



Expanding Boundaries: Systems Thinking for the Built Environment

ECONOMIC AND ECOLOGICAL ASSESSMENT OF CUBAN HOUSING SOLUTIONS USING ALTERNATIVE CEMENT

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Abstract

Concrete is the most manmade material solution produced and used worldwide. Its cornerstone is the cement composite due to the high emissions level and resources consumption volume. Roughly 5-7% of global carbon dioxide emissions come from cement manufacture process. The far-reaching alternative of replacement a clinker portion in the cement material composition has gained consensus. It becomes relevant in emerging economies since in the short-run there is not widely available ways for increasing the production capacity while diminish the environmental impact with no additional investment cost. Low carbon cement (LC³) is leading the contemporary paths towards facing environmental challenges and resource scarcity. This article aims at assessing the theoretical consideration of replacement of the Cuban traditional cements by LC³ according to housing case studies in Villa Clara province. On the basis of LCA background and the supply chain rationale, a procedure for discussing sustainable contribution of LC³ is designed and applied. Hollow blocks and mortars have been included in the calculations as well as the manufacturing/transportation processes for the entire supply chain of one semi-detached two-storey row houses built in the core of a slum-like settlement at Condado suburb-Santa Clara city. This approach demonstrates that the LC³ incorporation in the Cuban construction sector could afford considerable economic savings with the subsequent contribution in favour of the environment.

Keywords:

Low carbon cement; LCA; sustainability; eco-efficiency

1 INTRODUCTION

One of the most acute concerns of current century is the survival of mankind. Global carbon dioxide (CO₂) emissions from fossil fuel combustion and from industrial processes (cement and metal production) increased in 2013 to the new record of 35.3 billion tonnes (Gt) CO₂, which is 0.7 Gt higher than last year's record [1]. Cement production accounts for roughly 5-7% of this environmental damage. So far, cementitious materials are not replaceable when building up infrastructure since

concrete is a composite that requires a binder reacting with water to further harden. Cement production and consumption is meant to be trending upward in developing countries in forthcoming decades. This is the case of Cuba, where the demand for cement has been forecasted in a growth rate of 18% (short term), 10% (middle term) and 5% (long term). The clinker is the active ingredient of cement and its production process is quite energy intensive. That is why cement manufacture is not only a matter of



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pollution, but a matter of economy. Ordinary Portland Cement (OPC), with at least 88% of clinker, becomes a very pricey good. Bearing these two sustainability dimensions in mind (Economy and Ecology), the use of a potential surrogate for clinker in the cement content has been deeply studied and well-documented. Funded by Swiss Agency for Development and Cooperation, a joint project with participation of Swiss, Cuban and Indian scientists has developed a new type of cement, named Limestone Calcined Clay Cement (LC³). LC³, a low carbon cement, which is a blended cement containing 30% of metakaolin (calcined kaolinite clay), has been produced in Cuba in an industrial trial form in 2013 and 2015. This paper is aimed to present the economic and ecological impact of this alternative cement when used in Cuban housing projects in the province of Villa Clara.

2 METHODOLOGY AND DATA COLLECTION

2.1 Defining the assessment protocol

In order to assess the economic and environmental contribution of LC³ in housing applications in Cuba, the following 5-phases procedure is proposed and later applied.

- I. Definition of goals and scope
- II. Supply chain characterization and mapping
- III. Creation of Data inventory
- IV. Setting eco-efficiency indicators and calculations
- V. Reporting eco-efficiency profile and interpretation

Phase I is intended to clarify the construction type and all technical features associated to the construction system to be assessed. Functional unit (F.U.) and system boundaries (S.B.) should be defined as well. Limitations or assumptions derived from F.U. and S.B. are adopted in this Phase. Alternatives, strategies or scenarios are also described, if necessary (especially when comparing different technologies).

Phase II characterizes all flows downstream from the target building, identifying key players over the whole supply chain and their roles on the construction system under analysis. A diagram for mapping the supply chain is recommended so that a holistic understanding could be possible by inspecting the drawing.

