Financial Attractiveness of LC^3

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EXECUTIVE SUMMARY

Cement is the most widely consumed building product in the world. Due to the huge volume produced, cement production is responsible for around 8% of man-made CO_2 emissions. In 2017, the level of cement consumption worldwide reached 4'133 million tons. This represents a 60% increase since 2006, with continuing growth projected by an additional 12–23% by 2050. Among the four principle CO_2 reduction levers for the cement industry developed by the International Energy Agency (IEA), reducing clinker in cement is by far the most effective. Moreover, of the different potential alternatives to clinker, calcined clay is the most sustainable and promising.

Limestone together with calcined clay are unique among supplementary cementitious material (SCMs), as they not only offer excellent properties when used in combination with cement, but conversely to other SCM's their availability is unlimited. Limestone calcined clay cements (LC^3) are blended cements that combine clinker, calcined clay, limestone, and gypsum. They take advantage of the high reactivity of calcined clay and the synergistic reaction between limestone and clay, offering equivalent mechanical performance to Ordinary Portland Cement (CEM I/OPC), with the benefit of decreasing clinker factors to 50%. LC^3, while retaining the mechanical behaviour of OPC, also significantly improves some relevant properties such as resistance to chloride ingress and alkali silica reaction as compared to other cements. Furthermore, limestone and calcined clays are among the few raw materials available in the quantities required to constitute a technology suitable for coping with the projected worldwide demand for cement.

In addition to these technical advantages of LC^3, this technology also allows significant CO_2 emission savings. A detailed assessment of the environmental benefits of the LC^3-50 formulation, as compared to OPC, shows that this technology can offer up to 40% CO_2 savings beyond that of the technology used to produce calcined clay and clinker.

However, the advantages of LC^3 will not allow for its worldwide propagation if its production does not prove financially attractive. A deciding factor is which cement should be used for the financial benchmark. Since the cement type having the closest performance to LC^3 is CEM I or OPC, the benchmark should be done with cement composed of 95% clinker and 5% gypsum.

Three different implementation scenarios were analysed:

1. An existing integrated cement plant willing to replace some of its CEM I / OPC production with LC^3
2. A grinding station willing to do the same using its imported clinker
3. An investor willing to produce LC^3 out of a greenfield grinding station project also with imported clinker.

Flash calciner and rotary kiln were assessed as alternatives for clay calcination. Additionally, the location of a suitable clay close to (10km) or far from (200 km) the production site was considered. Location significantly impacts project profitability, because cost differential of transport is estimated at USD 13/T of clay. All considered scenarios assume the use of coal; fuel costs, such as diesel, would make LC^3 production economically unviable unless such combustion is heavily subsidised. The cost of CEM I / OPC to be benchmarked with is estimated at USD 30/Ton cement if produced in a cement plant, and USD 47/Ton if produced with imported clinker. The results are summarised in Table 1.

SCENARIO 1: 1 MMTon LC3 in Cement Plant (300 kT C. Clay)				
CALCINER TYPE	CAPEX (MM USD)	CLAY AVAILABILITY	LC3 PRODUCTION COST (USD/TON)	ATTRACTIVENESS (IRR)
Flash calciner	10.3	10 km	23.4	63%
		200 km	27.3	22%
Rotary kiln	6.6	10 km	24.2	87%
		200 km	28.1	24%
SCENARIO 2: 413 kTon LC3 in Grinding Station (124 kT C. Clay)				
CALCINER TYPE	CAPEX (MM USD)	CLAY AVAILABILITY	LC3 PRODUCTION COST (USD/TON)	ATTRACTIVENESS (IRR)
Flash calciner	8.15	10 km	32.1	75%
		200 km	36.0	55%
Rotary kiln	6.1	10 km	32.6	98%
		200 km	36.5	71%
SCENARIO 3: 413 kTon LC3 in greenfield project (124 kT C. Clay)				
CALCINER TYPE	CAPEX (MM USD)	CLAY AVAILABILITY	LC3 PRODUCTION COST (USD/TON)	ATTRACTIVENESS (IRR)
Flash calciner	27.0	10 km	32.1	17%
		200 km	36.0	9%
Rotary kiln	26.0	10 km	32.6	17%
		200 km	36.5	9%

Table 1: Economic feasibility scenarios studied for LC3 production

Assuming the sales price of LC^3 is identical to CEM I, the profitability of producing LC^3 as compared to CEM I/OPC is extremely high (IRR >60%)—if produced in an existing cement plant and provided the clay is located nearby. Should the clay be located 200 km from the plant, the resulting profitability is much lower (IRR 22–24%), though still acceptable. In the of grinding station scenario, profitability remains high (IRR >50%) even when clay is located a long distance from the plant, since the impact of transport cost on total production cost is less than in an integrated cement plant. In the greenfield scenario, profitability is rather low (IRR 17%) if clay is located close to the plant, and not attractive if clay is located further (IRR 9%). The profitability of a greenfield grinding station is lower than for an existing grinding station, because the latter requires investment in a clinker grinding unit.

These profitability projections are based on average cement industry assumptions and costs, and therefore should only be treated as a point of reference. Nevertheless, LC^3 production is a compelling solution because it offers a sustainable, high performance and cost-effective alternative for future cements.

1. Preamble

This report offers an analysis of a new type of cement, LC^3 (Limestone Calcined Clay Cement), a low-carbon cement developed by the École Polytechnique Fédérale de Lausanne, the Central University of Las Villas (Cuba), IIT-Delhi, IIT-Bombay, Technology and Action for Rural Development (TARA) and IIT-Madras in India. The goal is to present non-technical stakeholders with an overview LC^3's environmental, technical and financial advantages. Because this feasibility study is based on standard cement industry assumptions and average costs, findings should therefore be treated only as a point of reference. Each project should be evaluated with its own specificities and particular domestic costs.

2. Introduction

Concrete is the most widely consumed single building product in the world, due to its ease of use, excellent properties, relatively low-cost and wide availability. It provides the unique advantage among all the construction materials of being used used in almost all types of construction—residential housing, industrial and high-rise buildings, roads and infrastructure such as dams and bridges. Concrete primarily consists of three components: cement, water, and aggregates (including sand). Of these three components, cement is not only the most expensive, it is also the only one that emits the largest quantities of CO_2 when produced. On the other hand, increasing world population and urbanisation will require increasing volumes of concrete—and thus, cement. Understandably, the building sector's primary objective is to reduce costs. This can be achieved by:

- Reducing concrete's cement content, as this is the costliest component, and
- Reducing cement production cost.

Cement content reduction can be achieved by using cement with higher compression strength. Cement production cost reduction generally means decreased clinker content, as this is the costliest semi-finished product.

The challenge is to produce a new cement that performs as well as ordinary cement, but with significantly lower clinker content.

2.1 World Cement Consumption

In 2017, the level of cement consumption worldwide reached 4'133 million tons, an increase of 60% since 2006 (Cemnet, 2017). The "Top 20 countries", depicted in Figure 1, (opposite page) represent 85% of global cement consumption. China alone, consumes 2'347 million tons, representing 57%. Together with India, at 297 million tons and as the second largest producer, these two countries represent 64% of total global cement consumption.

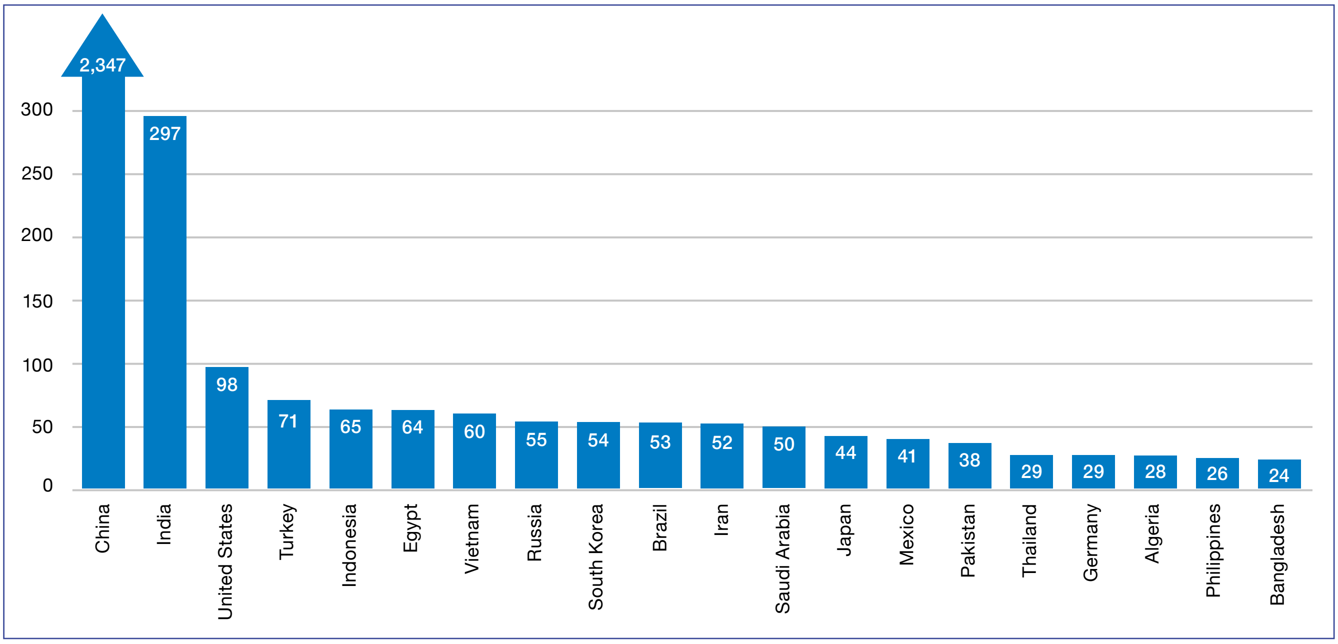


Figure 1: Top 20 Countries per Cement Consumption (in million tons)–Global Cement Report 12th edition.

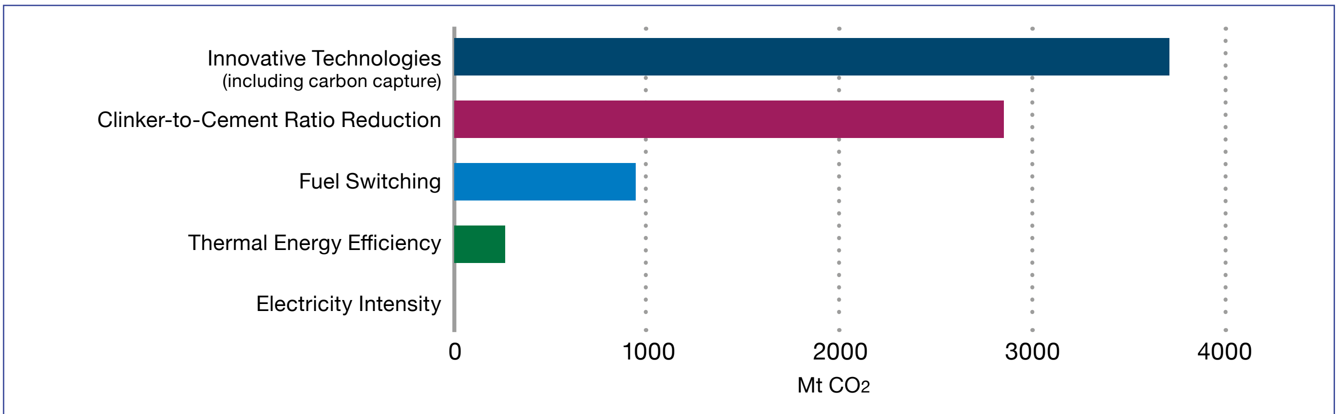


Figure 2: CO_2 emissions reductions—IEA & WBCSD-CSI-2018. Cumulative CO_2 emissions reductions refer to the period from 2020–2050 and are based on the low-variability case of the Scenarios.

The cement sector is the third-largest industrial energy consumer, comprising 7% of global industrial energy use, or 10.7 exajoules [EJ] (IEA & WBCSD-CSI, 2018).

Depending on the scenario, global cement production is set to increase an additional 12–23% by 2050. However, this would result in only a 4% increase in CO_2 emissions globally in 2050 under the International Energy Agency (IEA) Reference Technology Scenario (RTS), despite a 12% increase in global cement production during the same time frame. This cannot be achieved without mitigative action in the cement industry.

2.2 The Cement Industry Technology Roadmap

The April 2018 revision of the Cement Industry Technology Roadmap, developed by the IEA and Cement Sustainability Initiative (CSI), updates the previous edition produced in 2009. The revised Roadmap takes into account the December 2015 Paris Agreement's objective to limit the rise in global temperatures this century to less than 2°C above preindustrial levels.

Realising this 2-degree Celsius Scenario (2DS) by 2050 implies a 24% reduction in current levels of global direct CO_2 emissions from cement manufacture, despite a projected increase in global cement production. The **Roadmap vision requires 7.7 $GtCO_2$ cumulative direct carbon emissions savings from cement making by 2050,** compared to the Reference Technology Scenario. There are essentially four significant CO_2 reduction levers in the cement industry that urgently need effectuation:

- Improving energy efficiency
- Switching to less carbon intensive (alternative) fuels
- Reducing clinker content in cement
- Implementing innovative technologies, such as carbon capture

According to the IEA and WBCSD-CSI report, depicted in Figure 2 (above), reduction levers such as carbon capture and clinker content reduction in cement have been determined to provide the largest cumulative CO_2 emissions reductions in the 2DS, with 48% and 37% contributions, respectively.

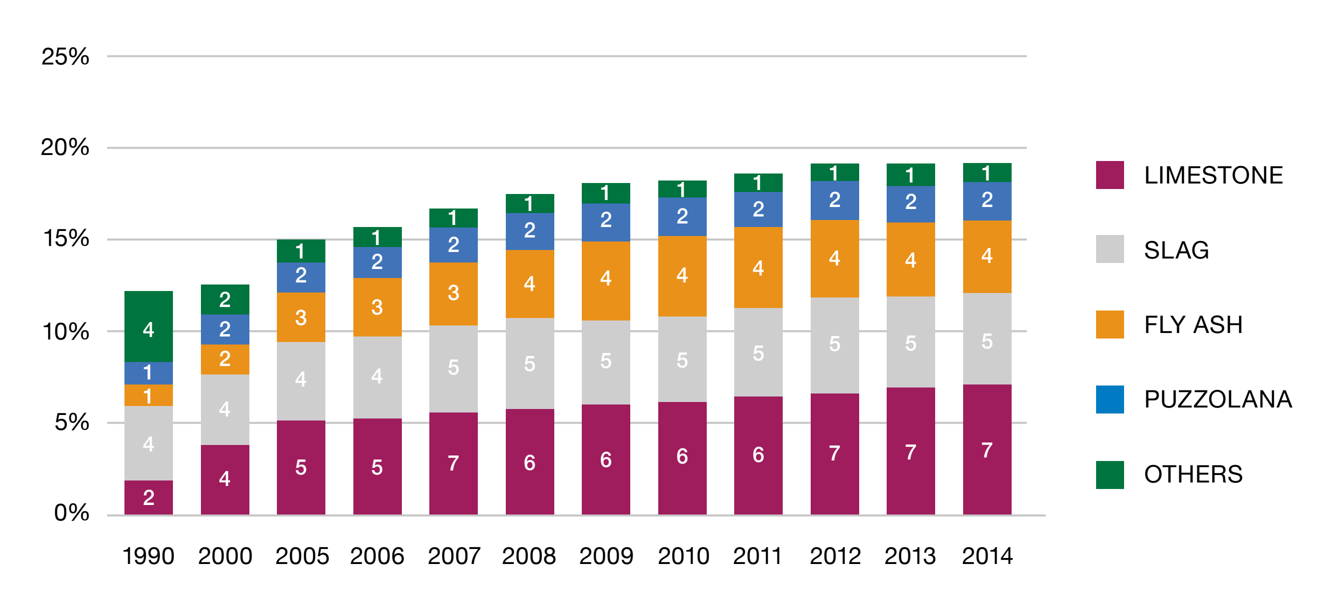


Figure 3: Evolution of Clinker substitution, WBCSD-CSI data

This feasibility study analyses the potential CO_2 decrease of **reducing the clinker factor** in cement, which is by far the most effective CO_2 emissions mitigation lever.

In the 2DS scenario, **reducing the clinker-to-cement ratio delivers 2.9 $GtCO_2$,** or 37% of the cumulative CO_2 global emissions savings by 2050.

2.3 The clinker factor ratio as CO_2 reduction lever

The percentage of clinker in cement, based on mass, is defined as the clinker to cement ratio. Clinker is the semi-finished product, which is then mixed with different mineral components and ground into a fine powder in order to make Ordinary Portland Cement (OPC). However, clinker manufacture is the only part of this process that generates CO_2. This is only partly because producing clinker requires an enormous amount of thermal energy, which is generally of fossil origin. The chemical reaction of de-carbonation, essential to clinker production, is responsible for some 60% of total CO_2 emitted by the manufacturing process. Integrating alternative cement constituents reduces the clinker to cement ratio, and thus the resulting release of CO_2.

Considering the upward trend in demand for cement, innovative and sustainable solutions must be implemented. For decades the percentage of clinker content in cement was considered a main criteria for cement performance. With the development of this new cement with lower clinker content, this is no longer the case.

According to IEA data, the current clinker factor of 65% is expected to reach 60% by 2050. This would mean a 5% drop globally, or a reduction of 364 million tonnes of carbon dioxide ($MtCO_2$). This is equivalent to 16% of current global direct CO_2 emissions from cement manufacture. Clinker reduction also enables CO_2 emissions savings resulting from decreased thermal energy consumption, even in the cases of substitution with calcined clay.

