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Sustainability rating of lightweight expanded clay aggregates using energy inputs and carbon dioxide emissions in life-cycle analysis

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ABSTRACT This paper highlights the result of a case study on energy inputs and carbon dioxide emissions of lightweight expanded clay aggregates. These aggregates have numerous applications in various areas of civil engineering and agriculture, including lightweight construction, geotechnical backfills, pavement sections, water treatment, and horticulture. Replacement of non-renewable natural aggregates with alternative lightweight aggregates in these applications offer new opportunities and challenges. The environmental consequence of such replacement is particularly significant for geotechnical fill applications involving large volume of materials, often in direct contact with natural ground and undisturbed soil. Such significance justifies implementation of sustainable means, methods, and materials of construction. Evaluating the potential of these aggregates to enhance sustainability rating of infrastructures requires analyzing energy inputs and carbon dioxide emissions as major sustainability performance measures. These measures contribute to the production phase of any lifecycle cost analysis, where environmental footprints represent the cost. Similarly, physical and mechanical characteristics of materials, such as lightness, damping, insulation, and durability, will alter the consumption of energy and the release of greenhouse gas emissions during operation, maintenance, and decommissioning phases of the lifecycle analysis. The presented case study employs these techniques to reframe lifecycle analysis based on environmental measures and to compare the outcome with conventional cost analyses. Moreover, conclusions discuss the link between these comparative analyses and ENVISION sustainability rating measures.

1 INTRODUCTION

Resource allocation is a primary focus in environmental evaluations and is in direct relationship with environmental footprints of a project. Best practices in resource allocation often involve replacement of non-renewable natural resources, such as mineral aggregates, with alternative products. General expectations from these alternatives may include reduction of materials, waste, energy, and emissions associated with targeted applications (ISI 2012).

Lightweight expanded clay aggregates often replace mineral aggregates in various applications, such as geotechnical fills, cementitious materials, pavement sections, water treatment filters, and horticulture mediums. These aggregates are products of treating clay materials at 1100 degrees Celsius in rotary kilns. The outcome is a porous medium with unconnected voids. These voids are responsible for lightness, thermal and sound insulation, and water absorption properties of aggregates. In addition, the chemical composition of this amorphous material is also responsible for the non-decomposability and durability of the resulted product. These properties directly influence the environmental footprints of applications during production, hauling, construction, operation and maintenance. In addition, lightweight expanded clay aggregates offer specific benefits for particular applications that would further improve the life time of the project, such as mass reduction in earthquake design, water absorption in internally cured concrete, thermal insulation in building construction, drainage in mechanically stabilized walls, and others (Tehrani 1998, Ries et al. 2010).

Analyzing energy inputs and carbon dioxide emissions facilitate determination of sustainability measures for particular materials, as well specific means and methods of construction. The results of such analyses are essential to develop lifecycle analysis of proposed application. In this area, replacement of mineral aggregates with lightweight expanded clay aggregates require a comprehensive lifecycle to include environmental footprints from the beginning of the production to the end of the operation. Such comprehensive

Table 1. Phases of the lifecycle analysis.

Phase	Description
Production	Mining, producing, and hauling to the job site
Construction	Building masonry walls
Operation	Maintaining thermal comfort

Table 2. Production information.

Task	Machines and Equipment
Mining	Wheel Loader, Crawler Dozer, Truck
Production	Rotary Kiln, Concrete Block Machine
Hauling	Wheel Loader, Truck

approach can translate characteristics of materials, such as lightness, damping, insulation, and durability, to changes in the consumption of energy and the release of greenhouse gas emissions (Tehrani et al. 2014).

The outcome of lifecycle analyses of energy and emissions are key inputs for objectively appraising the sustainability of infrastructure projects using rating systems, such as ENVISION. The ENVISION facilitates sustainability rating through a scoring system in six different credits, including quality of life, leadership, resource allocation, natural world, risk and resilience, and innovation. Thus, ENVISION can capture broader socio-economic impacts of replacing mineral aggregates with lightweight expanded clay aggregates (Dadkhah & Tehrani 2018).

Table 3. Construction information.

Item	Components
Materials	Concrete Block, Mortar, Water
Team	Foreman, Mason 1 and 2, Assistant, Labor
Equipment	Wheelbarrow, Mortar box

Table 4. Operation information.

Parameters	Components
System	Openings, Lighting, Heating, Ventilation, and Air Conditioning (HVAC)
Building	Exterior Walls, Interior Walls, Roof, Floor
Source	System Pump, System Fan, Heating Gas, Electricity

2 METHODOLOGY

In order to develop a better understanding regarding the benefits of the use of lightweight expended clay aggregate within varying aspects of civil engineering, a life cycle analysis of the energy input and carbon dioxide emissions was developed. This analysis began with mining raw materials for production of lightweight expanded clay aggregates and continued to production of aggregates and concrete masonry units containing those aggregates. The ending cycle of the analysis was the application of lightweight masonry units in a selected building construction to incorporate thermal properties of aggregates in the process. Table 1 summarizes these steps.