In Phase III all required data is collected following the flow route described in Phase II. Background

and foreground data should be clearly organized in order to further be combined into eco-indicators. All material flows generate physical quantities and monetary quantities throughout the supply chain. Building materials are needed to be traced from quarries to building (construction site), determining economic and environmental inflows and outflows (inputs and outputs).

Phase IV integrates all material and economic flows along the chain, yielding an overall measure for both economic and ecologic performance of the alternatives confronted. Afterwards, for interpretation purposes it is recommended to combine both dimensions by means of an eco-efficiency indicator. According to the WBCSD [2] an eco-efficiency indicator is the ratio that relates an economic performance measure with an environmental load. Damini et al. (2010) [3] proposed two basic eco-efficiency indicators in order to measure and assess the cement use, namely *binder intensity* (bi) and *CO₂ intensity* (ci). However, these indicators are more applicable to concrete mix design assessment, when a large number of observations or sample is taken into account. For the case of the functional unit targeted in this paper, a conventional eco-efficiency indicator proposed by WBCSD is employed, relating revenues (at the level of 1 m² of wall) and carbon dioxide emissions.

Phase V is intended to draw up conclusions as from the findings achieved in Phase IV, setting up the eco-efficiency profile of each option evaluated. This procedure takes theoretical background from Life Cycle Assessment based on ISO 14040 (2006) [4] and the Eco-efficiency procedure been standardised by ISO 14045 (2012) [5].

2.2 Data collection

The primary variables included on database (foreground data) are cement, sand, gravel, calcium hydrate, crushed stone, water and hollow blocks. Data comes from the housing project design and was contrasted with the construction company as well. The concrete blocks data were taken from Vizcaino-Andres (2014, 2015) [6], [7], based on industrial blocks manufacture (for OPC-made blocks) and LC³ blocks been produced at local level in an *eco-materials' workshop* at Manicaragua (Villa Clara). Economic and environmental inputs for cement are taken from Sanchez (2015) [8], who has assessed in-depth the cement cost and the environmental effects for different types of cement produced in Cuba, especially comparing to LC³ production.



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Transportation fuel consumption was obtained from the Enterprise for Construction Materials Transportation at provincial level. Fuel consumption per kg of material for different types of aggregates was obtained from Building Materials Trading Company at regional level. Electricity consumption per unit material was also gathered from the referred enterprises. In respect of background data, environmental calculations have assumed an emission factor of 3.21 kg CO₂ per kg of diesel, according to annual report of National Enterprise for Fuel Trading (CUPET), titled *Fuel Quality Specifications*. Diesel density of 0.8379 kg/L is used for needed conversions, as disclosed on the above-mentioned report. Electricity emission factor is assumed to be 7.44x10⁻⁴ kg CO₂ per kWh, according to similar report from Cuban Electric Power Union. Standard unit material consumptions (material-intensity) were found in Perez (2013) [9], and served as documented reference while comparing material consumption originated from construction enterprises. Both data sources are coincident.

3 RESULTS

3.1 Definition of goals and scope

After the first industrial trial of LC3 cement in Cuba, a subsequent use of this cement took place in the construction sector. The local government supported the construction of one semi-detached two-storey row houses in the core of a slum-like settlement at Condado suburb-Santa Clara city. All masonry mortars consumed in the second floor employed LC3, which encompasses placing blocks, plastering, patching walls and all finishing activities.

Definition of scenarios

In this case study, LC3 was used in masonry activities; nevertheless, the blocks used in the whole construction were produced with cement P-35 (the Cuban equivalent of OPC). That is why three scenarios were devised in order to undertake the eco-efficiency assessment, which are described as follows.

Scenario 1: Traditional cements-Scenario, which means that blocks are made of P-35 and mortars are made of PP-25 (the Cuban equivalent of PPC), both are traditional cements in Cuba.