In most cement international standards, clinker substitution is limited to around 35%, with the exception of slags, where up to 90% of clinker can be substituted.

Figure 3 shows the evolution of clinker substitutes over the past 25 years for member companies of the World Business Council for Sustainable Development CSI's GNR database, revealing that the significant progress made from 1990 to 2010 is now levelling off.

Among the main reasons for this are two-fold:

I the decreasing availability of these cement constituents at affordable prices, with the exception of limestone which is abundantly available, and

II the maximum percentage of such materials which can be substituted for clinker without significantly diminishing cement performance.

Cement constituent alternatives to clinker include natural volcanic materials, limestone, industrial by-products such as **Ground Granulated Blast-Furnace Slag (GGBFS)**—generated in the iron and steel industry—fly ash (produced in coal-fired thermal plants), as well as other components, such as calcined clay, derived from widely available resources. Over the long term, availability of these materials will continue declining, except calcined clay and limestone.

GGBFS is generated during the production of pig iron. Slag cement is categorized in EN197 (the European standards for cement) under CEM III and can potentially replace clinker up to high levels (70% is common). The volume of blast furnace and steel slag available globally is estimated between 480–560 million t/year (2014 figure) (IEA & WBCSD-CSI, 2018). This availability has decreased from 17% of cement production in 1980 to only 8% in 2014 (K. Scrivener, J. Vanderley, E. Gartner, 2016). The volume of GGBFS as a percentage of cement production is expected to continue decreasing due to the increasing recycling rate of scrap steel for recycling and the development of more efficient steel-making technologies. Another factor is that iron production is concentrated in industrialised countries while cement demand is expected to grow in developing countries. Slag will then become financially unattractive due to its higher logistical costs.

Fly ash is a by-product of pulverised coal fired in power plants that is available globally. Though more abundant than slag (around 900 Million t/year), only one-third of this volume meets the quality required for cement production. Fly ash cement is classified under EN 197 CEM II B V and W with a maximum of 35% content in cement to avoid technical performance issues. The volume of fly ash is also expected to decrease dramatically, since burning coal to produce electricity is by far the largest source of anthropogenic CO_2. Some countries are already phasing out coal fired electricity production. Additionally, HSBC, Europe's largest bank, stated in April 2018 that it would cease funding new coal power plants, oil sands and arctic drilling.

It is also important to note that cements containing GGBFS and siliceous fly ash may have lower short-term strength despite increased long-term strength. Due to such low short-term strength development these two cements are only suitable for limited applications

Another cement constituent is **natural Pozzolan,** which can be used either calcined or not. Availability and reactivity vary widely from country to country. Pozzolan can also be calcined with the goal of being activated by thermal treatment.

Limestone is another well-known alternative with practically unlimited availability. However, when used alone as clinker substitution it will decrease cement performance beyond the accepted 10% substitution rate.

Consequently, none of these constituents will yield the clinker factor required for achieving the global CO_2 emissions goal for the cement industry worldwide. This ambitious initiative necessitates a new type of cement.

2.4 Calcined clay in the new Cement Roadmap 2018 (IEA)

Though cement made of calcined clay has been researched for many years, it is only recently that more extensive studies, along with initial constructions, reveal the significant potential resulting from combining **calcined clay and limestone** as a clinker substitute.

These results were encouraging enough for the IEA to include this new technology in its newly released Roadmap. According to IEA, cements, based on calcined clay and ground limestone,

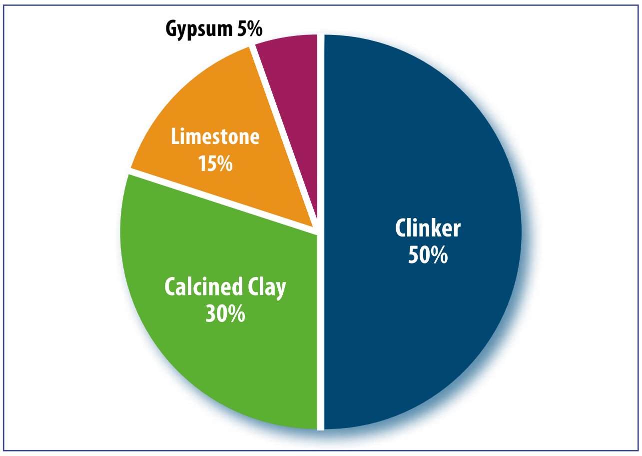


Figure 4: LC^3 composition

are expected to penetrate the market in the 2DS, reaching **27% of global cement production** by 2050 (IEA & WBCSD-CSI, 2018). Indeed, blended cement developments have shown that up to 50% clinker substitution is possible through optimised blends of calcined clay and ground limestone—without affecting cement properties. This new blend is called LC^3

3. LC^3

3.1 What is LC^3

LC^3 stands for Limestone Calcined Clay Cement and allows clinker factor as low as 50%. It is a combination of clinker, calcined clay, limestone and gypsum.

If clay, together with stone and wood, is one of the oldest building materials, it is only during the last century that calcined clay was used in large-scale construction. As of 1932, some bridges built in San Francisco, and since the 1970s, Brazil has been using cement made of clinker and calcined clay (see Figure 4 above).

Though different formulas exist for LC^3, this report will concentrate on a mixture with the clinker content of 50%, because this has the lowest production cost and CO_2 emissions level, while maintaining a performance similar to ordinary cement with 95% clinker content.

Limestone use is already quite common in cement. However, cement performance generally deteriorates above 15% limestone content when not used in association with other constituents like slag, which will become increasingly scarce and expensive. The merit of LC^3 is to allow the use of 50% clinker content in combination with cheaper and widely available constituents, like clay and limestone, without sacrificing cement performance. Moreover, low-grade limestone with impurities like quartz and dolomite can also be used, thereby increasing the potential geographic locations for LC^3 manufacturing, and more efficiently exploiting the limestone quarries.

The calcination of the clay takes place at 750–850°C —much lower than the 1450°C needed for clinkerisation. Because

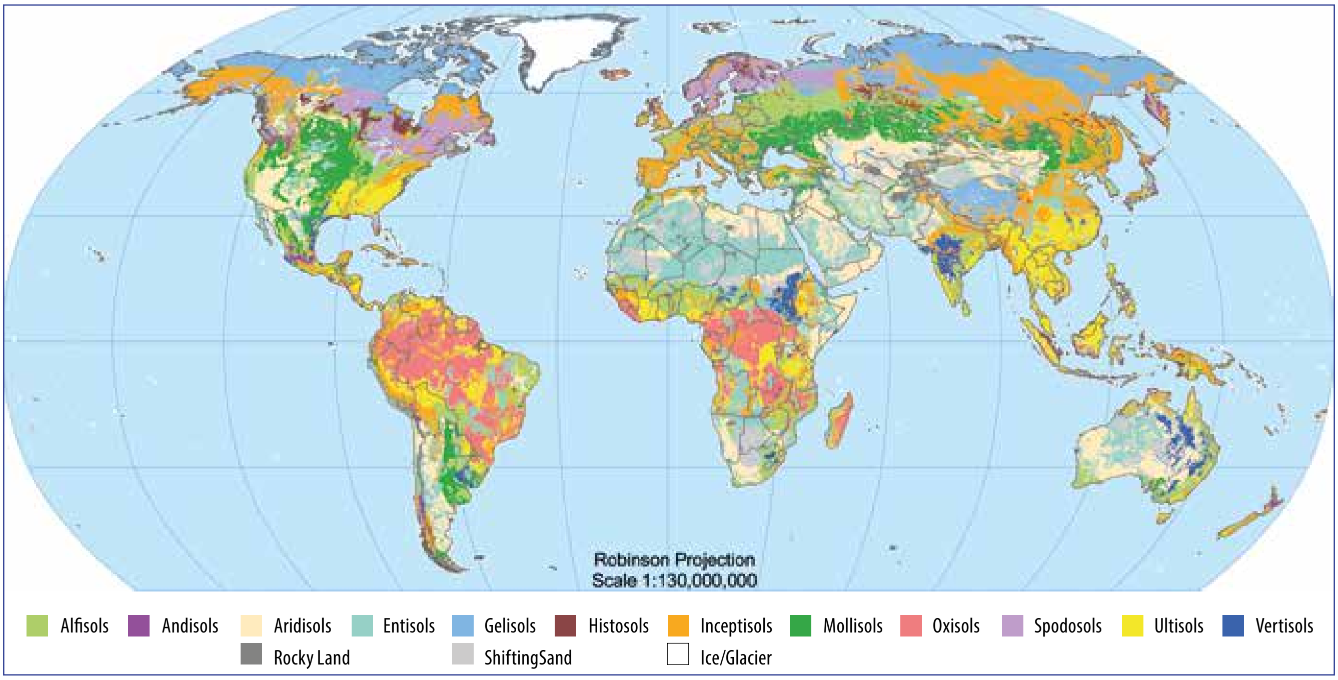


Figure 5: Availability of suitable clays, yellow pink and light green regions, and others. Source: USDA Natural Resources Conservation Service, Soil Survey Division.

limestone is not calcined it does not contribute to CO_2 emissions.

Clay, the key raw material

Tests show that clays with a kaolinite content between 40% to 70% are ideal for LC3. Clay reserves are so vast as to be effectively limitless when compared to the amount of cement produced. In countries such as India and China, where 64% of the total cement production is concentrated and with well-established ceramic industries, substantial reserves of suitable clays are currently stockpiled as waste. Clay is largely present in over- or under-burden from existing quarrying operations all around the world. Large deposits of suitable clays of kaolinite type are abundant in the tropical belt of the world, where high economic growth corresponds to cement consumption.

The map above shows approximate locations where suitable clay could be found. As a first approximation, the pink, yellow and pale green areas contain kaolinite as one of the main minerals. However, kaolinitic clays can also be found in other places. More precise assessments would need to be made on a case-by-case basis.

In countries where clay reserves are either unavailable or only available in limited quantities, LC3 production will not be feasible or recommended in order to preserve natural resources.

Calcined kaolinitic clays have the advantage of reacting quite rapidly—more rapidly than siliceous fly ashes and even faster than slag. The high alumina content of calcined kaolinitic clays makes them particularly suitable for co-substitution with limestone.

3.2 Production of calcined clay

Clays, containing some kaolinite, produce reactive materials when calcined to around 700–850°C. This report discusses two technological options to calcine clays: rotary kilns and flash calciner. The four components of LC3 would either be ground individually and blended together, or ground together. Because calcined clay is softer than clinker it requires less energy to grind. High surface area and high-water demand, along with colour control, have been problems that recent technologies are progressively solving.

4. LC3 mechanical and physical performances

The main technical characteristics for describing cement are:

- Compressive strength
- Durability
- Workability and water demand
- Colour

All tests performed demonstrated similar or better performance than OPC. According to Shashank Bishnoi (Indian Institute of Technology Delhi, New Delhi) and Soumen Maity (Technology and Action for Rural Advancement, New Delhi):

> "the pore-structure of LC3 has been found to be finer than OPC and PPC. For this reason, even when the total porosity in the cement may be slightly higher than the other cements, the permeability is lower. This is partly due to the wider particle size distribution of LC3 and partly due to the pore refinement from the reactions of the SCMs. This leads to a significant improvement in the durability parameters of LC3. It has been seen that the surface resistivity of concretes made using LC3 is significantly higher even than PPC.As a result, the rate of corrosion of steel in LC3 concretes is lower than in the other cements. Chloride ingress in the cement is lower due to the finer pores."

S1 No.	Mix ID	w/b	Cement	Fly Ash	Water Content	Fine Aggregate	Coarse Aggregate		SP Dosage
			<-------------------------------		kg/m3	-------------------------------	>		(% cement wt.)
1	OPC-M30	0.50	310	0	155	695	496	744	0.02
2	FA30-M30	0.45	217	93	140	723	491	737	0.65
3	LC3-M30	0.50	310	0	155	708	491	736	1.00
4	OPC-M50	0.40	360	0	144	703	477	716	0.65
5	FA30-M50	0.35	266	114	133	699	475	713	0.60
6	LC3-M50	0.40	340	0	136	704	488	732	0.85
7	OPC-C		360	0	162	721	463	694	0.10
8	FA30-C	0.45	252	108	162	721	463	694	0.23
9	LC3-C		360	0	162	721	463	694	0.36

Figure 6: Concrete mix design – IIT Madras

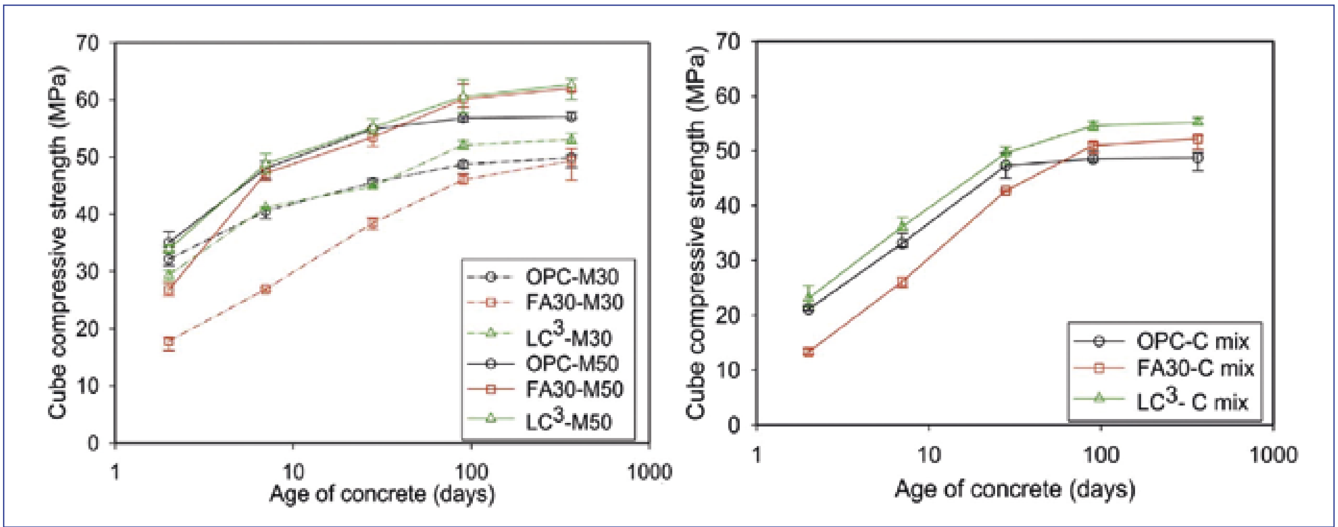


Figure 7: Evolution of compressive strength in the concrete mixes: (a) M30 concretes and M50 concrete, and (b) common mix (C-mix)

Extensive tests were undertaken in India. The results were presented by Manu Santhanam, Professor of Civil Engineering, IIT Madras and Karen Scrivener, Professor at EPFL. The outcome is summarised as follows:

4.1 LC3 performance on compression strength

Compressive strength is usually the first technical criteria assessed when evaluating a new cement. If several blended cements achieve similar, if not better, performance than OPC on the long term, they lack early strength as compared to ordinary Portland cement. This could hamper a broader use of blended cement as it increases the demoulding time. Compression strengths tests were carried out on the following concrete mix:

Conventional mix design methods can be followed for concretes with LC3. Compared to fly ash based concrete, LC3 binder requirement was lower and strengths of specific grades could be achieved at higher water contents.

In the following tests unless otherwise specified, LC3 refers to a blend of 50% clinker, 30% calcined clay, 15% limestone, and 5% gypsum. FA30 refers to a blend of 65% clinker, 30% fly ash, and 5% gypsum. Strength development characteristics for LC3 concretes matched OPC concrete and exceeded fly ash based concrete in the early ages.

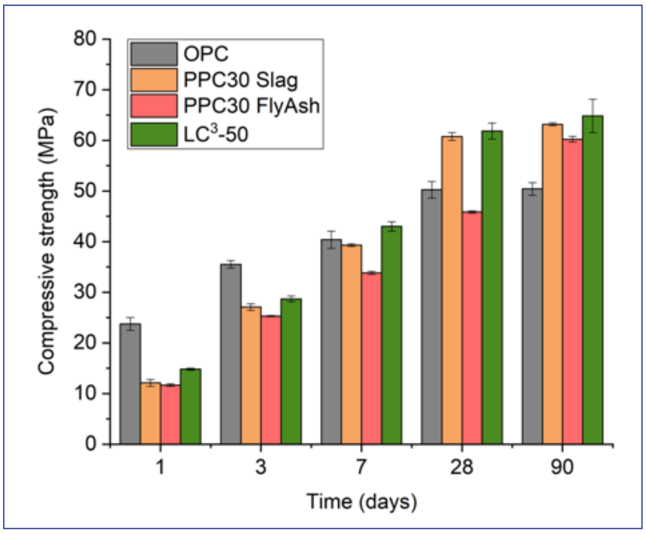


Figure 8: Compressive strength of LC3 versus OPC and blends containing 30% slag or fly ash

Other tests compared LC^3 with OPC and blends containing 30% slag or fly ash. From 7 days onwards, LC^3 shows higher strength than OPC. Moreover, LC^3 shows higher early strength than other blended cements.

Significant reasons for this performance are additional chemical reactions compared to OPC:

- Pozzolanic reaction of calcined clay,
- Limestone reaction
- Synergetic reaction of calcined clay and limestone, as the alumna content of calcined clay enhances limestone reaction.

Despite the higher clinker substitution rate, the ternary system performed better compared to most binary systems with several types of Pozzolan. Notably, this system's early strength is much better than other blended cements with a lower substitution rate. This results from the alumina phase reacting vigorously during the first 7 days, thus mitigating the main problem of Pozzolanic cements, which is slow strength gain at early ages.

