other applications. With a view toward commercialisation, environmental remediation agents produced locally using concrete sludges may require onsite assessment for treating AMD at mining sites or for recovering phosphorous at sewage treatment facilities.

Furthermore, common practice, market awareness and acceptance need to be enhanced as in some regions consumers/contractors are reluctant to use ERAs. This can be attributed primarily to a lack of awareness on the side of consumers/ contractors and to a lack of commercialisation of by-products such as environmental remediation agents on the procurement side.

- **Business plans**

Three categories of business plan, all excluding the introduction of carbon tax, are proposed in this study. It was explored that each major segment of WHR and MCC&U equipment excluding a turbine could be procured in RSA. When a pilot hybrid plant is installed at the cement plant produced more than 3,000t-clinker/d, an approximate average investment cost for WHR is estimated between US$14 and 20million based on information and construction experiences in several developing countries.

On the aspect of the SDGs (e.g. Goal 5 and Goal 8), the MCC technology is relatively unsophisticated so this may give a new horizon of opportunities to less skilled workers (male and female) to work in an environment surrounded by the more highly-skilled workforce of cement plants. As a result of introducing the MCC&U technology, more than 16 workers at each site will be newly employed.

On the other hand, since one unit of MCC reactors with 60 m^3 is estimated to cost US$1 million, MAC calculation suggests that the project would be feasible only when the by-products can be sold at high price in the market. From the viewpoint of economic feasibility, further marketing of both by-products in RSA will be a priority action to support the introduction of the MCC&U technology. In West Cape, demolished concrete particularly has to be treated in accordance with strict local regulations. The environmental regulations in Johannesburg and Pretoria are generally severe.

Therefore, the introduction of MCC&U could be initiated in such areas to encourage appropriate disposal treatment of concrete sludges.

- **Finance assistance**

The CTCN study on the proposed hybrid technology concluded that a potential emissions reduction of approximately 7.5 to 7.7% could be realised from the cement industry in RSA. The MCC&U component is a technology that could deliver a "paradigm shift" as a new means to reduce GHG emissions (Goal 13 of SDGs) while contributing to other SDGs (e.g. Goal 9 and Goal 12) and also scale-up the level of the GHG emissions reduction by diffusing the technology not only in RSA but also in other countries. The technology also holds a promising potential to apply to other sectors and further create positive impacts. However, securing finance for new, innovative technologies is always difficult as financiers often perceive them as high-risk investments.

Applying for the UN's Green Climate Fund (GCF) could be one possible solution to mobilise finance for the innovative technologies. GCF is an appropriate funding source to introduce sector-wise measures as well. The MCC&U technology needs to be added to the priority list in the government's "South Africa's Green Climate Fund Strategic Framework" if GCF is to be used for the project implementation.

Founded in 2010, GCF "*aims to catalyze a flow of climate finance to invest in low-emission and climate-resilient development, driving a paradigm shift in the global response to climate change*[52]". CTCN has already paved a linkage with GCF to assist project developers to prepare funding proposals and access to GCF funding. If CTCN can also guide the cement companies an easier pathway to securing financial support to conduct the demonstration project recommended by the TA team may be realised. Consequently, diffusion of the innovative technology will be accelerated toward contributing to meeting the 2^{o}C target.

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52 http://www.greenclimate.fund/who-we-are/about-the-fund

Glossary

- **aggregates**: materials used in construction, including sand (fine aggregate), gravel (coarse aggregate) and crushed stone
- **cement**: a material made by crushing and heating limestone with small amounts of other natural materials, such as clay or shale, in a rotating kiln to a temperature of 1450°C. The intermediate product, clinker, is then ground together with various mineral components such as gypsum, limestone, blast furnace slag, coal fly ash and natural volcanic material to produce cement. It acts as the binding agent when mixed with sand, gravel or crushed stone and water to make concrete. While cement qualities are defined by national standards, there is no worldwide, harmonised definition or standard for cement.
- **cement sludge**: sludge without any aggregates generated when concrete products are manufactured using centrifugal molding techniques
- **concrete sludge**: sludge generated from ready-mixed concrete plants
- **clinker**: an intermediate product in cement manufacturing and the main substance in cement. Clinker is the result of calcination of limestone in the kiln and subsequent reactions caused through burning
- **CTCN**: established in December 2010 within the operation of the UNFCCC for the purpose of accelerating the transfer of environmentally-sound technologies for low carbon and climate resilient development.
- **ERA**: environmental remediation agent delivered from MCC&U technology
- **fly ash**: exhaust-borne particulates generated and captured at coal-fired power plants
- **NDC**: nationally determined contribution
- **pH**: index of the density of a hydrogen ion
- **portland cement**: the most common type of cement, consisting of over 90% clinker and about 5% gypsum
- **recycled aggregate**: aggregate produced by crushing and milling demolished concrete
- **TA**: technical assistance under the CTCN
- **U_{mac}**: utilised $CaCO_3$ delivered from MCC&U technology as a minor additional constituent of portland cement
- **waste concrete**: waste concrete generated from secondary concrete product manufacturing plants

Abbreviations, acronyms and units of measure

Abbreviations and acronyms

- **ACMP**: Association of Cementitious Material Producers
- **AMD**: acid mine drainage
- **AQC**: air quenching cooler
- **CCS**: carbon capture and sequestration
- **CCU**: carbon capture and utilisation

- **CGS**: Council for Geoscience; see www.geoscience.org.za
- **CO_2**: carbon dioxide
- **CO_2U**: CO_2 utilisation
- **CSI**: Cement Sustainability Initiative; see www. wbcsdcement.org
- **GHG**: greenhouse gas
- **ICEF**: Innovation for Cool Earth Forum; see www.icef-forum.org/index.html
- **IEA**: International Energy Agency; see www.iea.org
- **MAC**: marginal abatement cost
- **MCC&U**: mineral carbon capture and utilisation
- **NDE**: nationally designated entity
- **PH**: pre-heater of a cement kiln
- **RSA**: Republic of South Africa
- **UCT**: University of Cape Town; see www.uct.ac.za
- **USD**: United States dollar
- **UNFCCC**: United Nations Framework Convention on Climate Change; see unfccc.int/2860.php
- **WHR**: waste heat recovery for electric power generation
- **WBCSD**: World Business Council for Sustainable Development

Units of measure

^{o}C : degree Celsius

kWh : kilowatt hour (10^3 watt hour)

L: litre

ML: million litre(10^6 litres)

Mt: million tonne (10^6 tonnes)

Mt/yr : million tonne (10^6 tonnes) per year

MW: megawatts (10^6 watts)

MWh: megawatts (10^6 watts) per hour

m^3 : cubic meter

R : Rand (currency of South Africa (ZAR))

R/t : Rand per tonne

t : tonne

t/d : tonne per day

t/yr : tonne per year

t-clinker: tonne of clinker production

t-CO_2 : tonne of CO_2 emissions

t-CO_2/t-km: tonne of CO_2 emissions per tonne and kilometer

yr : year

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