Scenario 2: Combined P-35/LC3 Scenario, in which blocks are made of OPC and mortars of LC3 (this is the real scenario of house built at Condado-SC).

Scenario 3: Entire LC3 Scenario, which supposes that both blocks and mortars are made of LC3.

Ecological and economic implications of LC3 use, in this case study, is assessed based on one squared meter of wall as a functional unit. As cement sustainability assessment taken from [6], [7] and [8] starts in quarrying activities (cradle-to-gate approach), the present study covers the material cycle from quarrying up to use phase. It ends up at the construction level and does not take into account neither the recycling of materials nor the operational emissions derived from the use-phase of building.

3.2 Supply Chain characterization and mapping

Fig.1 shows the supply chain (S.CH.) from materials' procurement up to construction site. As shown in this diagram, 12 enterprises were involved in the housing construction throughout the supply chain. Among them, 9 are producers and suppliers of raw materials (building materials), two are intermediary companies which main function is merely commercial entity and one is a construction company. Dashed lines indicate the links between nodes or enterprises along the supply chain, and the arrows' direction indicates the material flows throughout the S.CH. Conversely, the economic flows are traced back from the end to starting point in the sense that each enterprise pays for the goods supplied by the preceding entity. The links are deeply important because through the economic relationship between firms the value-added has been created from quarrying to final building and, in the same principle, the environmental flows are considered as a cumulative amount.

3.3 Creation of Data inventory

Table 1 shows the unit material consumption used in one square meter of wall, which becomes the base for economic and environmental assessment, therefore, for eco-efficiency indicators.

It is presented separately according to the kind of masonry activity; the materials involved in the production of 13 hollow concrete blocks—those

Table1. Consumption material 1 m² of wall

Materials consumed	Cement (kg)	Sand (m ³)	Gravel (m ³)	Crushed stone powder (m ³)	Calcium hydroxide (kg)
Blocks/materials consumed	22.36	0.052	0.078	0.013	
Mortar/Blocks placement	6.25	0.018			3.6
Mortar/Finishing	5.27	0.038			2.85
Total	33.88	0.108	0.078	0.013	6.45



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required to build up one m² of wall– are reported in the first row. Economic cost and CO₂ emitted were calculated on the base of material consumption stated in Table 1. CO₂ released due to transportation was calculated based on the amounts of material specified. Table 2 presents the fuel consumption and electricity consumption scaled to the level of 1 m² of wall. Table 3 shows the fuel consumption per kilometer according to the building material shipped.

Table 2. Diesel and electricity consumed in material obtaining (1 m² of wall)

Building material (excluding cement)	Diesel (L)	Electricity (KWh)
Blocks (U)	0.312	0.481
Sand (m3)	0.0684	0.204
Ca(OH) ₂ (kg)	0.0438	0.045
Total	0.4242	0.73

Load capacity is later used to derive an impact index due to transport activities. In this study, the environmental assessment covers the carbon dioxide emissions generated largely due to the

embodied energy into all materials consumed in one square meter of wall, resulting from its previous production process in itself.

Table 3. Fuel consumption (shipping)

Building material	Consumption index (L/km)	Load capacity	Unit	Distance (km)
Cement	0.4504	20000	kg	188
Sand	0.4	10000	kg	96
Ca(OH) ₂	0.4	10000	kg	188
Block	0.3086	1290	U	110
Water	0.2222	6000	L	20

Input data is taken from two different sources. Cement emissions have been taken from previous research results shown in [6], [7] and [8], who have extensively examined the Cuban cement industry and its related cement types. The remaining building materials CO₂ related emissions, i.e. sand, gravel, crushed stone powder, calcium hydroxide, have been derived as a direct result of the present study. Emissions due to transportation of all building materials have been estimated in this study.