The rates of energy consumption and emissions directly relate to productivity of each machine or process. For earthwork operations, calculations were based on recommended procedures by Peurifoy et al. (2011) and published records based on local practices by ACCO (2004). The energy input for machines and equipment have been estimated based on recommended values and procedures by Pimental et al. (1973), Fluck (1985), and Lower et al. (1977). Calculation of sequestered and fuel emissions have also been based on industry standards as reported by Barths (2008), Wells (2001), Ortiz-Cañavate & Hernanz (1999), IPCC (1996), and Fluck & Baird (1980). In these calculations, the sequestered emission is assumed to be directly related to the energy input, while fuel emissions are directly calculated from fuel consumption rates per existing records at the plant.

The analysis of production phase included calculation of energy input and emissions for involved equipment and their consumed fuels and electricity. These equipment and tools covered a broad range of machines, such as earthmoving machines, rotary kiln, conveyors, and others. Calculation of energy input and emissions for manufactured machines were based on certain simplifying assumptions. However, calculation of productivity rates, and fuel and electricity consumption rates were based on collected records in the plant. Table 2 lists essential equipment and machines to mine and haul raw materials to the plant, produce aggregate and masonry units, and haul products to the construction site (Tehrani et al. 2014, Dadkhah & Tehrani 2018).

Analysis of energy and emissions during construction phase also incorporated materials, labors, and tools required for construction of masonry walls. These calculations were based on standard productivity rates and published records by industry, and adjusted to account for the effect of lightness of aggregates on the speed of construction. Table 3 highlights the components of masonry construction (Tehrani 1998).

Further, Assari & Ziarani (2015) have provided detailed analysis for operation phase using numerical simulations. Results highlighted savings in energy and fuels due to thermal properties of lightweight concrete masonry walls. These results were combined with statistical analyses on construction data to obtain broader understanding about resulted savings in energy and fuel at national level. Table 4 lists parameters of these analyses.

Table 5. Specifications of mining, production, and hauling machines and equipment.

Machine	Power (kW)	Mass (ton)	Fuel (l/hr)	Electricity (kW/hr)	Output (m^3/d)
Wheel Loader (site)	203	23.99	30	N/A	3168
Crawler Dozer	264	40.50	60	N/A	2543
Truck (mine)	224	8.93	20	N/A	2395
Rotary Kiln	N/A	450	873	368	630
Block Machine	N/A	200	12.5	1800	320
Crushing Machine	N/A	3	N/A	45	12
Wheel Loader (plant)	162	16.7	8	N/A	310
Truck (plant)	224	8.93	20	N/A	4160
Truck (site)	224	8.93	17.5	N/A	2160

3 RESULTS

3.1 *Mining*

Table 5 contains a summary of machine specifications per manufacturer's documentation for mining and production phases. Fuel consumption rates have been obtained from plant records. The productivity rate at the mine has been calculated based on cycle time of 31.5 seconds for a 40 m distance between trucks and excavator on a nearly flat surface, and travel speeds based on transmission specifications of each machine. The average hauling distance to carry the soil to plant is 40 km. The bulk density of the soil at the mine is nearly 1600 kg/m^3, indicating an expansion ratio of nearly 4.57 to produce lightweight expanded clay aggregates with average bulk density of 350 kg/m^3. There is no waste in the imported soil to the plant.

3.2 *Production*

Production of lightweight expanded clay aggregates and resulted concrete masonry blocks primarily utilizes the rotary kiln and the block machine, respectively. The fuel consumption of the rotary kiln includes direct fueling and a small portion of production additives. Rejected aggregates will be sent to crushing machine to be screened to proper sizes, leaving virtually no waste in the process. The block manufacturing process also produces nearly 0.5% of masonry blocks, which 0.4% of them would be recycled as aggregates using the crushing machine, leaving less than 0.1% waste. A wheel loader feeds products to trucks over a 400-m distance at the plant. The nominal hauling distance is about 100 km.

Table 6. Specifications of construction crew.

Labor (number)	Equipment (number)	Output (m^3/hr)
Foreman (1) Mason 1 (1) Mason 2 (1) Assistant (1) Labor (1))	Wheelbarrow (1) Mortar box (1)	5

Table 7. Summary of energy savings during operation.

System	Net energy saving (kW/hr)
Heating	12,776
Cooling	13,719

3.3 *Construction*

Table 6 summarizes the characteristics of masonry crew at the job site. The productivity rate is based on construction of exterior walls at 0.2-m nominal thickness, using $0.49 \times 0.19 \times 0.19$ m hollow masonry units with 10 kg weight. The small weight and large dimensions of masonry units accelerate construction time and reduce the amount of mortar for the unit of work. The waste during construction is estimated to be 2%. The life of masonry tools is assumed to be 75 days for these calculations. The entire operation is assumed to be based on manual labor to simplify calculations.