Conclusions for LC^3 compressive strength: LC^3 reaches slightly lower values than OPC at very early ages but matches OPC at 7 days and exceeds OPC strength after 7 days.

4.2 LC3 durability

Surface resistivity (see Annex 1): LC^3 concretes resistivity was an order of magnitude higher than OPC, and also significantly higher than PPC, which indicates better resistance to corrosion propagation.

Chloride penetrability by RCPT (ASTM C1202) and Migration test (NT 492) (see Annex 2 and 3)**:** There is dramatic improvement of chloride resistance improvement at an early age irrespective of the different concrete grades, unlike a fly ash based PPC system which requires additional curing at higher water-binder ratios.

Oxygen permeability test (Durability Index Manual, South Africa) (see Annex 4)**:** All concretes in the 'Excellent' category as per South African criteria, gas penetration resistance increased for higher grade concretes.

Sorptivity Index (Durability Index Manual, South Africa) (see Annex 5) Tortuous pore structure has reduced sorptivity in the LC^3 system; FA30 system also has a relatively lower sorptivity compared to the OPC mix.

Chloride profile in M30 and M50 grade of concrete (56 days Chloride exposure) – Bulk Diffusion test (ASTM C1556) (see Annex 6)

- Higher resistance to ingress of chloride was seen in LC^3 and FA30
- At equivalent strength, performance is better in OPC and comparable with FA30, since FA30 had lower w/b ratio to produce equivalent strength of concrete
- Lower variability in LC^3 chloride profiles may be due to better concrete quality (i.e. homogeneity) with LC^3 binder

Chloride profile in concrete with Common mix (56 days Chloride exposure) (see Annex 7)

- With similar binder content and w/b ratio, LC^3 performance is better than OPC and FA30
- Increased chloride binding due to additional formation of aluminate hydrates from calcined clay—better resistance to chloride ingress

Pore structure evolution in LC^3 (see Annex 8)

- LC^3 shows lowered threshold diameter even as early as 3 days
- Refined pore structure is a major factor for better durability performance at early ages

Comparative pore size distribution by MIP –OPC, FA30 and LC^3 (see Annex 9)**:** There is a shift in the pore sizes to the lower pore size (0.1-0.01 microns) at an early age with LC^3—resulting in better durability parameter in concrete at an early age

Chloride-induced corrosion performance of steel-cementitious system with OPC, blended cement with 30% fly ash content (FA30), and LC^3

- ICC test method (to assess resistance against corrosion-induced cracking of concrete cover): LC^3 system has higher resistance against impressed current corrosion compared to OPC and FA30 systems
- ASTM G109 (to evaluate long term performance OPC, FA30 and LC^3 steel-cementitious system): OPC and FA30 systems without inhibitors showed some corrosion activity. OPC, FA30 systems with inhibitors and LC^3 system with and without inhibitors showed no corrosion activity

Resistance to sulphate attack.

Methodology

- To evaluate the performance of LC^3 binder systemin:(i) Sodium Sulphate immersion, and (ii) Magnesium Sulphate immersion tests
- Compare performance with OPC and FA30 mortars
- Length and mass change measurements
- Evaluation of alteration in hydrated phases by X-ray diffraction

Results

- No expansion in LC^3 and FA30 mortars even after more than 70 weeks of exposure; OPC mortars show very high expansion

- **Resistance to alkali-silica reaction** (see Annex 10)
  LC3 outstands OPC for ASR mitigation
- Almost no expansion is measured for LC3.

Conclusions for LC3 durability:

- **LC3 system has higher resistance against chloride ingress compared to OPC and FA30 systems**
- **LC3 performs well in tests for sulfate resistence**
- **LC3 shows a significant improvement of ASR mitigation compared with OPC**

4.3 Workability and Water demand

It is well known that the presence of calcined can impact workability. In LC3, limestone partially mitigates the impact of calcined clay. Moreover, the most suitable clays used in LC3 are not pure kaolinite. Figure 9 shows that the amount of plasticiser required to reach similar workability to OPC is about half for clays with 50% of kaolinite compared with pure kaolinitic clays.

Furthermore, workability can be optimised. Siam Cement Group (SCG) did not need any addition of plasticiser to reach similar flow between OPC and LC3, independent on the replacement level.

4.4 Colour

Colour has always been a major concern with cement made from clay. However, LC3 colour depends on two factors:

- Iron content in the clay
- Atmosphere during calcination
  (i.e. oxidation or reduction)

For clays with fairly low iron content, resulting colour change in the final product is almost imperceptible. For iron-rich clays the colour can be adjusted. The type of red to grey colour depends on the oxidation or reduction conditions. Figure 11, from FLS, shows the range of colour possible from the same clay by changing the atmosphere during calcination.

In India, where a rotary kiln and an oxidation atmosphere were used, the resulting clay colour was reddish. When used with a combination of clinker and limestone, the LC3 cement was pinkish.

It is also possible to produce greyish calcined clay by firing it in a reduction atmosphere. For this type a flash calciner is most suitable.

5. Sustainability impact of LC3

5.1 CO_2 impact of the cement production

Clinker production generates two sources of CO_2 emissions:

- Chemical decomposition of calcium carbonate ($CaCO_3$). At around 900 °C, calcium carbonate becomes calcium

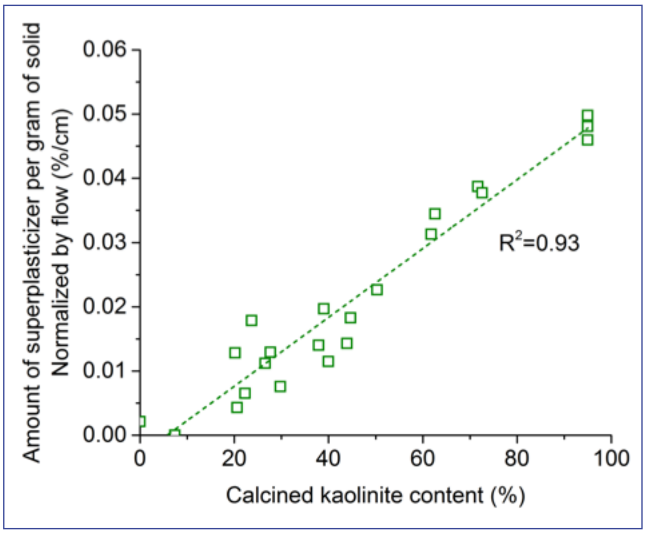


Figure 9: Plasticiser addition as a function of the kaolinite content of clay to reach similar flow to PC.

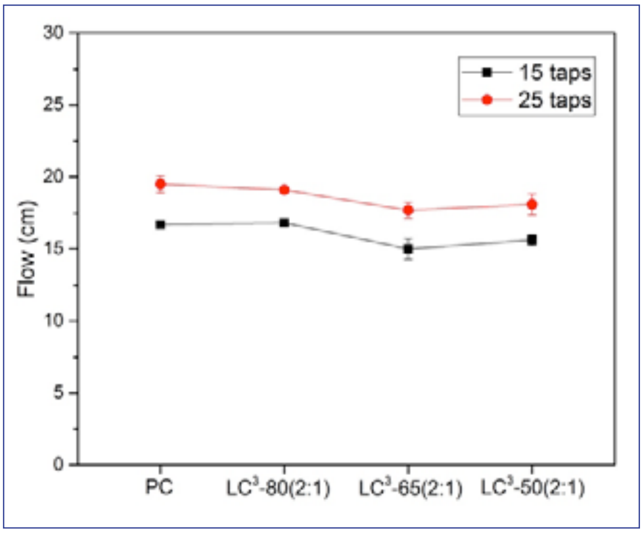


Figure 10: Flow value for PC and LC3 with three different replacement levels. No plasticiser was used.

Figure 11: Colour test done by FLS.

oxide, releasing CO_2 into the atmosphere. This represents approximately 60% of the CO_2 emitted during cement manufacture
- Fossil fuel combustion, which is responsible for the remaining 40%

Depending on the kiln efficiency, the emission rate of cement production ranges between 0.67–1.00 tonnes CO_2/tonne cement.

5.2 CO_2 and LC3

Since LC^3 replaces 50% of clinker content with 30% calcined Clay and 15% non-calcined limestone, the CO_2 emissions associated with clinker are considerably reduced.

Life cycle Analysis (LCA) has been calculated. The new cement formulation presented in this report enables a clinker substitution increase to 50% without compromising performance; this represents an approximate reduction of up to 40% in CO_2 emissions associated with cement manufacture (Figure 12).

6. Technical options available for metakaolin production

6.1 Calcined clay for the production of LC3

Metakaolin is the main hydraulically-active component of calcined clay. Metakaolin forms under atmospheric conditions from kaolinite, through dehydroxilation at temperatures of 600–800 °C.

$Al_2Si_2O_5(OH)4 \rightarrow Al_2Si_2O7 + 2\ H_2O$

This metakaolin can be used due to its hydraulic activity as a mineral component in Supplementary Cementitious Materials (SCM) cements, thereby replacing clinker or other SCM additives. Replacing clinker in cement manufacture could yield economic benefits and reduce resulting CO_2 emissions.

If metakaolin is heated up at higher temperature than 850°C, a physical coarsening of metakaolin particles leads to decreased reactivity. At even higher temperature, about 920–950°C, metakaolin is transformed into an alumina-silica spinel.

$2\ Al_2Si_2O_7 \rightarrow Si3Al_4O12 + SiO_2$

If this alumina-silica spinel is further heated to temperatures above 1050°C, it is transformed into mullite and highly crystalline cristobalite.

$3\ Si_3Al_4O12 \rightarrow 2\ (3\ Al_2O_3 + 2\ SiO_2) + 5\ SiO_2$

The alumina-silica spinel, as well as the mullite and cristobalite, are inactive and therefore do not contribute to the cement strength development by chemical reaction with the water.

kaolinite is transformed into metakaolin—by achieving the required temperature of 800°C throughout the entire material grain for complete reaction, and by absolutely avoiding overheating the material and transforming the metakaolin into hydraulically inactive minerals.

CO_2 emissions and Energy consumed comparison

Impact	OPC	LC3	Delta
CO_2 Emission (kg/ton of cement)	745	450	-40%

6.2 Storage and material preparation

The storage and transport of the raw kaolinite has to be built in new green field projects. In brown field projects, within the site of an integrated cement plant, the storage and transport of the raw kaolinite may utilise already existing facilities.

6.3 Flash calciner with hammer crusher and flash dryer

In preparing the clay, the material must to be crushed before being fed to the furnace. In most cases, this takes place in a heated hammer crusher and the material is dried further with hot gases from the calciner in a flash dryer (static riser tube dryer). An alternative is to grind the clay in a Vertical Roller Mill and dry the clay in this mill, which is only economically viable if the plant already includes one (i.e. excessive raw mill capacity or mothballed Vertical Roller Mill of an existing cement plant).

This is essential for rendering the clay airworthy in flash calciners and to achieve the smallest possible clay granulometry—which is important for complete calcination, especially with the typical low residence of the material in the calciner.

If the grain size is sufficiently small (< 1mm) and the clay is already pre-dried, the raw materials can also be fed to a cyclone preheater for preheating, calcined in the flash calciner and then cooled in a cooling cyclone system, which allows heat to be recuperated with secondary air from the metakaolin.

In such systems, the combustion temperature only achieves a maximum temperature of 750–800 °C, since "cold combustion" takes place; this is comparable to the calciners in a cement plant with precalciner kilns. The fuel is always in close contact with the material, which therefore burns at the same temperature as gas and material via heat transfer by convection and conduction.

Since many countries have environmental regulations that prohibit burning alternative fuels at such "low" temperatures—to avoid the risk of dioxin or furan formation—such calciner systems may not be suitable in such countries for the combustion of alternative low-grade fuels. However, if formation of toxic intermediate combustion products can be precluded, for instance in biomass fuels like rice husks, and palm kern shells, the usage of such alternative fuels may be considered.

An advantage of this flash calciner type is the temperature measurement ease and material control. Since gas temperature at the calciner outlet, which is used as an indicator for the material temperature (material temperature is almost the same as the gas temperature), is easy to measure and overheating is avoided because "cold combustion" takes place in the furnace.

The complete calcination system hot section can be designed with a 2-layer refractory lining—insulation and work lining layers—minimising radiation and convection loss. This contributes to the system's high-energy efficiency. Colder sections, like gas ducts or low temperature cyclone stages, are traditionally insulated from the exterior. This ensures increased insulation properties with decreased heat loss, and also avoids the creation of condensation and corrosion from calcination gases within the ductwork.

6.4 Rotary kiln with cooler

In this option, the open flame is available, is much hotter than the maximum material temperature, and thus transfers the heat to the material via radiation.

A homogeneous granulometry is required in order to achieve homogeneous granular calcination. However, the granulometry of the fed material can be coarser, since the residence time of the material in the hot section is much longer than compared to a flash calciner. Thus, complete calcination of material grain can be ensured, assuming proper kiln design and operation, and granulometry is not excessive.

A pelletiser—a rotating granulating table comparable to those used in semi-dry cement kiln systems, which increase and homogenise the material's grain size—can be installed before the granulated clay is fed to the rotary kiln.

In the case of an integrated cement plant with an existing clay crusher, the pre-crushed quarry clay is fed directly into the kiln without any further additional size reduction. Nevertheless, in such cases the grain size distribution is broad, up to 25 mm or more. Thus, calcined clay quality may suffer due to potential over-burning of fine fractions—formation of hydraulically inactive minerals. Quality may also suffer due to potential under-burning of very coarse fractions—incomplete conversion of kaolinite into metakaolin, especially in the coarse grain

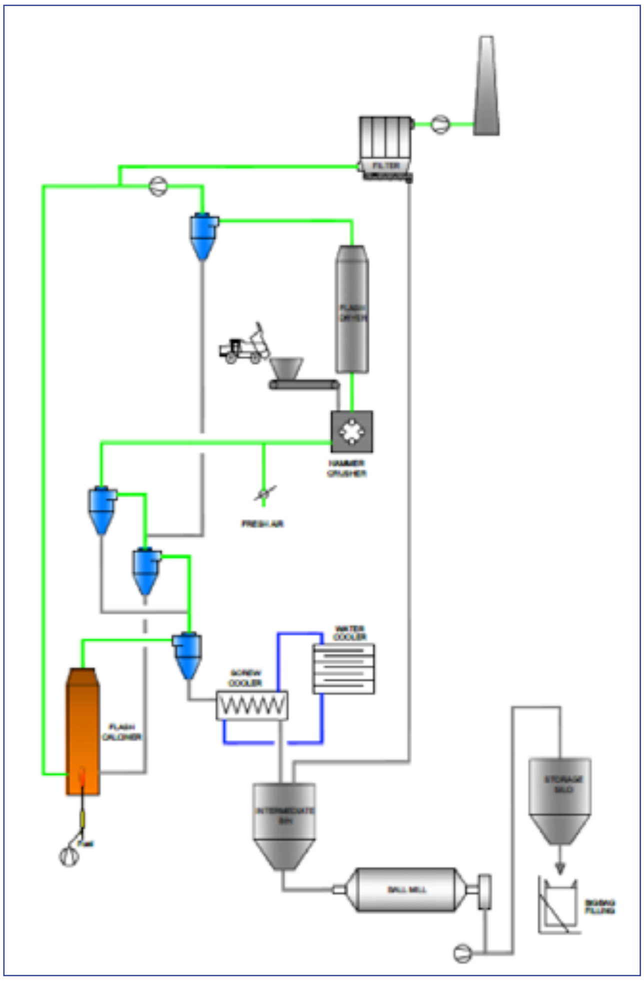


Figure 12: Flash calciner with hammer crusher and flash dryer

cores, which also reduces metakaolin's hydraulic activity. Feeding uncrushed and undried material into a kiln system only seems possible for long rotary kilns (L/D > 20).

The material temperature in a rotary kiln has to be measured indirectly, by pyrometer, since flame and gas temperatures are not representative. This is not a fully reliable measurement method, because of disturbances to emitted radiation by external factors. This makes material temperature control much more challenging when compared to a flash calciner.