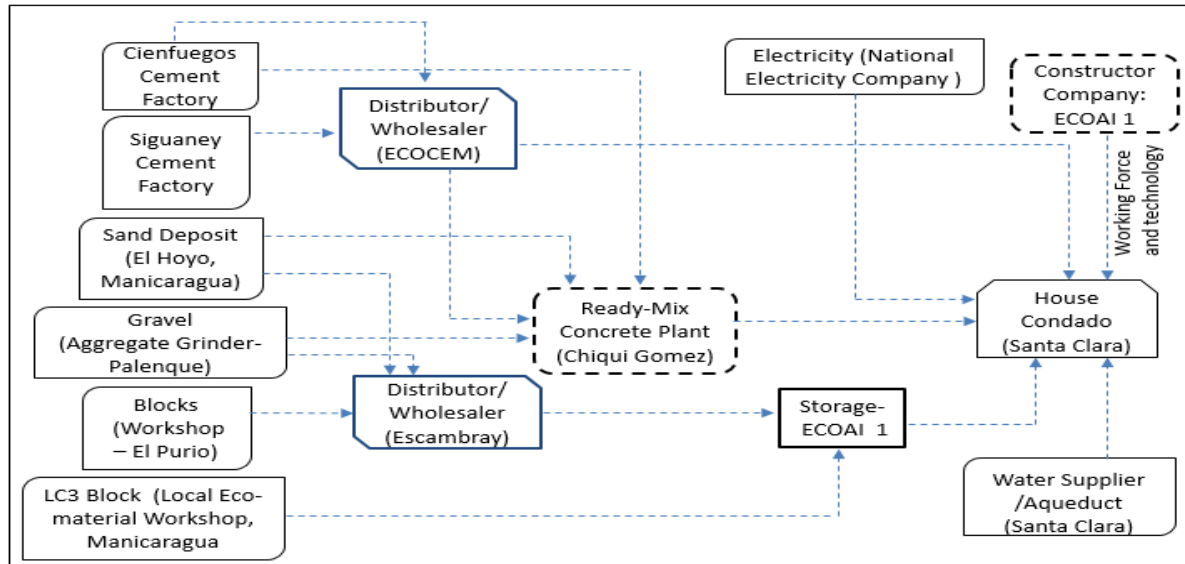


Fig. 1. Supply chain mapping for housing case study

3.4 Setting eco-efficiency indicators and calculations

Table 4 summarizes the CO₂ emitted during obtaining the building materials involved in 1 m² of wall as well as the emissions derived from

transporting all materials from suppliers to construction site. In this report, an allocation method is proposed, ensuring distribution of all CO₂ released during transportation process amongst different units of material shipped. For simplification reasons, the means of transportation are not declared in table 3, although, conventional



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trucks—which are representative in Cuban construction sector—have been considered. The framework of table 3 lets us to apportion the fuel consumption among the truck carrying capacity (e.g. 20 000 kg of cement) by means of a conversion coefficient. Furthermore, a generic scalar value is attained when dividing consumption index (L/km) by the carrying capacity. The resulting number indicates the share of fuel consumption that corresponds to each unit quantity of material shipped (i.e., L/km/U). Afterwards, this conversion index is multiplied by the transportation distance and later by the amount of material used in real construction. This is the prior calculation needed before reckoning the CO₂ released due to transportation. Diesel engines release ~2.6 kg CO₂ per L of diesel fuel burned [10]. This reference figure was used while determining environmental loads associated to transportation.

Table 4 summarizes the environmental load of each scenario, by adding CO₂ emissions due to fabrication process to those released during shipping raw materials. Cement manufacturing impact is also summed as it appears in the first row.

Table 4. CO₂ emissions by pollutant source

Pollutant Source	Sc. 1	Sc. 2	Sc. 3
Cement production	32.87	30.48	22.77
Obtaining aggregates and blocks*	1.14	1.14	1.14
Transportation	1.44	1.44	1.44
Total	35.45	33.07	25.35

*Cement consumed in block production is counted in first row
(Sc: scenario)

Table 5 presents the eco-efficiency upshot, according to the ratio explained in section 2.