3.4 *Operation*

Table 7 highlights energy saving due to replacement of normal masonry units with lightweight units containing expanded clay aggregates in a 495-m^2 residential 3-story house. The building utilized 75 m^3 of lightweight expanded clay aggregate. Architectural spaces included three bedrooms, hall, kitchen, bath, and staircase. Standard openings, lighting and HVAC systems were considered for the building. Energy savings indicated nearly 35.4% and 24.1% reductions in heating and cooling demands, respectively. These reductions directly translate to reduction of electricity and fuel consumption over the life of the building for cooling and heating, respectively (Assari & Ziarani 2015).

3.5 *Economy*

It should be noted that the cost of natural gas, as the main fuel for heating is several fold higher than the cost of electricity, e.g., 4.5 times for the studied region (Sadeghzadeh 2015, ISNA 2016, EIA 2018a, b). Further, subsidization of the cost of energy, a common tool to achieve social justice; have major influences on the regime of energy consumption and choice of energy sourcing (Daemi 2017). Thus, the results of economic analyses can be substantially different from the results of energy consumption shown in the Table 7. Furthermore, the increased demand for natural gas

Table 8. Energy inputs and emissions.

Phase	Energy (MJ/m^3)	Emissions (kg/m^3)
Mining	112.1	6.53
Production	1099.1	61.8
Construction	18.24	0.0
Operation	1522.8	113,364

(45%) and electricity (40%), and the climate change (requiring 70% additional energy to address global warming) will also influence presented results from both energy and economic perspectives (IEA 2017, Herring 2012, NASA 2017, Dahlman 2017, IPCC 2014).

3.6 *Energy input and emissions*

Table 8 provides a summary of energy inputs and emissions for each phase of the lifecycle. Energy inputs are sums of mass energy sequestered in machines, fuel energy, and labor energy. Similarly, total reported emissions are summation of mass and fuel emissions.

These results will most likely change as the efficiency of machines and equipment changes over time. For instance, existing reports indicate substantial increase in the efficiency of cooling and heating equipment up to 40% between 1980 and 2015 (Nadel et al. 2015). Similar reports are available for construction machines, suggesting that heavier machines with higher rates of embodied energy offer higher rates of production, and thus offsetting their environmental footprints (Peurifoy et al. 2010). Thus, projection of energy inputs and emissions require regional studies on available technologies.

3.7 *ENVISION*

Table 9 summarizes achievable ENVISION credits for various phases of the case study in respect to application of lightweight expanded clay aggregate products as opposed to conventional normal-weight aggregate products.

In the mining phase, the major savings has roots in the expansive nature of the process, requiring nearly one-third of raw materials to produce one unit volume of aggregates. Additional savings during transportation are linked to fuel efficiency of hauling trucks due to lighter loads, which is estimated at 10%.

It is understandable that the production process of synthetic aggregates would take more energy and emissions than processing raw materials. Therefore, no savings are associated with these measures. However, production of lightweight aggregate masonry units benefit from savings in water consumption due to internal curing advantages. It should also be noted that waste reduction strategies can be equally applied to all materials, and, thus, not reported in this comparative study. But, replacing portion of fossil fuel with waste materials are reported as part of innovation credits.

Table 9. Selected ENVISION credits (after ISI 2012).

Category	Resource Allocation				Climate And Risk	
Phase	1.1[a]	2.1[b]	3.2[c]	0.0[d]	1.1[e]	1.2[f]
Total credit	18	18	17	8	18	11
Mining	12	12			13	6
Production			4	8		
Construction	6	3			7	
Operation	6	7			7	6
Weighted Average	4	4	2	3	7	6

[a] RA1.1: Reduce net embodied energy
[b] RA2.1: Reduce energy consumption
[c] RA3.2: Reduce potable water consumption
[d] RA0.0: Innovate or exceed credit requirements
[e] CR1.1: Reduce greenhouse gas emissions
[f] CR1.2: Reduce air pollutant emissions

Major savings during construction have sources in enhanced efficiency of crew due to lighter weight of units, and lower need for mortars due to larger size of units. These savings could be more substantial in automated systems of construction with less manual labor.

The energy and emissions associated with operational demands are key factors in generation of ENVISION credits for the proposed case. These credits are based on existing data, projected over the lifecycle of the building. Average credits are reported based on the contributions of each phase, as shown in Table 8.

4 CONCLUSIONS

A case study on energy inputs and carbon dioxide emissions of lightweight expanded clay aggregate products was presented. Results included estimation of proposed measures from mining raw materials to operation of buildings incorporating final products These results indicated that energy savings due to application of proposed materials can offset the energy consumption and emission production during the production processes. Thus, the cradle-to-gate approach to the determination of energy and emissions is not adequate to fully understand the environmental footprints of proposed products. Furthermore, the interaction between energy pricing strategies, climate change, and machine efficiencies influences the projection of results over the life of the project. Application of ENVISION rating provided a simplified approach to evaluate the sustainability of proposed application.

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