Flash Calciner: Advantages and Disadvantages

+ Good control of material temperature with homogeneous calcination of the material
+ Easy to operate
+ Low maintenance cost, since little rotating equipment
+ Low radiation and convection losses (2-layer refractory lining in hot section)
– Material must be prepared to a fine granulometry to ensure proper pneumatic transport in the system and complete calcination for duration within the calciner
– Most alternative fuel types cannot be used due to environmental regulations in many countries
– Flash calciner not suitable for feeding uncrushed and undried material into the system, especially if additionally using cyclones for preheating and cooling

Rotary Kiln: Advantages and Disadvantages

+ Certain alternative fuels can be used if allowed by local environmental regulations (due to low setting time and temperature as compared to clinker production)
+ Easy to operate
+ Little material preparation cost (CAPEX & OPEX), if pre-crushed material fed directly to rotary kiln (only in long kilns possible)
+ Low CAPEX, especially if required production rate is low (see Annex 11)
– Difficult control of material temperature with homogeneous calcination of the material
– Increased maintenance cost, especially for the rotary kiln (mechanics and refractory since little rotating equipment)

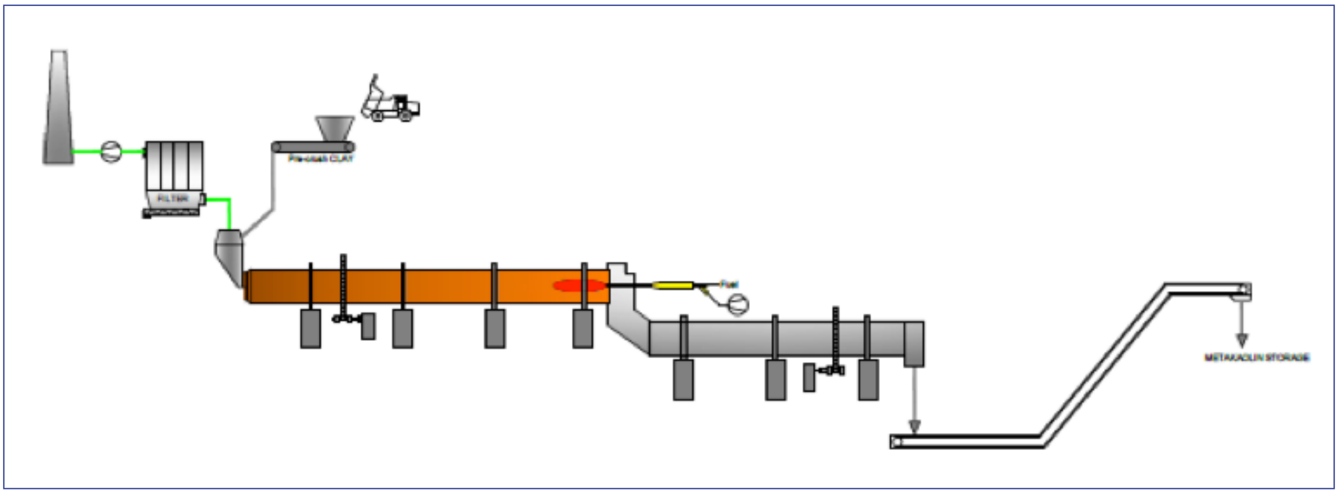


Figure 13: Long kiln (L/D > 20) with rotary cooler

Additionally, any dust passing through the open flame, due to recirculation from the cooler, is overheated and thus deactivated for the use as hydraulic binder.

If a cement plant has a mothballed cement kiln system readily available, an assessment of whether modifications would have to be made in order for the entire production line to also be suitable for metakaolin production.

Typical aspects to be evaluated would include:

- Raw material handling system for storage and feeding to the raw mill
- Type of raw mill and maximum drying capacity which can be achieved in such a grinding system (e.g. drying capacity could potentially be too low for a ball mill system as compared to a Vertical Roller Mill)
- Kiln main dimensions, specific load factors and process parameters
- Suitability of cooling system (e.g. a grate or satellite cooler would most likely be unsuitable, due to high dust recirculation generated from the fine granulometry of the metakaolin)
- Material handling system for the transport, storage and dosing of the metakaolin

Especially in case of idle **"long kilns"** (length to diameter ratio >20), the revamping of such kilns could be economically viable, taking into account a new concept for the cooling of the resulting material.

6.5 Emissions

Emissions in the rotary kiln, where "hot combustion" takes place—an open flame with a temperature defined by the fuel type and combustion air temperature—the development of "thermal NOx" can be expected.

This does not apply to "cold combustion", which takes place in the flash calciner, since combustion temperature is defined by the chemical reaction and therefore is limited to around 850°C. Consequently, the produced NOx formation is only "fuel NOx", which is significantly lower compared to the "hot combustion" of a rotary kiln, and depends only on the nitrogen content of the fuel used.

For all other critical gaseous emissions—like SO_2, CO or volatile organic carbon—the emission rate depends primarily on the properties of the raw materials, especially the volatile organic carbon content, and on fuel properties, especially sulphur content.

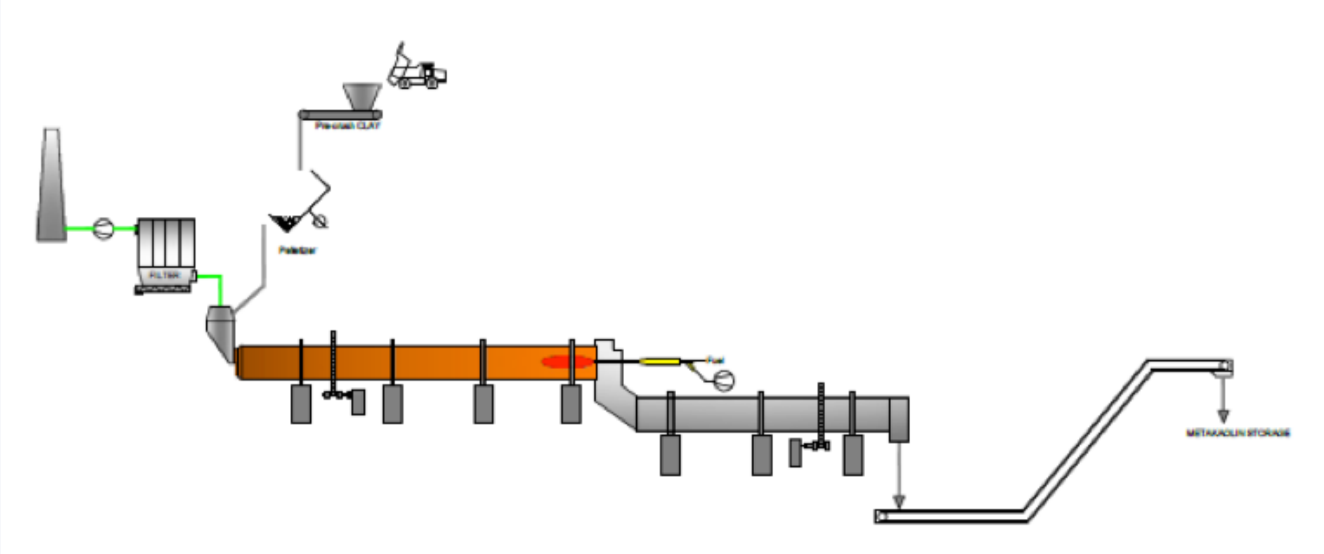


Figure 14: Long kiln (L/D > 20) with pelletizer and rotary cooler

7. Case studies and financial benefits

7.1 Introduction

For industrial-scale installation production of calcined clay, three basic scenarios were assumed and the clay's material properties were clearly defined to enable design and dimension the required equipment accordingly.

The three scenarios are as follows:

Scenario 1–Clay thermal processing solution of 960 tons per day (tpd) suitable for 1 mtpa LC^3 cement production. Utilisation, to the greatest extent possible, of infrastructure and production assets at an existing integrated cement production plant, including fuel preparation, integrated cement grinding and inventories.

Scenario 2–Clay thermal processing solution of 400 tpd suitable for 0.4mtpa LC^3 cement production. Utilisation, to the greatest extent possible, of infrastructure and production assets of an existing cement grinding station, including integrated cement grinding and inventories. A thermal fuel preparation (coal based) grinding plant complete with Just In Time (JIT) dimensioned inventories is provided.

Scenario 3–A 0.4mtpa LC^3 greenfield cement grinding plant which considers a complete clay thermal processing solution, dimensioned for 400tpd, thermal fuel preparation (coal based), and a cement grinding for intergrinding LC^3 cement complete with relevant JIT dimensioned inventories.

The following sub-critera were considered for each scenario:

- Clay calcination with (1) flash calciner and (2) rotary kiln
- Clay sourcing with (1) clay available close to the production facility and (2) at a distance of 200 km

It is noted that access to low cost thermal fuel, such as natural gas, would also make Scenario 1 suitable for implementation at a larger capacity stand-alone, or satellite, cement grinding station. This scenario is beyond the scope of this evaluation

The objective of these case studies is to compare LC^3 production cost with CEM I. The CEM I has been selected because it performs closest to LC^3.

In all scenarios, CEM I is considered to be made of 95% clinker and 5% gypsum. For integrated cement plants, both clinker and CEM I costs have been estimated based on average production costs in emerging countries.

- Estimated cash production clinker: USD 23.9 /T
- Estimated cash production cost CEM I: USD 30.0 /T
- In the absence of clinker production an average import price for clinker has been estimated.
- Estimated import cost clinker: USD 40.0 /T delivered
- Estimated cash production cost CEM I with imported clinker: USD 47.0 /T

LC^3 is made of 50% clinker, 30% calcined clay, 15% limestone and 5% gypsum.

Other assumptions include:

- Kaolinite content in clay: minimum 40%
- Particle size: < 25mm
- Moisture content: < 12%
- Calcination temperature of clay: 800°C
- Fuel: All scenarios are base on coal as the combustible, with a delivered cost of USD 80 per ton coal and a lowest heat value of 26 MJ /kg. If petcoke is used for clinker production in the integrated cement plant, either an additional, easy to burn "ignition fuel" must be used, and thus guarantee safe ignition and complete petcoke

SCENARIO 1

- In a Cement Plant
- 1 Mio ton LC^3
- FC vs. RT
- Clay <10km vs. 200km

SCENARIO 2

- In a Grinding Plant
- 0.4 Mio ton LC^3
- FC vs. RT
- Clay <10km vs. 200km

SCENARIO 3

- Greenfield
- 0.4 Mio ton LC^3
- FC vs. RT
- Clay <10km vs. 200km

combustion in the clay calcining system, or a separate grinding of petcoke solid fuels with easier ignition behaviour. Due to higher volatilities, including additional equipment like storage bins should be considered, particularly if available secondary air temperatures are low because of low system recuperation efficiency of the from the hot finished product. Other fuel types like natural gas and diesel could be considered, but unless these are heavily subsidised their international market price makes LC^3 production less financially attractive when compared to CEM I.

- Limestone is assumed at USD 2.8 /T limestone (poor quality or reject limestone from existing quarry)
- Gypsum cost: USD 20 /T gypsum

NOTE: These scenarios are only estimations. They are based on average numbers applicable in emerging countries. These numbers should be revised on a case per case basis. However, the overall conclusion remains valid in most cases except two:

- If very cheap mineral components, like natural Pozzolanic material, fly ash, or slag, available at competitive cost, or
- If clay is located more than 200 km from the plant.

Profitability compares producing LC3 with CEM I. This indirectly implies that the sales price of LC3 is aligned to the sales price of CEM I.

7.2 LC^3 capacities scenarios

Two different capacities will be considered: a large capacity for 1 million t/year LC^3 cement production—960 tpd calcined clay—LC^3 for production in an integrated cement plant, and a smaller capacity for 413'000 t/year LC^3 cement production (400 tpd calcined clay) for production in a non-integrated cement plant. This smaller capacity is typical for a medium-sized cement grinding plant

7.2.1 Calciner system for a production of 960 tpd: integrated cement plant

In this scenario, the calcined clay is produced within the premises of an integrated cement plant. The already existing inexpensive solid fuel preparation system in most of the cases may therefore be used. This is particularly true if the cement kiln system uses a significant amount of alternative fuels—which reduces the demand of fine solid noble fuel from the cement kiln line—or if the coal mill by design and fuel type (i.e. fineness requirements, grindability) has sufficient capacity reserves.

Since the production rate is already in the low capacity range of existing mineral process equipment, the required equipment sizes (cyclones, rotary kiln, etc.) are now common from other mineral industries, and therefore the engineering costs would be within a normal range.

Due to the higher production rate, with a reasonable and normal specific capital expenditure (CAPEX) spending, more modern and efficient kiln designs can be used—number of cyclone stages for preheating and cooling for a flash calciner, reduced specific radiation losses of the kiln shell for a rotary kiln. This makes such calcination systems more energy efficient and also more suitable for more difficult to ignite fuels—like petcoke with a certain volatile content, especially if costly support burners with ignition fuels are also used).

Affordable solid fuels, or natural gas where already available, are the first choice, significantly reducing operational costs.

With higher thermal efficiency from the more sophisticated design, compared to the smaller capacity scenario, the standard solution for lower operational cost is a suspension preheater system before the calciner, to preheat the already dried clay. The same could apply for the cooling of the material, where an efficient cyclone system, possibly in combination with fluidised bed coolers, could be used on the one hand, and also to preheat the secondary air used for combustion in the calciner. A prerequisite is that the feed size to the calciner system must be sufficiently fine to be lifted adequately with normal system gas velocities.

The raw clay is fed into a hammer crusher to reduce clay size enough for all of it to be lifted by the gas flow, dried in the flash dryer and then be pneumatically transported to the flash calciner, where dehydroxylation takes place at temperatures around 800°C. To preheat the combustion gases and simultaneously cool the 900°C hot flash calciner exhaust gases adequately, gas from the flash dryer passes through an Air to Air Heat Exchanger.

Regardless, a significant amount of the flash calciner exhaust gas cooling is realised by the fresh air, which provides sufficient oxygen for combustion in the gas circuit, and when required, also by additional water injection into the gas duct.

If no proper clay preparation—fine crushing, grinding and drying before being fed—is available, an alternative could be using a long rotary kiln and cooler, if disadvantages such as higher maintenance costs can be tolerated. This could be particularly interesting if a plant's mothballed dry rotary kiln system is readily available, and no longer used for clinker production. If so, detailed consideration would include the system adaptions necessary for clay preparation and handling, since the properties of pure clay are markedly different from normal clinker raw materials (stickiness, moisture content, particularly if only a simple ball mill is available, etc.)

Cement rotary kiln systems with grate coolers are not very suitable, since the calcined clay's fine granulometry may produce high dust cycles towards the rotary kiln, reducing calcined clay quality. Such coolers may not allow for proper functionality—transport of the fine material, grate plate blockage, material fall through the grate, et cetera. In such cases, more suitable cooling systems—fluidised bed coolers, cyclones, cooling screws, rotary coolers, would most likely need to be installed.

7.2.2 Calciner system for a production of 400 tpd: integrated cement plant

A 400tpd calcined clay system is considered for Scenarios 2 and 3, with a total LC^3 production of 413,000 tons of cement, which is a typical grinding station dimension. A smaller capacity system could also be considered at integrated cement plants. This possibility remains for further plant specific evaluation.

The calcined clay is produced too distantly from the integrated cement plant; thus no advantage results from an already existing cheap solid fuel preparation system.

This also limits the range of fuels that can be burned, and is thus limited either to liquid fuels like diesel or heavy fuel oils, or to natural gas, where already available. Only in exceptional cases, where ground solid fuel is available from an outside source—such as lignite dust from a power plant—and where such fine solid fuels can be reasonably transported to the calcination system—via train connection, or over a short distance—utilising solid fuels could be considered without additional specific CAPEX. Otherwise a coal mill and storage facility should be installed.

Since with a low production rate, modern and efficient kiln designs cannot be downscaled with a still reasonable CAPEX, such calcination systems must be simpler, and also will therefore be much less energy efficient. Additionally, the required equipment sizes (cyclones, rotary kiln, etc.) are not common in other mineral industries, therefore a higher engineering cost must be considered.

Due to the lower efficiency of a simple design, the use of fine, solid fuels purchased, if available, would mainly be limited to easily ignitable fuels, since ignition temperatures are low because of low secondary air temperatures.

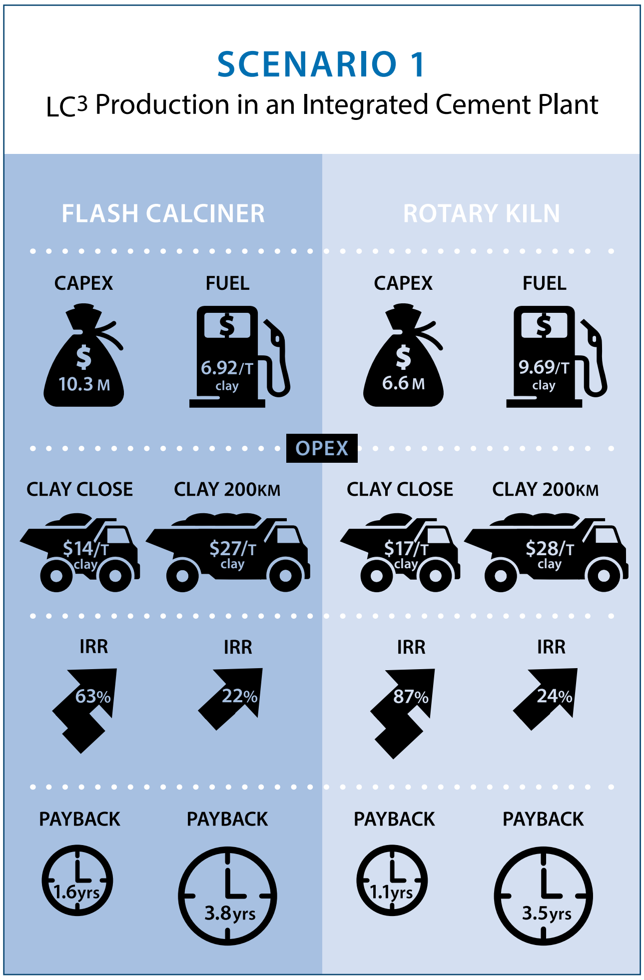
If petcoke is used, most likely an easy-to-ignite, and likely an expensive auxiliary fuel would required to ensure adequate petcoke ignition, and to support its complete combustion. This is particularly important for flash calciners, where the fuel residence time is short, and any post-combustion phenomena hampers the process.

If no kiln system is available, a small rotary kiln would be the standard solution having the lowest specific investment cost and moderately high operational costs.

The raw clay is fed into a hammer crusher in order to pre-crush the clay to a size allowing for satisfactory calcination—depending on material properties, fuel type, kiln design, etc. Since kaolin clay with its natural moisture can be fed to the kiln, no additional drying or preheating equipment is necessary.

However, such a small rotary kiln with a suitable cooler has a high specific maintenance and operational cost. This is a consequence of maintaining intensive rotating equipment and the system's low thermal efficiency—the kiln's low heat recuperation, high specific heat losses caused by hot rotary kiln convection, and cooler from a single-layer refractory lining, poor heat exchange in the "cold" section of the kiln, etc.