Table 5. Eco-efficiency indicator over scenarios

Item	Sc. 1	Sc. 2	Sc. 3	Δ (%)
Revenues	6.96	6.85	6.29	2 vs. 3 20
Emissions	35.45	33.07	25.35	1 vs. 2 5
Eco-indicator	0.20	0.21	0.25	1 vs. 3 26

3.5 Reporting eco-efficiency profile and interpretation

It is clearly noticeable that ~92% of overall emissions embedded in 1 m² of wall belongs to cement, as expected (Table 4). That is why its negative impact to the environment is a global concern, therefore, encourages this kind of

research. Aggregates and blocks represent altogether the remaining 8% (roughly 4.5% each). By only switching from cement P-35 to LC3 in mortar, emission savings account for 7% (scenario 1 vs. 2). This is the real environmental advantage of House-Condado-Santa Clara, which employed the technology depicted in scenario 2. Moving from scenario 2 to 3, which in addition means producing LC3 blocks, savings ~30% might be achieved. This is merely the effect of introducing LC3 in block production plants. Full replacement of traditional cements currently being used in the construction sector in Cuba (P-35 for blocks and PP-25 for mortars) leads to a 40% carbon dioxide emission savings. In terms of economic cost, replacing traditional existing cements by LC3 lessens the production cost by ~11%. Looking at the joint effect (economy-environment), LC3 mortars could increase the eco-efficiency of cement use by 5%; moreover, producing LC3 blocks would rise the eco-indicator 20% higher.

The combination of both (mortars and blocks made of LC3) would rise the sustainability of buildings in roughly 26%. It is difficult to mention a consideration around performance of 1 m² of wall, since all materials are combined into a structure. Structures like walls, floors roofing decks are built to last and provide comfort to dwellers. Nevertheless, once all building materials are embedded into a structure, properties like durability and comfort are difficult to forecast, in large extent. It should be revisited and still is a challenge.

4 DISCUSSION

The results emerging from eco-efficiency analysis can be read as follows: 0.20 US\$ of revenue per kg of CO₂ emitted is achieved in each square meter of wall when using conventional cements. When introducing LC3 in mortars, at the same level of functional unit, 0.21 US\$ of revenue per kg of CO₂ would be reached. The full LC3 scenario let elicit 0.25 US\$ of revenue per kg of CO₂, which represents a straightforward advantage in terms of economic and environmental impact. Taking into account a 28-days compressive strength of 4.47 MPa for LC3 hollow blocks and 5.3% absorption [6], the replacement of traditional cements in blocks manufacture would be feasible from a technical, economic and environmental viewpoint. Compressive strength in LC3 mortars are in the order of 8.98 MPa and absorption by capillarity 7-



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days is ranking like PPC mortars (1.58 g/cm²) (Alvarez, 2014) [10]. Additional goodness of LC3 mortars can be found in [10], like medium adherence, open porosity.

The social dimension of sustainability is understood as from the odds to use less costly building materials like LC3, which in turn let producing a wide range of related construction materials using the same low clinker binder. This implies a better purchase power for end consumers at existing markets.

5 CONCLUSIONS

The methodology proposed and applied in this case study is proven to be feasible and easy to handle if the purpose lies on the sustainability concept, which encompasses economic, environmental and social dimensions. The scenarios evaluated showed the marginal effect of replacing traditional cements in mortars and blocks while building one square meter of wall. LC3 performs in a very cost-effective way and environmentally friendly, ~26% more sustainable than conventional cements. Potential cost-efficiency and CO₂ savings would be induced if the analysis is scaled to the level of entire house. The supply chain approach is deeply aligned with LCA methodology. Combining both provides researches with a comprehensive framework in understanding the links between economic and environmental flows when tracing the route of building materials. The findings presented in this paper shed light to policymakers in the Cuban cement industry and governmental key players on the potential core decisions concerning construction sector investments.

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