7.3 Scenario 1: LC^3 Production in an Integrated Cement Plant



7.3.1 Specific Scenario 1 Assumptions

- Capacity target:
  –Production capacity of calcined clay: 300'000 t/year or 960 tpd or 40t/h
  –Production capacity of LC^3: 1'000'000 t/y
- Fuel: already available coal using existing fuel storage, preparation and transport facilities
- Estimated cash production clinker: USD 23.9 /T
- Estimated cash production cost CEM I: USD 30.0 /T

7.3.2 Scenario 1.1: Flash Calciner

- Specific assumptions
  –CAPEX: USD 10.3 million for the flash calciner (see Annex 11)
  –Specific thermal energy consumption: 2 MJ/kg
  –Specific fuel cost: USD 6.92 /T clay
  –Specific variable costs for calcined clay production
    - Fuel for mobile equipment USD 0.5 /T clay
    - Variable electricity costs: USD 1 /T clay
    - Wear parts: USD 0.4 /T clay
  –Specific fixed costs for calcined clay production
    - Fix electrical energy: USD 0.2 /T clay
    - Labor expenses: USD 1.0 /T clay
    - Maintenance material: USD 0.2 /T clay
- Productions costs LC^3
  –Sub-scenario 1.1 assuming clay available close to the plant, thus cost of clay as raw material is estimated at USD 4 /T clay (Appendix 1, page 31)
  –Sub-scenario 1.1 assuming clay available at around 200 km from the plant, thus cost of clay as raw material is estimated at USD 17 /T clay (Appendix 1, page 31)
- Financials
  –If calcined clay is available at the plant, the profitability as compared to production cost of CEM I will generate an outstanding 63% IRR and a payback of 1.6 years! (Appendix 1, page 31)
  –If calcined clay not available at the plant, the profitability as compared to production cost of CEM I will still be an attractive 22% IRR and a payback of 3.8 years. (Appendix 1, page 31)

7.3.3 Scenario 1.2: Rotary Kiln

- Specific assumptions:
  –CAPEX: USD 6.6 million for the rotary kiln (see Annex 11)
  –Specific thermal energy consumption: 2.8 MJ/kg
  –Specific fuel cost: USD 9.69 /T clay
  –Specific variable costs for calcined clay production
    - Fuel for mobile equipment USD 0.5 /T clay
    - Variable electricity costs: USD 0.3 /T clay
    - Wear parts: USD 1.0 /T clay
    - Major kiln repairs: USD 1.0 /T clay
  –Specific fixed costs for calcined clay production
    - Fix electrical energy: USD 0.2 /T clay
    - Labor expenses: USD 1.0 /T clay
    - Maintenance material: USD 0.4 /T clay
- Productions costs LC^3
  –Sub-scenario 1.2 assuming clay is available close to the plant, thus cost of clay as raw material is estimated at USD 4 /T clay (Appendix 1, page 31)
  –Sub-scenario 1.1 assuming clay is available approximately 200 km from the plant, thus cost of clay as raw material is estimated at USD 17 /T clay (Appendix 1, page 31)
- Financials
  –If calcined clay is available at the plant, the profitability as compared to production cost of CEM I will generate an outstanding 87% IRR and a payback of 1.1 years! (Appendix 1, page 31)
  –If calcined clay not available at the plant, the profitability as compared to production cost of CEM I will still be an attractive 24% IRR and a payback of 3.5 years. (Appendix 1, page 31)

7.4 Scenario 2: LC3 Produced in a Grinding Station Plant

7.4.1 Specific Scenario 2 Assumptions:

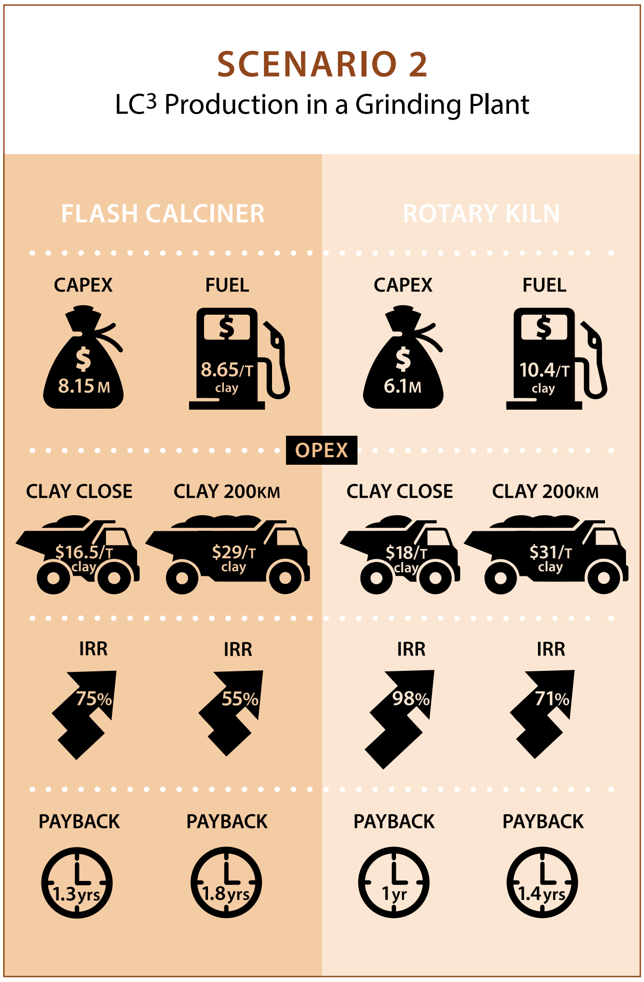
- Capacity target:
  –Production capacity of calcined clay: 124'000 t/year or 400 tpd or 16t/h
  –Production capacity of LC3: 413'000 t/y
- **Fuel:** coal will have to be imported and prepared in a coal mill (alternatively natural gas, but not investigated under this scenario)
- **Cement Grinding:** existing capacity 413,000 tpa, ~55tph
- **Estimated import cost clinker:** USD 40.0 /T
- **Estimated cash production cost CEM I:** USD 47.0 /T

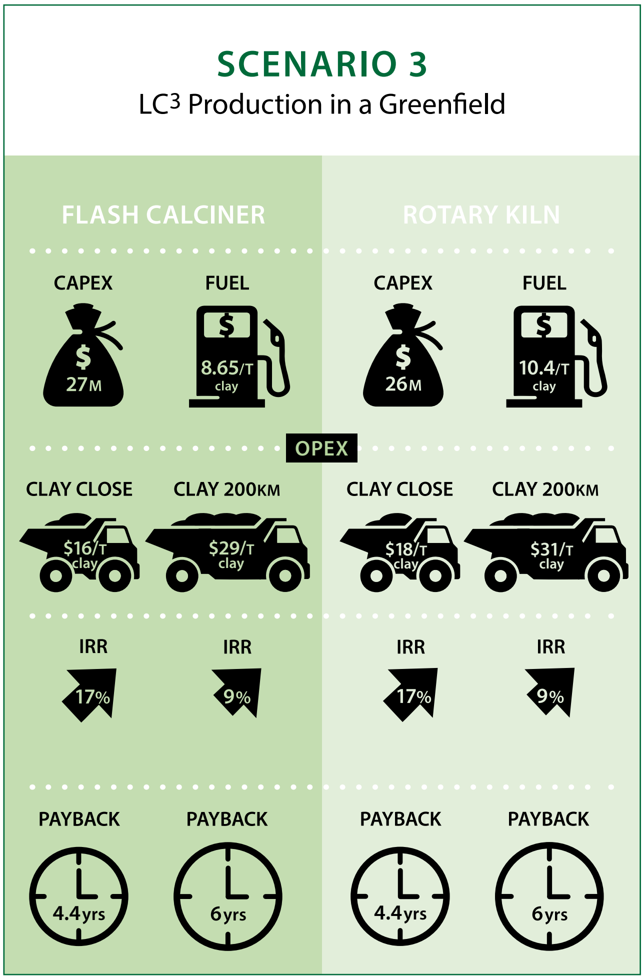
7.4.2 Scenario 2.1: Flash Calciner

- Specific assumptions:
  –CAPEX: USD 8.15 million for the flash calciner and coal mill (see Annex 11 & 12)
  –Specific thermal energy consumption: 2.5 MJ/kg
  –Specific fuel cost: USD 8.65 /T clay
  –Specific variable costs for calcined clay production
    •Fuel for mobile equipment USD 0.5 /T clay
    •Variable electricity costs: USD 1.2 /T clay
    •Wear parts: USD 0.4 /T clay
  –Specific fixed costs for calcined clay production
    •Fixed electrical energy: USD 0.2 /T clay
    •Labor expenses: USD 1.4 /T clay
    •Maintenance material: USD 0.2 /T clay
- Productions costs LC3
  –Sub-scenario 2.1 assuming clay is available close to the plant, thus cost of clay as raw material is estimated at USD 4 /T clay (Appendix 2, page 32)
  –Sub-scenario 2.1 assuming clay available approximately 200 km from the plant, thus cost of clay as raw material is estimated at USD 17 /T clay (Appendix 2, page 32)
- Financials
  –If calcined clay is available at the plant, the profitability as compared to production cost of CEM I will generate an outstanding 75% IRR and a payback of 1.3 years! (Appendix 2, page 32)
  –If calcined clay not available at the plant, the profitability as compared to production cost of CEM I will generate an outstanding 56% IRR and a payback of 1.8 years. (Appendix 2, page 32)

7.4.3 Scenario 2.2: Rotary Kiln

- Specific assumptions
  –CAPEX: USD 6.1 million for the rotary kiln and coal mill (see Annex 11 & 12)
  –Specific thermal energy consumption: 3.0 MJ/kg
  –Specific fuel cost: USD 10.38 /T clay
  –Specific variable costs for calcined clay production
    •Fuel for mobile equipment USD 0.5 /T clay
    •Variable electricity costs: USD 0.4 /T clay
    •Wear parts: USD 1.0 /T clay
    •Major kiln repairs: USD 1.0 /T clay
  –Specific fixed costs for calcined clay production
    •Fixed electrical energy: USD 0.2 /T clay
    •Labor expenses: USD 1.4 /T clay
    •Maintenance material: USD 0.4 /T clay
- Productions costs LC3
  –Sub-scenario 2.2 assuming clay is available close to the plant, thus cost of clay as raw material is estimated at USD 4 /T clay (Appendix 2, page 32)
  –Sub-scenario 2.2 assuming clay available approximately 200 km from the plant, thus cost of clay as raw material is estimated at USD 17 /T clay (Appendix 2, page 32)
- Financials
  –If calcined clay is available at the plant, the profitability as compared to production cost of CEM I will generate an outstanding 98% IRR and a payback of 1 year! (Appendix 2, page 32)
  –If calcined clay not available at the plant, the profitability as compared to production cost of CEM I will generate an outstanding 71% IRR and a payback of 1.4 years. (Appendix 2, page 32)





7.5 Scenario 3: Greenfield for Production of Calcined Clay and Cement

In this case, complete infrastructure—such as a cement grinding system, coal mill, coal storage, natural and calcined clay, as well as complete other facilities such as laboratories, electrical energy supply on medium and low voltage levels, storage facilities, maintenance workshops, etc—would have to be newly created. Clinker has to be imported or bought from nearby cement companies.

- **Capacity target:**
  –Production capacity of calcined clay: 124'000 t/year or 400 tpd or 16t/h
  –Production capacity of LC3: 413'000 t/y
- **Fuel:** coal will have to be prepared in a new coal grinding installation (import scenario considered)
- **Cement:** Will have to be prepared in a new installation
- **Estimated import cost clinker:** USD 40.0 /T
- **Estimated cash production cost CEM I:** USD 47.0 /T

7.5.1 Scenario 3.1: Flash Calciner

- Specific assumptions
  –CAPEX: USD 27 million for the flash calciner, coal mill, and grinding plant (see Annex 11 & 12)
  –Specific thermal energy consumption: 2.5 MJ/kg
  –Specific fuel cost: USD 8.65 /T clay
  –Specific variable costs for calcined clay production
    •Fuel for mobile equipment USD 0.5 /T clay
    •Variable electricity costs: USD 1.2 /T clay
    •Wear parts: USD 0.4 /T clay
  –Specific fixed costs for calcined clay production
    •Fixed electrical energy: USD 0.2 /T clay
    •Labor expenses: USD 1.4 /T clay
    •Maintenance material: USD 0.2 /T clay
- Productions costs LC3
  –Sub-scenario 3.1 assuming clay available close to the plant, thus cost of clay as raw material is estimated at USD 4 /T clay (Appendix 3, page 33)
  –Sub-scenario 3.1 assuming clay available approximately 200 km from the plant, thus cost of clay as raw material is estimated at USD 17 /T clay (Appendix 3, page 33)
- Financials
  –If calcined clay available at the plant, the profitability as compared to production cost of CEM I will generate an acceptable 17% IRR and a payback of 4.4 years. (Appendix 3, page 33)
  –If calcined clay unavailable at the plant, profitability as compared to production cost of CEM I will generate a low 9% IRR and a payback of 6 years. (Appendix 3, page 33)

7.5.2 Scenario 3.2: Rotary Kiln

- Specific assumptions
  –CAPEX: USD 26 million for the rotary kiln calciner, coal mill, and grinding plant (see Annex 11 & 12)
  –Specific thermal energy consumption: 3.0 MJ/kg
  –Specific fuel cost: USD 10.38 /T clay
  –Specific variable costs for calcined clay production
    •Fuel for mobile equipment USD 0.5 /T clay
    •Variable electricity costs: USD 0.4 /T clay
    •Wear parts: USD 1.0 /T clay
    •Major kiln repairs: USD 2.0 /T clay
  –Specific fixed costs for calcined clay production
    •Fixed electrical energy: USD 0.2 /T clay
    •Labor expenses: USD 1.4 /T clay
    •Maintenance material: USD 0.4 /T clay
- Productions costs LC3
  –Sub-scenario 3.2 assuming clay available close to the plant, thus cost of clay as raw material is estimated at USD 4 /T clay (Appendix 3, page 33)
  –Sub-scenario 3.2 assuming clay available approximately 200 km from the plant, thus cost of clay as raw material is estimated at USD 17 /T clay (Appendix 3, page 33)
- Financials
  –If calcined clay is available at the plant, the profitability as compared to production cost of CEM I will generate an acceptable 17% IRR and a payback of 4.4 years. (Appendix 3, page 33)

	Scenario 1.1 FD 300	Scenario 1.2 RK 300	Scenario 2.1 FD 124	Scenario 2.2 RK 124	Scenario 3.1 FD 124	Scenario 3.2 RK 124
CAPEX USD	10,333,170	6,617,380	8,149,450	6,069,600	27,149,450	26,069,600
CAPEX /T LC3	10.3	6.6	18.8	14.0	62.7	60.2
CLAY < 10 KM						
Cash Production Costs Calcined Clay USD /T MK	14.2	17.1	16.5	18.3	16.5	18.3
Total Production Cost LC3 USD /T LC3	23.4	24.2	32.1	32.6	32.1	32.6
CLAY AT 200 KM						
Cash Production Costs Calcined Clay USD /T MK	27.2	30.1	29.5	31.3	29.5	31.3
Total Production Cost LC3 USD /T LC3	27.3	28.1	36.0	36.5	36.0	36.5
|-------- COMPARISON WITH --------|	|---- CEM I @ 30 USD PRODUCED ----|		|--------------- CEM I @ 47 USD WITH IMPORTED CLK -------------|			
CLAY < 10 KM						
IRR %	63%	87%	75%	98%	17%	17%
Payback Years (not inflated)	1.6	1.1	1.3	1.0	4.4	4.4
CLAY AT 200 KM						
IRR %	22%	24%	55%	71%	9%	9%
Payback Years (not inflated)	3.8	3.5	1.8	1.4	6.0	6.0

[KEY > FD: Flash Dryer or Flash Calciner RK: Rotary Kiln 300: 300 ktpa 124: 124 ktpa]

	Scenario 1.1 FD 300	Scenario 1.2 RK 300	Scenario 2.1 FD 124	Scenario 2.2 RK 124	Scenario 3.1 FD 124	Scenario 3.2 RK 124
|----------- BASE CASE -----------|	|--------------------------------- MINUS 2 USD MARGIN ---------------------------------|					
CLAY < 10 KM						
IRR%	56%	76%	67%	87%	14%	14%
Payback Years (not inflated)	1.8	1.3	1.5	1.1	4.9	4.9
CLAY AT 200 KM						
IRR %	13%	10%	46%	60%	5%	5%
Payback Years (not inflated)	5.2	5.9	2.1	1.6	7.0	7.1

–If calcined clay not available at the plant, the profitability as compared to production cost of CEM I will generate a rather low 9% IRR and a payback of 6 years. (Appendix 3, page 33)

7.6 Conclusion: Financial Attractiveness

As previously stated in the Introduction, these calculations are only estimations. A simplified DCF (Discounted Cash Flow) calculation has been used to assess financial attractiveness. However, the following conclusions apply in most cases:

- Producing LC3 versus CEM I is attractive in case of an existing integrated or grinding plant, even if the clay is located as far as 200 km from the plant
- Producing LC3 instead of CEM I out of a greenfield project remains attractive, though to a lesser extent, because of the high investment costs required for the grinding plant. However, clay must be located close to the plant.
- Distance of clay from the production facility is crucial.

To be more accurate, the profitability is based on respective sales prices. However, the CEM I sales price can vary from country to country. Production costs are more standard. Therefore, the attractiveness of LC3 versus CEM I is assessed on basis of respective production costs.

The way financial attractiveness is assessed also indirectly implies that the sales price of both LC3 and "CEM I" are equal. As we cannot simulate a discount of LC3 price versus CEM I, we assessed the respective IRR and payback assuming there is a USD 2 per ton less margin of LC3 versus CEM I, as compared to the above scenarios.

With the standard scenario, the key difference is that LC3 is no longer attractive in an integrated plant if the clay is not located nearby.

Cost comparisons are summarised in the table above. Figure 15 (page 20) compares the cost of producing LC3 in USD/t and the CAPEX needed. As previously stated, the most attractive options with the lowest production cost and CAPEX, Scenarios 1.1 and 1.2, are positioned in the lower left corner. The relative bubble sizes represent the importance of necessary CAPEX.

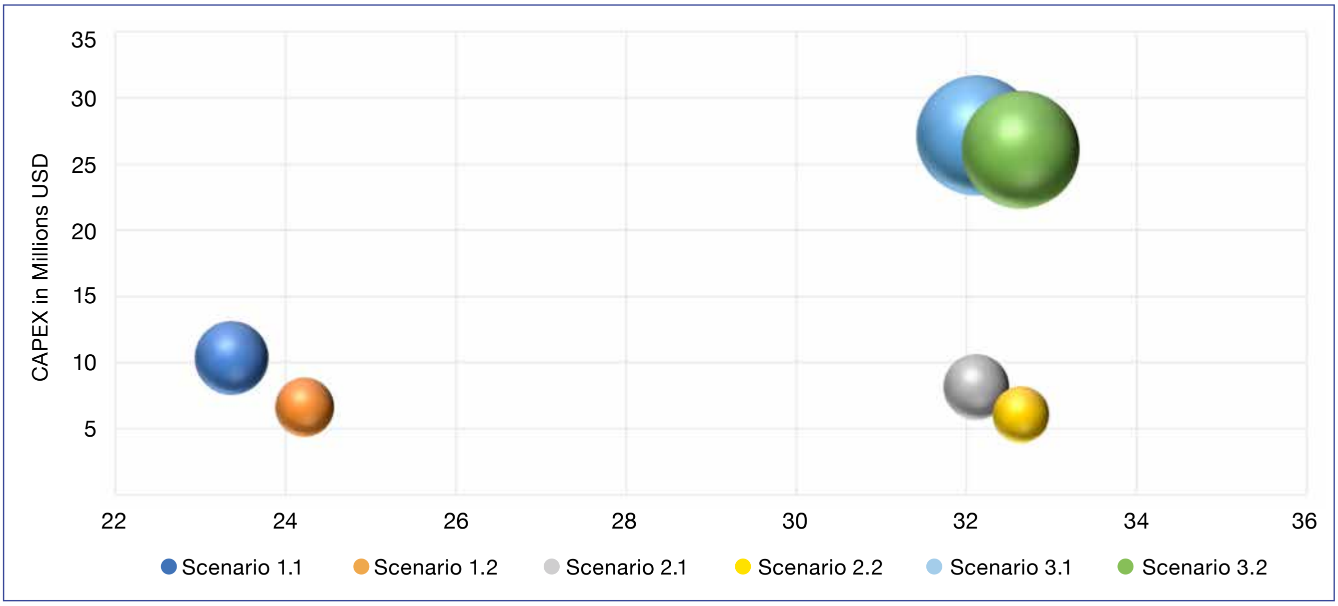


Figure 15: CAPEX vs Cost comparison (when clay is close to plant)

8. CONCLUSIONS

Mitigation of CO_2 emissions is becoming mandatory in most countries in order to comply with Paris Agreement commitments. Sooner or later, CO_2 emissions will become a significant liability for any emitter.

For the cement industry, which is a substantial CO_2 emitter, the most efficient way to reduce emissions is to reduce clinker content. For many years, cement with high clinker content was considered to be of a higher quality. Currently, many construction codes worldwide forbid the use of blended cement in standard concrete production. This continues despite the improved performance of blended cement. At the same time, no blended cement with significantly low clinker content (< 60%) has, until now, been able to achieve performace standards comparable, both short and long duration, with OPC.

LC^3, a blended cement composed of only 50% clinker, can successfully replace OPC with significantly lower production costs and CAPEX. Additionally, LC3 will eventually replace blended cement made of fly ash or slag as their availability decreases and their cost increases.

Clay, LC^3 main SCM, is widely available in most every country. Initial economic feasibility assessment demonstrates LC^3 production attractiveness in most scenarios, whether it is in an existing cement plant, in a grinding station, or a greenfield project.

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Pore refinement: Dhandapani. *Assessment of pore structure evolution in the limestone calcined clay cementitious system and its implications for performance*

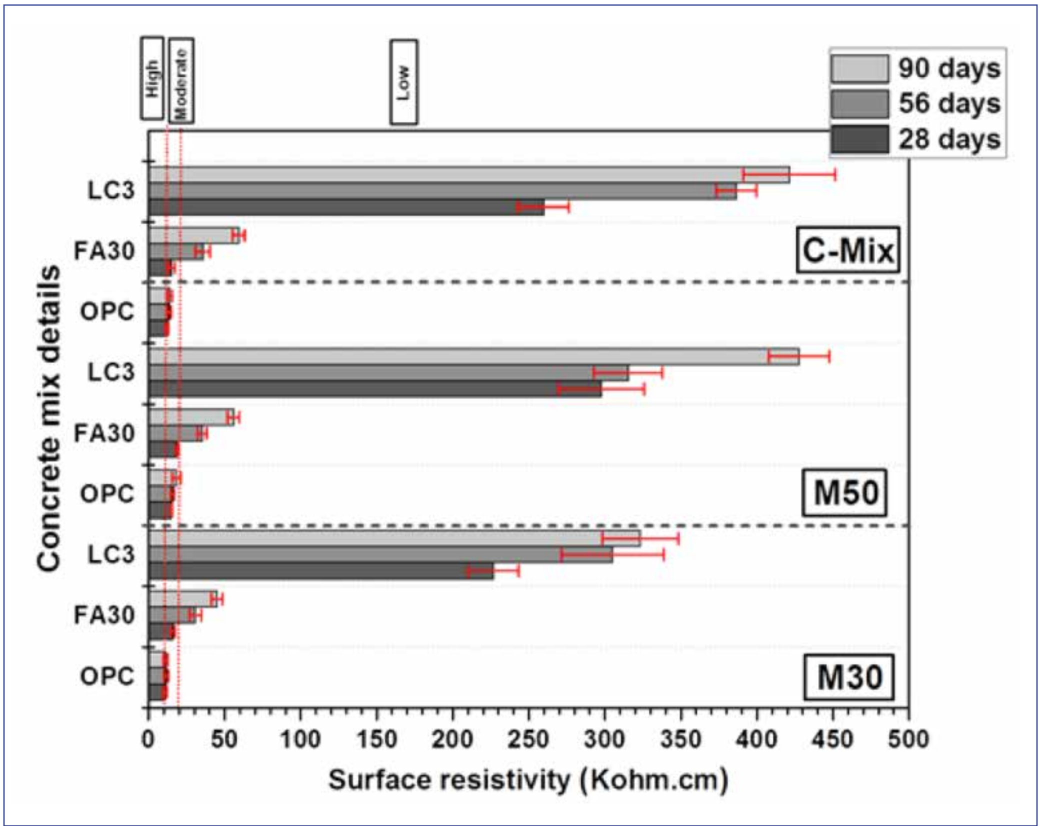
Concrete strength + some durability: Dhandapani. *Mechanical properties and durability performance of concretes with Limestone Calcined Clay Cement*

ASR: Scrivener. *Impacting factors and properties of limestone calcined clay cements (LC^3)*

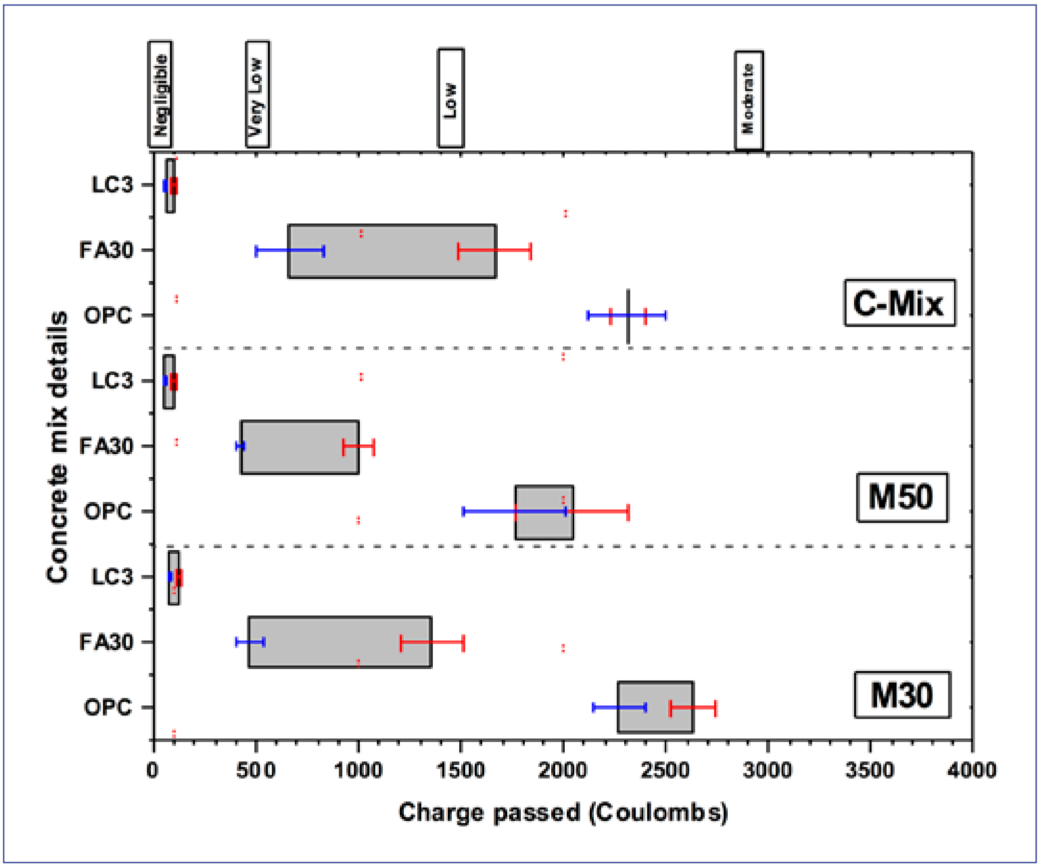
Chloride resistance: Maraghechi. *Performance of Limestone Calcined Clay Cement (LC^3) with various kaolinite contents with respect to chloride transport*

ANNEXES

ANNEX 1: SURFACE RESISTIVITY

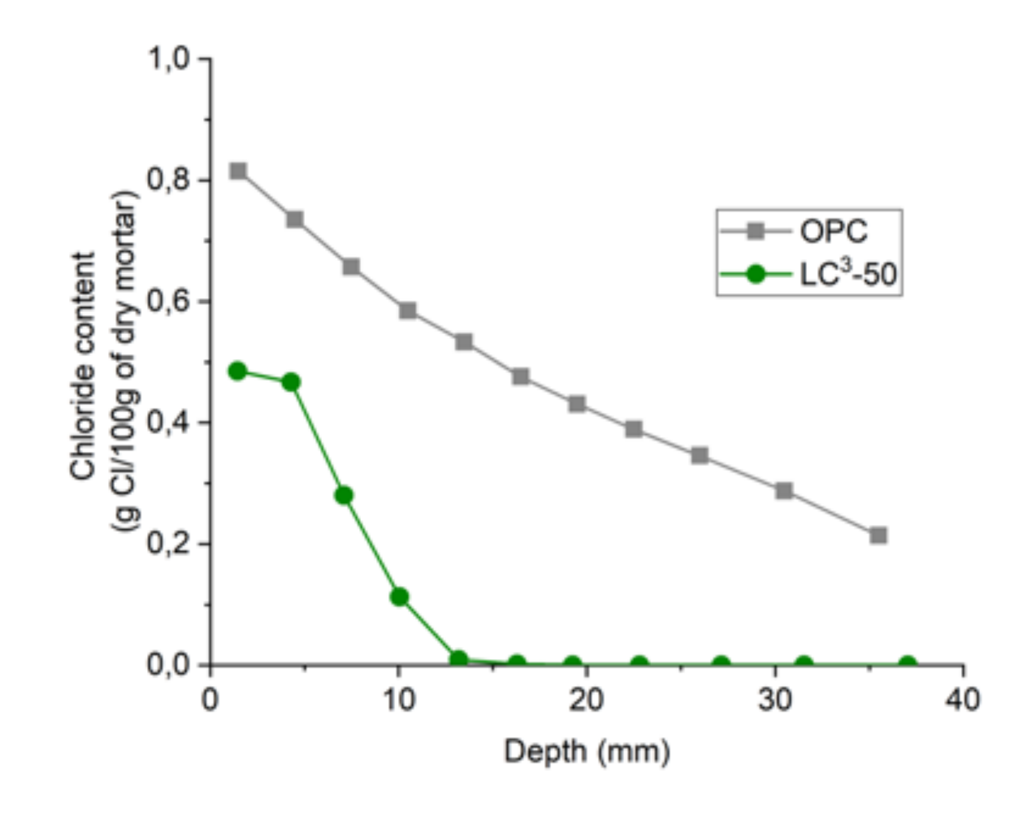


ANNEX 2: CHLORIDE PENETRABILITY BY RCPT (ASTM C1202) AND MIGRATION TEST (NT 492)

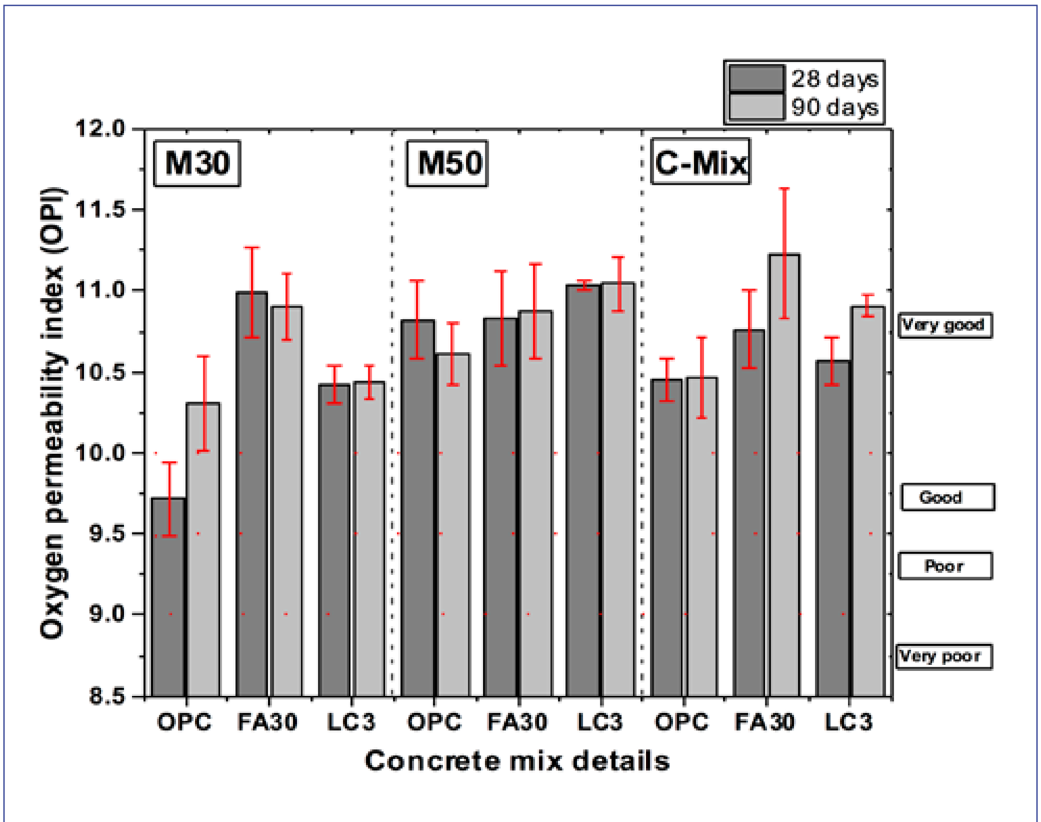


Red-28 days Blue-90 days

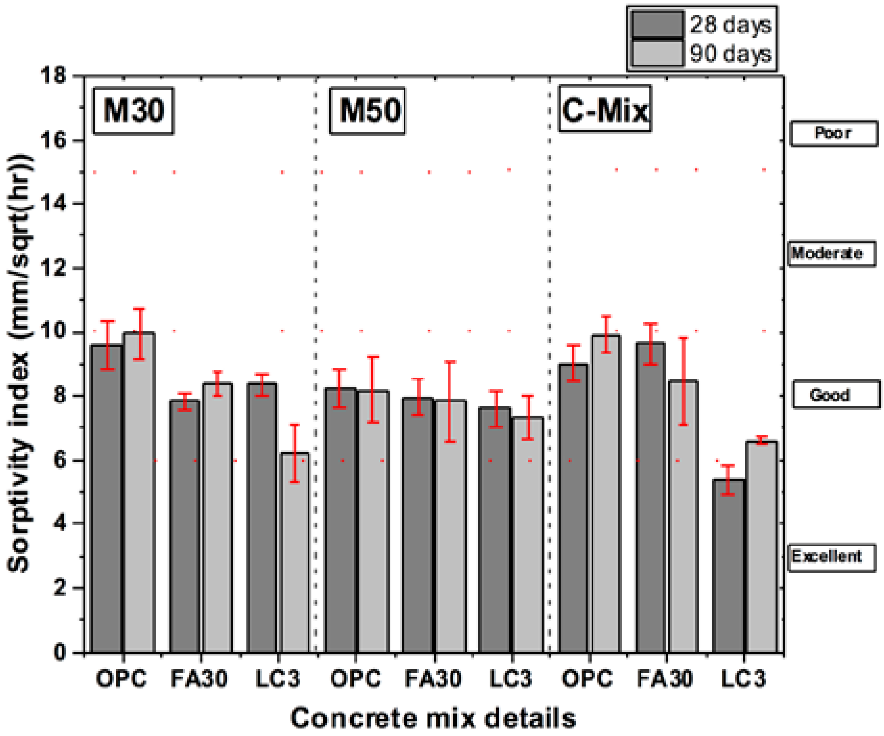
ANNEX 3: CHLORIDE PONDING OPC VS LC3



ANNEX 4: OXYGEN PERMEABILITY TEST (DURABILITY INDEX MANUAL, SOUTH AFRICA)

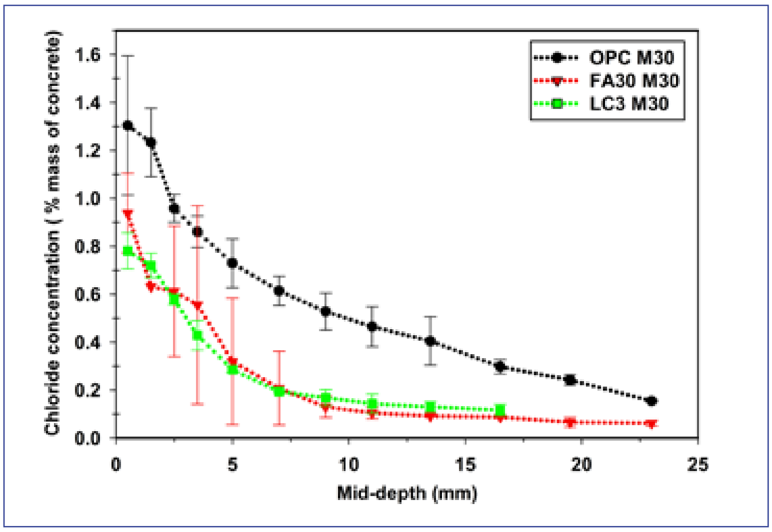


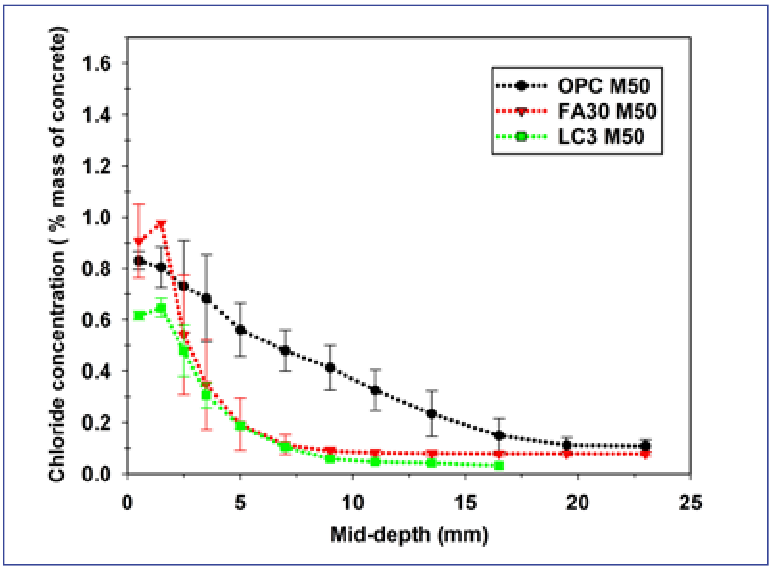
ANNEX 5: SORPTIVITY INDEX (DURABILITY INDEX MANUAL, SOUTH AFRICA)



ANNEX 6: CHLORIDE PROFILE IN M30 AND M50 GRADE OF CONCRETE

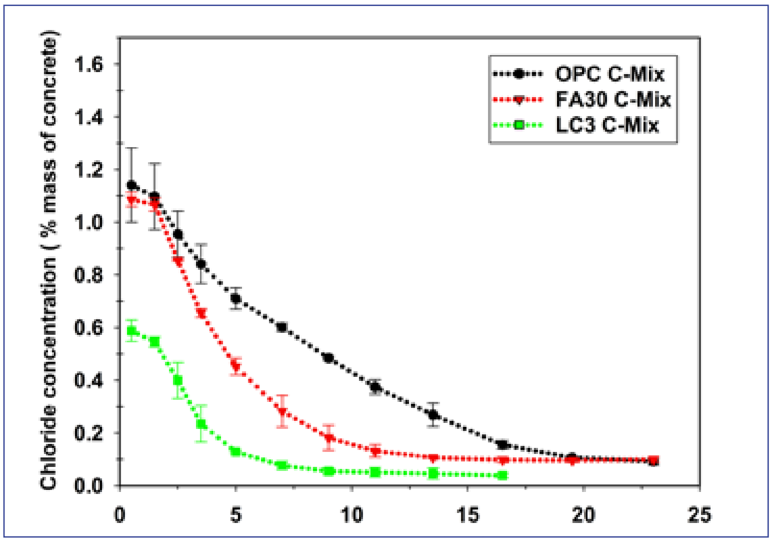
(56 DAYS CHLORIDE EXPOSURE) — BULK DIFFUSION TEST (ASTM C1556)



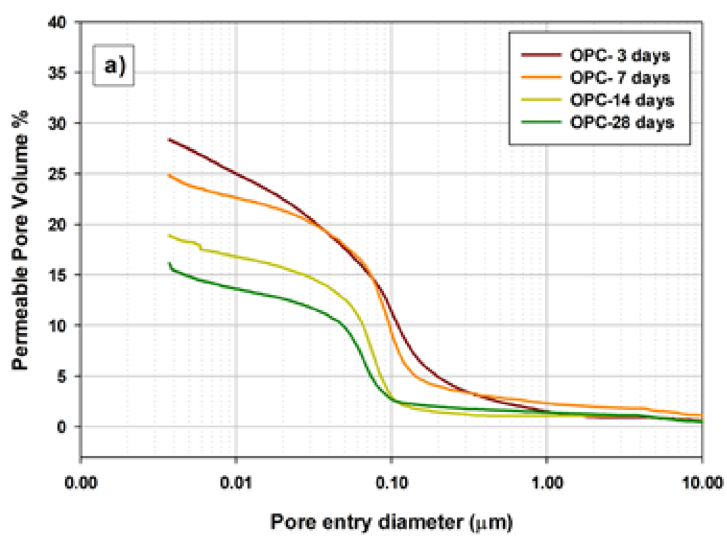


ANNEX 7: CHLORIDE PROFILE IN CONCRETE WITH COMMON MIX

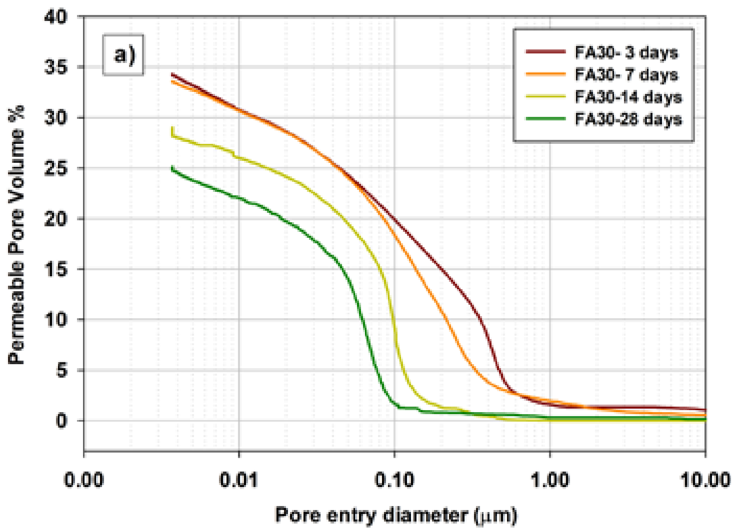
(56 DAYS CHLORIDE EXPOSURE)

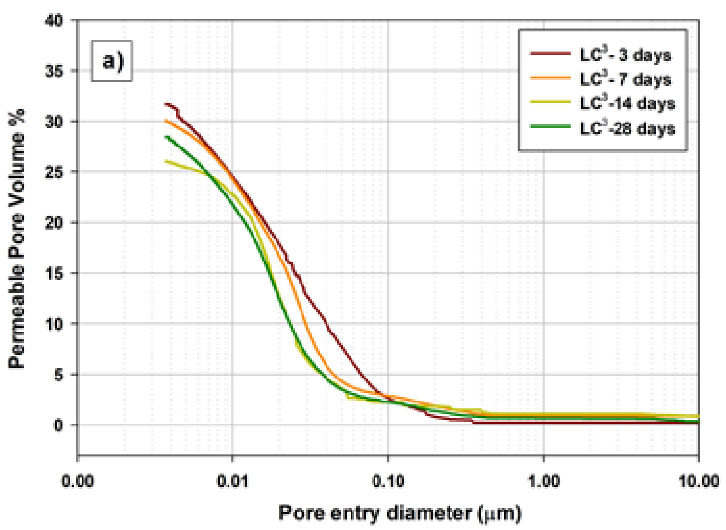


ANNEX 8: PORE STRUCTURE EVOLUTION IN LC3

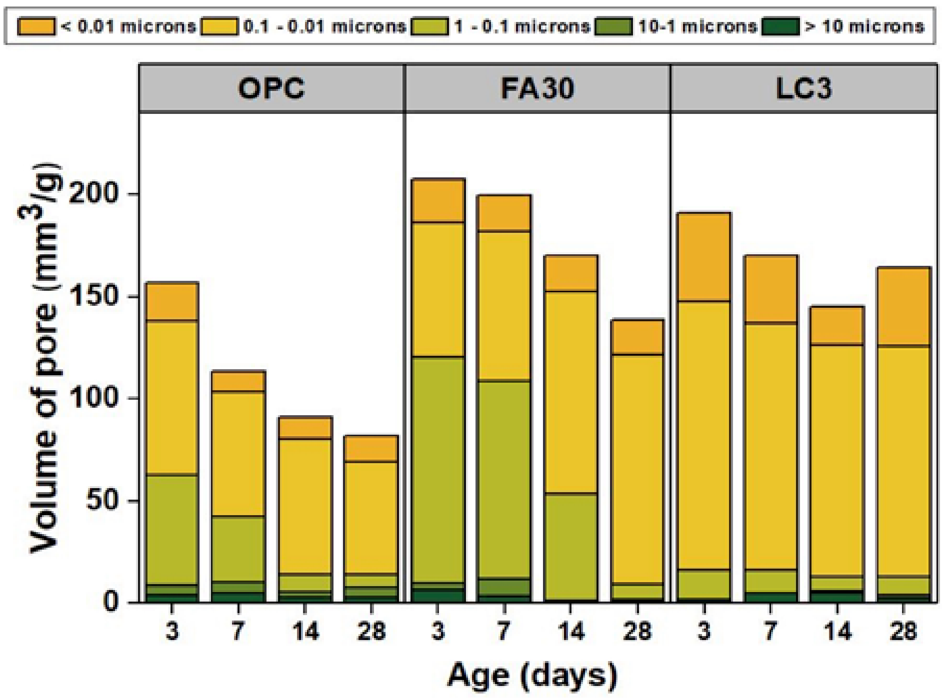


Permeable Porosity Vs Pore diameter of OPC



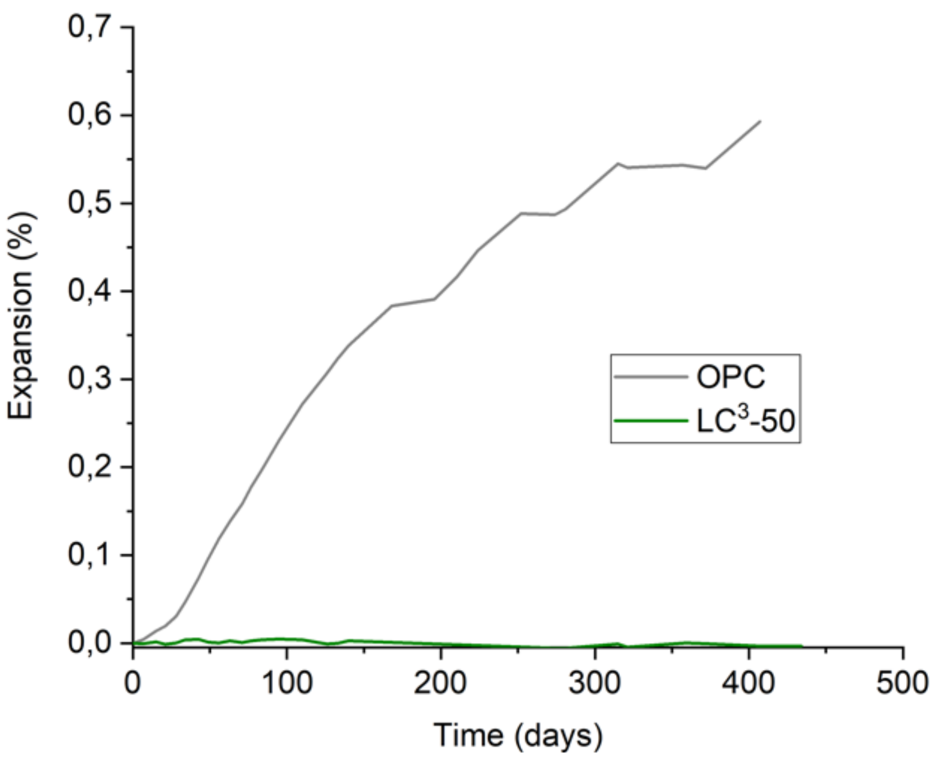


ANNEX 9: COMPARATIVE PORE SIZE DISTRIBUTION BY MIP –OPC, FA30 AND LC3



There is a shift in the pore sizes to the lower pore size (0.1–0.01 microns) at an early age with LC3; results in better durability parameter in concrete at an early age.

ANNEX 10: ALKALI SULPHATE RESISTANCE



ANNEX 11: CAPEX FLASH CALCINER & ROTARY KILN

Main Investment Cost headings	Cost Position	Cemcon Estimation Long rotary kiln 300000 kUSD	Cemcon Estimation Long rotary kiln 124000 kUSD	Cemcon Estimation Flash dryer 300000 kUSD	Cemcon Estimation Flash dryer 124000 kUSD
LAND / CONCESSIONS		-	-	-	-
	Plant site(s) acquisition	-	-	-	-
	Quarries	-	-	-	-
	Access to Quarries	-	-	-	-
	Access to Infrastructure (i.e. Power Lines)	-	-	-	-
	Access to Infrastructure (roads)	-	-	-	-
	Mining Concessions/Rights (Pre production)	-	-	-	-
	Royalties (Preproduction)	-	-	-	-
	Mineral reserves Fee (Preproduction)	-	-	-	-
CIVIL WORKS		1'056	470	1'354	640
Site Development	leveling	13	10	13	10
	Temporary Installations (Project)		-	-	-
	Preliminary Roads		-	-	-
	Storage Areas (On/Off Site)	65	50	65	50
Special Foundations	Soil Replacement (Incl. Disposal)	39	30	26	20
	Piling	-	-	-	-
Production Buildings and Structures	Foundation Works	300	100	150	50
	Concrete Works	300	100	150	50
	Structural Steel Works	150	50	540	180
	Finishing works	-	-	-	-
Internal Infrastructure	Roads/Landscaping	-	-	-	-
	Water Supply/Drainage	-	-	-	-
	General Plant Services	-	-	-	-
	Power/Control Networks	39	30	65	50
	CPP/Main Transformer	150	100	345	230
	Warehouses/Stores	-	-	-	-
	Workshops	-	-	-	-
	Garages/Parking	-	-	-	-
	Sewage Plant	-	-	-	-
	Administration Buildings	-	-	-	-
	Personnel Amenities Buildings	-	-	-	-
External Infrastructure	Railways/Spurs	-	-	-	-
	Bridges	-	-	-	-
	roads	-	-	-	-
	Port Construction	-	-	-	-
	Power Line	-	-	-	-
	Port Facilities (Harbour)	-	-	-	-
	land conveyor harbor / cement plant	-	-	-	-
	Cement Terminal	-	-	-	-
	Pipelines/Drainages	-	-	-	-
	Housing Estate (Personnel)	-	-	-	-
		-	-	-	
EQUIPMENT		2'975	2'075	4'625	2'725
Mechanical Equipment	Plant	2'250	1'500	3'000	2'000
	Peripheral (Infrastructure)	-	-	150	50
		-	-	-	-
Electrical Equipment	Plant (main & aux drives)	450	300	1'200	400
	Peripheral (Infrastructure)	200	200	200	200
		-	-	-	-
Other Equipment	Mobile Equipment (Quarries)	-	-	-	-
	Mobile Equipment (Plant)	75	75	75	75
	Laboratory Equipment	-	-	-	-
	Tools (Maint)	-	-	-	-
	Office Equipment	-	-	-	-
	Household Equipment (Estate)	-	-	-	-
		-	-		

ANNEX 11: CAPEX FLASH CALCINER & ROTARY KILN (CONTINUED)

SPARE PARTS		**585**	**450**	**455**	**350**
	Mechanical Equipment	390	300	260	200
	Electrical Equipment	130	100	130	100
	Other Equipment	65	50	65	50
				-	-
FREIGHT & TRANSPORT INSURANCE		**446**	**311**	**463**	**273**
		446	311	463	273
ERECTION / INSTALLATION		**1'140**	**900**	**2'910**	**1'700**
	Mechanical Erection	650	500	2'000	1'000
	Electrical Installation	390	300	650	500
	Equipment Supplier Supervision	100	100	260	200
PRE-PRODUCTION COSTS		**215**	**163**	**327**	**212**
Taxes and Duties	Land Acquisition	-	-	-	-
	Civil Works	-	-	-	-
	Erection & Installation	-	-	-	-
	Mechanical Equipment	-	-	-	-
	Electrical Equipment	-	-	-	-
	Mobile Equipment	-	-	-	-
		-	-	-	-
Capitalized	Pre Project Studies (FS etc.)	-	-	-	-
	Soil Investigations	20	20	20	20
	geotechnical investigations	-	-	-	-
	Topographical Surveys	-	-	-	-
	Raw Material Investigations	-	-	-	-
	Quarry Opening/Development	-	-	-	-
	ESIA (Env. Impact Studies)	-	-	-	-
	Project Administration (Owners team)	-	-	-	-
	Other Professional Services	-	-	-	-
	Project Insurances (Pre Production)	155	103	267	152
	Project Permitting process	20	20	20	20
		-	-		
Non Capitalized	Personnel Recruitment	20	20	20	20
	Personnel Training	-	-	-	-
	Expenses - Project Site	-	-	-	-
	Expenses - Owner Head Office	-	-	-	-
	Finance Charges	-	-	-	-
		-	-		
ENGINEERING & SUPERVISION		**200**	**200**	**200**	**250**
	Plant Engineering (Civil, Mechanical, Electrical)	100	100	100	150
	Internal Infrastructure Engineering	-	-	-	-
	External Infrastructure Engineering (port)	-	-	-	-
	Other Project Engineering	-	-	-	-
	Project Procurement	-	-	-	-
	Plant Site Supervision (Construction) - Contractor	50	50	50	50
	Plant Site Supervision (Construction) - Owner & (	-	-	-	-
	Commissioning Supervision - Supplier/Contractor	40	40	40	40
	Commissioning Supervision - Owner & Other	10	10	10	10
		-	-		
PROJECT TOTAL		**6'617**	**4'570**	**10'333**	**6'149**
PROJECT CONTINGENCY		-	-	-	-
PROJECT FINANCING COSTS (PRE-PROJECT)		-	-	-	-
WORKING CAPITAL (INVENTORIES)		-	-	-	-
PROJECT PRICE ESCALATION		-	-	-	-
PROJECT INVESTMENT (kUSD)		**6'617**	**4'570**	**10'333**	**6'149**
Specific INVESTMENT COST (USD/tpy)		**22.06**	**36.85**	**34.44**	**49.59**

ANNEX 12: CAPEX BALL MILL & STORAGE

Main Investment Cost headings	Cost Position	*Cemcon Estimation* Ball mill (open circuit) 300000 *kUSD*	*Cemcon Estimation* Storage and packing 300000 *kUSD*
LAND / CONCESSIONS		-	-
	Plant site(s) acquisition	-	-
	Quarries	-	-
	Access to Quarries	-	-
	Access to Infrastructure (i.e. Pow er Lines)	-	-
	Access to Infrastructure (roads)	-	-
	Mining Concessions/Rights (Pre production)	-	-
	Royalties (Preproduction)	-	-
	Mineral reserves Fee (Preproduction)	-	-
CIVIL WORKS		425	215
Site Development	leveling	10	5
	Temporary Installations (Project)	-	-
	Preliminary Roads	-	-
	Storage Areas (On/Off Site)	-	-
Special Foundations	Soil Replacement (Incl. Disposal)	15	10
	Piling	-	-
Production Buildings and Structures	Foundation Works	100	50
	Concrete Works	100	50
	Structural Steel Works	100	100
	Finishing w orks	-	-
Internal Infrastructure	Roads/Landscaping	-	-
	Water Supply/Drainage	-	-
	General Plant Services	-	-
	Pow er/Control Netw orks	-	-
	CPP/Main Transformer	100	
	Warehouses/Stores	-	-
	Workshops	-	-
	Garages/Parking	-	-
	Sew age Plant	-	-
	Administration Buildings	-	-
	Personnel Amenities Buildings	-	-
External Infrastructure	Railw ays/Spurs	-	-
	Bridges	-	-
	roads	-	-
	Port Construction	-	-
	Pow er Line	-	-
	Port Facilities (Harbour)	-	-
	land conveyor harbor / cement plant	-	-
	Cement Terminal	-	-
	Pipelines/Drainages	-	-
	Housing Estate (Personnel)	-	-
		-	
EQUIPMENT		1'990	605
Mechanical Equipment	Plant	1'500	500
	Peripheral (Infrastructure)	50	50
		-	-
Electrical Equipment	Plant (main & aux drives)	400	20
	Peripheral (Infrastructure)	40	5
		-	-
Other Equipment	Mobile Equipment (Quarries)	-	-
	Mobile Equipment (Plant)	-	30
	Laboratory Equipment	-	-
	Tools (Maint)	-	-
	Office Equipment	-	-
	Household Equipment (Estate)	-	-

ANNEX 12: CAPEX BALL MILL & STORAGE (CONTINUED)

SPARE PARTS		**80**	**40**
	Mechanical Equipment	40	20
	Electrical Equipment	20	10
	Other Equipment	20	10
		-	-
FREIGHT & TRANSPORT INSURANCE		**199**	**61**
		199	61
ERECTION / INSTALLATION		**850**	**420**
	Mechanical Erection	500	200
	Electrical Installation	300	200
	Equipment Supplier Supervision	50	20
PRE-PRODUCTION COSTS		**473**	**287**
Taxes and Duties	Land Acquisition	100	50
	Civil Works	-	-
	Erection & Installation	-	-
	Mechanical Equipment	-	-
	Electrical Equipment	-	-
	Mobile Equipment	-	-
		-	-
Capitalized	Pre Project Studies (FS etc.)	10	10
	Soil Investigations	20	20
	geotechnical investigations	-	-
	Topographical Surveys	-	-
	Raw Material Investigations	-	-
	Quarry Opening/Development	-	-
	ESIA (Env. Impact Studies)	-	-
	Project Administration (Owners team)	-	-
	Other Professional Services	-	-
	Project Insurances (Pre Production)	98	37
	Project Permitting process	20	20
Non Capitalized	Personnel Recruitment	-	-
	Personnel Training	-	-
	Expenses - Project Site	-	-
	Expenses - Owner Head Office	-	-
	Finance Charges	225	150
ENGINEERING & SUPERVISION		**115**	**95**
	Plant Engineering (Civil, Mechanical, Electrical)	40	20
	Internal Infrastructure Engineering	-	-
	External Infrastructure Engineering (port)	-	-
	Other Project Engineering	-	-
	Project Procurement	-	-
	Plant Site Supervision (Construction) - Contractor	25	25
	Plant Site Supervision (Construction) - Owner &	-	-
	Commissioning Supervision - Supplier/Contractor	40	40
	Commissioning Supervision - Owner & Other	10	10
PROJECT TOTAL		**4'132**	**1'723**
PROJECT CONTINGENCY		413	172
PROJECT FINANCING COSTS (PRE-PROJECT)		-	-
WORKING CAPITAL (INVENTORIES)		-	-
PROJECT PRICE ESCALATION		-	-
PROJECT INVESTMENT (kUSD)		**4'545**	**1'895**
Specific INVESTMENT COST (USD/tpy)		**15.15**	**6.32**

APPENDIX

APPENDIX 1, SCENARIO 1: LC3 PRODUCTION IN AN INTEGRATED CEMENT PLANT

Scenario 1.1: Flash calciner

Cost of LC3	% in Cement	Volume	Cost USD	USD /T
Cost of clinker	50%	500,000	11,946,803	11.9
Cost of gypsum	5%	50,000	1,000,000	1.0
Cost of calcined clay	30%	300,000	4,256,923	4.3
Cost of limestone	15%	150,000	420000	0.4
Cost of grinding			5738574.521	5.7
Total production cost LC3		**1,000,000**	**23,362,300**	**23.4**

Cost of LC3	% in Cement	Volume	Cost USD	USD /T
Cost of clinker	50%	500,000	11,946,803	11.9
Cost of gypsum	5%	50,000	1,000,000	1.0
Cost of calcined clay	30%	300,000	8,156,923	8.2
Cost of limestone	15%	150,000	420000	0.4
Cost of grinding			5738574.521	5.7
Total production cost LC3		**1,000,000**	**27,262,300**	**27.3**

	Year 1	Years 2-10
Investment cost	-10,333,170	
Yearly saving through LC3		6,637,700
Cash flow	-10,333,170	6,637,700
NPV (5 year)	7,901,032	USD
NPV (10 year)	19,736,281	USD
WACC (50/50 @ 8%/20%)	14%	
IRR	**63%**	
Payback not inflated in years	**1.6**	

	Year 1	Years 2-10
Investment cost	-10,333,170	
Yearly saving through LC3		2,737,700
Cash flow	-10,333,170	2,737,700
NPV (5 year)	-2,066,931	USD
NPV (10 year)	2,814,482	USD
WACC (50/50 @ 8%/20%)	14%	
IRR	**22%**	
Payback not inflated in years	**3.8**	

Scenario 1.2: Rotary kiln

Cost of LC3	% in Cement	Volume	Cost USD	USD /T
Cost of clinker	50%	500,000	11,946,803	11.9
Cost of gypsum	5%	50,000	1,000,000	1.0
Cost of calcined clay	30%	300,000	5,117,692	5.1
Cost of limestone	15%	150,000	420000	0.4
Cost of grinding			5738574.52	5.7
Total production cost LC3		**1,000,000**	**24,223,070**	**24.2**

Cost of LC3	% in Cement	Volume	Cost USD	USD /T
Cost of clinker	50%	500,000	11,946,803	11.9
Cost of gypsum	5%	50,000	1,000,000	1.0
Cost of calcined clay	30%	300,000	9,017,692	9.0
Cost of limestone	15%	150,000	420,000	0.4
Cost of grinding			5,738,575	5.7
Total production cost LC3		**1,000,000**	**28,123,070**	**28.1**

	Year 1	Years 2-10
Investment cost	-6,617,380	
Yearly saving through LC3		5,776,930
Cash flow	-6,617,380	5,776,930
NPV (5 year)	8,960,467	USD
NPV (10 year)	19,260,934	USD
WACC (50/50 @ 8%/20%)	14%	
IRR	**87%**	
Payback not inflated in years	**1.1**	

	Year 1	Years 2-10
Investment cost	-6,617,380	
Yearly saving through LC3		1,876,930
Cash flow	-6,617,380	1,876,930
NPV (5 year)	-1,007,496	USD
NPV (10 year)	2,339,136	USD
WACC (50/50 @ 8%/20%)	14%	
IRR	**24%**	
Payback not inflated in years	**3.5**	

APPENDIX 2, SCENARIO 2: LC3 PRODUCED IN A GRINDING STATION PLANT

Scenario 2.1: Flash calciner

Cost of LC3	% in Cement	Volume	Cost USD	USD /T
Cost of clinker	50%	206,667	8,266,667	20.0
Cost of gypsum	5%	20,667	413,333	1.0
Cost of calcined clay	30%	124,000	2,049,077	5.0
Cost of limestone	15%	62,000	173600	0.4
Cost of grinding			2371944.14	5.7
Total production cost LC3		**413,333**	**13,274,621**	**32.1**

Cost of LC3	% in Cement	Volume	Cost USD	USD /T
Cost of clinker	50%	206,667	8,266,667	20.0
Cost of gypsum	5%	20,667	413,333	1.0
Cost of calcined clay	30%	124,000	3,661,077	8.9
Cost of limestone	15%	62,000	173600	0.4
Cost of grinding			2,371,944	5.7
Total production cost LC3		**413,333**	**14,886,621**	**36.0**

	Year 1	Years 2-10
Investment cost	-8,149,450	
Yearly saving through LC3		6,168,579
Cash flow	-8,149,450	6,168,579
NPV (5 year)	8,617,556	USD
NPV (10 year)	19,616,347	USD
WACC (50/50 @ 8%/20%)	14%	
IRR	**75%**	
Payback not inflated in years	**1.3**	

	Year 1	Years 2-10
Investment cost	-8,149,450	
Yearly saving through LC3		4,556,579
Cash flow	-8,149,450	4,556,579
NPV (5 year)	4,497,465	USD
NPV (10 year)	12,622,003	USD
WACC (50/50 @ 8%/20%)	14%	
IRR	**55%**	
Payback not inflated in years	**1.8**	

Scenario 2.2: Rotary kiln

Cost of LC3	% in Cement	Volume	Cost USD	USD /T
Cost of clinker	50%	206,667	8,266,667	20.0
Cost of gypsum	5%	20,667	413,333	1.0
Cost of calcined clay	30%	124,000	2,263,692	5.5
Cost of limestone	15%	62,000	173,600	0.4
Cost of grinding			2,371,944	5.7
Total production cost LC3		**413,333**	**13,489,236**	**32.6**

Cost of LC3	% in Cement	Volume	Cost USD	USD /T
Cost of clinker	50%	206,667	8,266,667	20.0
Cost of gypsum	5%	20,667	413,333	1.0
Cost of calcined clay	30%	124,000	3,875,692	9.4
Cost of limestone	15%	62,000	173,600	0.4
Cost of grinding			2,371,944	5.7
Total production cost LC3		**413,333**	**15,101,236**	**36.5**

	Year 1	Years 2-10
Investment cost	-6,069,600	
Yearly saving through LC3		5,953,964
Cash flow	-6,069,600	5,953,964
NPV (5 year)	9,893,453	USD
NPV (10 year)	20,509,577	USD
WACC (50/50 @ 8%/20%)	14%	
IRR	**98%**	
Payback not inflated in years	**1.0**	

	Year 1	Years 2-10
Investment cost	-6,069,600	
Yearly saving through LC3		4,341,964
Cash flow	-6,069,600	4,341,964
NPV (5 year)	5,773,362	USD
NPV (10 year)	13,515,234	USD
WACC (50/50 @ 8%/20%)	14%	
IRR	**71%**	
Payback not inflated in years	**1.4**	

APPENDIX 3, SCENARIO 3: GREENFIELD FOR PRODUCTION OF CALCINED CLAY AND CEMENT

Scenario 3.1: Flash calciner

Cost of LC3	% in Cement	Volume	Cost USD	USD /T
Cost of clinker	50%	206,667	8,266,667	20.0
Cost of gypsum	5%	20,667	413,333	1.0
Cost of calcined clay	30%	124,000	2,049,077	5.0
Cost of limestone	15%	62,000	173,600	0.4
Cost of grinding			2,371,944	5.7
Total production cost LC3		**413,333**	**13,274,621**	**32.1**

Cost of LC3	% in Cement	Volume	Cost USD	USD /T
Cost of clinker	50%	206,667	8,266,667	20.0
Cost of gypsum	5%	20,667	413,333	1.0
Cost of calcined clay	30%	124,000	3,661,077	8.9
Cost of limestone	15%	62,000	173,600	0.4
Cost of grinding			2,371,944	5.7
Total production cost LC3		**413,333**	**14,886,621**	**36.0**

	Year 1	Years 2-10
Investment cost	-27,149,450	
Yearly saving through LC3		6,168,579
Cash flow	-27,149,450	6,168,579
NPV (5 year)	-8,049,110	USD
NPV (10 year)	2,949,680	USD
WACC (50/50 @ 8%/20%)	14%	
IRR	**17%**	
Payback not inflated in years	**4.4**	

	Year 1	Years 2-10
Investment cost	-27,149,450	
Yearly saving through LC3		4,556,579
Cash flow	-27,149,450	4,556,579
NPV (5 year)	-12,169,202	USD
NPV (10 year)	-4,044,663	USD
WACC (50/50 @ 8%/20%)	14%	
IRR	**9%**	
Payback not inflated in years	**6.0**	

Scenario 3.2: Rotary kiln

Cost of LC3	% in Cement	Volume	Cost USD	USD /T
Cost of clinker	50%	206,667	8,266,667	20.0
Cost of gypsum	5%	20,667	413,333	1.0
Cost of calcined clay	30%	124,000	2,263,692	5.5
Cost of limestone	15%	62,000	173,600	0.4
Cost of grinding			2,371,944	5.7
Total production cost LC3		**413,333**	**13,489,236**	**32.6**

Cost of LC3	% in Cement	Volume	Cost USD	USD /T
Cost of clinker	50%	206,667	8,266,667	20.0
Cost of gypsum	5%	20,667	413,333	1.0
Cost of calcined clay	30%	124,000	3,875,692	9.4
Cost of limestone	15%	62,000	173,600	0.4
Cost of grinding			2,371,944	5.7
Total production cost LC3		**413,333**	**15,101,236**	**36.5**

	Year 1	Years 2-10
Investment cost	-26,069,600	
Yearly saving through LC3		5,953,964
Cash flow	-26,069,600	5,953,964
NPV (5 year)	-7,650,406	USD
NPV (10 year)	2,965,717	USD
WACC (50/50 @ 8%/20%)	14%	
IRR	**17%**	
Payback not inflated in years	**4.4**	

	Year 1	Years 2-10
Investment cost	-26,069,600	
Yearly saving through LC3		4,341,964
Cash flow	-26,069,600	4,341,964
NPV (5 year)	-11,770,498	USD
NPV (10 year)	-4,028,626	USD
WACC (50/50 @ 8%/20%)	14%	
IRR	**9%**	
Payback not inflated in years	**6.0**	

Financial Attractiveness of LC^3

CEMENTIS

EPFL

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Agency for Development
and Cooperation SDC