Leadership in Sustainable Infrastructure
Leadership en Infrastructures Durables

Vancouver, Canada
May 31 – June 3, 2017/ *Mai 31 – Juin 3, 2017*

ECO-EFFICIENCY ANALYSIS OF RECYCLED MATERIAL FOR RESIDENTIAL CONSTRUCTION: A CASE STUDY OF OKANAGAN (BC)

Piyaruwan Perera[1], Kasun Hewage[1,2], M. Shahria Alam[1], Rehan Sadiq[1]
[1] School of Engineering, University of British Columbia (Okanagan Campus), Canada
[2] Kasun.Hewage@ubc.ca

Abstract: Very high resources demand is one of major criticisms for construction industry. Furthermore, construction and demolition (C&D) waste constitutes one third of the national waste inventory. Renovation and demolishing projects generate 90% of the national C&D waste. Waste disposal is a critical issue today, especially in urban areas. Landfilling is currently the primary mode of disposal, which leads to the formation of leachate and landfill gases. Literature reveals that, the C&D waste can be turned into a resource, by producing recycled construction materials. This study compares the eco-efficiency of the use of recyclable inculcated concrete foam (ICF) blocks and recycled concrete aggregate (RCA) based concrete with conventional materials for single family detached housing (SFDH) construction. A typical Okanagan SFDH was selected as the case study. Life cycle assessment was conducted using HOT2000 and Athena Impact estimator software. Life cycle economical analysis was calculated using RSmeans database. The eco-efficiency of the use of recyclable ICF and RCA reinforced concrete is discussed. Three alternative models were used for this study on the material selection for walls. Alternative 1 used conventional wall system, Alternative 2 used conventional with ICF and RCA concrete walls, and Alternative 3 used ICF and RCA concrete wall system. The results of this study prove that conventional wall construction with ICF concrete and RCA based concrete wall systems have the highest eco-efficiency among the selected three alternatives. This research can be developed to support decision makers in planning for recycled material based residential construction in Canada.

1 INTRODUCTION

Extensive waste generation and waste management have become major concerns of the Government of Canada in the recent years. The Conference Board of Canada for the Organisation for Economic Co-operation and Development (OECD) countries has stated that the waste management practices in the country can be improved drastically (Giroux Environmental Consulting 2014). According to Statistics Canada (2010), the Canadian residential and non-residential sector collectively contributed to 25 million tons (729kg per person) of non-hazardous waste from the national waste inventory (Statistics Canada 2013). This has shown a 4% decrease while the waste management cost has shown 12% increase from 2008 (Statistics Canada 2013). Accordingly, the national waste management cost was reported as CAD 2.9 billion (CAD86 per person), which was approximately 0.02% of the national gross domestic production (GDP) in Canada in 2010 (Statistics Canada 2013).

Construction and Demolition (C&D) waste accounts for approximately one-third of the regional waste in British Columbia (BC) (Metro-Vancouver Regioanl Destrict 2008). Demolishing a structure generates a significant amount of C&D waste compared to the construction activities (Jeffery 2011). Moreover, renovation and demolishing projects collectively generate 90% of the national C&D waste, which is approximately 9.8kg per sq. meter demolished (Jeffery 2011). State-of-the-art technologies are available to recycle and reuse the aforementioned waste, which can reduce the resource requirement and emissions. However, the use of the above technologies is relatively expensive. Hence, the demolishing contractors are not interested in C&D waste recycling and re-using opportunities, due to low tipping fees for landfilling and affordable cost of fresh raw materials (Jeffery 2011). Hence, landfilling is considered the primary solution for C&D waste management, although this causes adverse effects on the environment due to leachate and landfill gas (Statistics Canada 2015).

The City of Kelowna in the Okanagan region was considered the city with highest population growth (2.7% per year) in Canada in 2012 (Okanagan Valley Economic Development Society 2013). According to the BC Real Estate Association (2016) and City of Kelowna (2016), the annual growth in the construction of single-family detached houses (SFDH) in Kelowna is 20% in 2015 (Muir and Ogmundson 2016). Hence, it is desirable to implement sustainable construction methods to reduce the resource demand and increase the use of recycled products.

This study is focused on the eco-efficiencies of recycled concrete and recyclable Insulated Concrete Foam (ICF) for the construction of SFDH in the Canadian context. A life cycle thinking approach was used to evaluate the energy consumption, cost, and emissions. The data corresponding to a SFDH located at Kelowna, BC was used to simulate the energy using HOT 2000 V11.3. Moreover, Athena Impact Estimator V5.2 was used to identify the lifecycle emissions. The life cycle cost was calculated using cost figures obtained from RSMeans 2016. Ultimately eco-efficiency of different ICF and recycled concrete materials for SFDH were compared. The results of this study can be used by building developers, policy makers, practitioners, government and private institutions to promote the use of ICF and recycled concrete for building construction in Canada.

2 LITERATURE REVIEW

Unwanted materials discarded by their producer can be classified as waste. Specifically, this can be a by-product (Statistics Canada 2013) or a product which lost its primary function (Bontoux and Leone 1997). Based on the United States Environmental Protection Agency (USEPA), C&D waste disposal can be categorized into three sectors as waste to recycle, reuse and landfill (U.S. Environmental Protection Agency (EPA) 2008). Figure 1 shows the conventional material flow and the advanced waste management options (U.S. Environmental Protection Agency (EPA) 2008). Accordingly, 50% to 70% of C&D waste can be recycled or re-used by improving the productivity of waste management (U.S. Environmental Protection Agency (EPA) 2008).

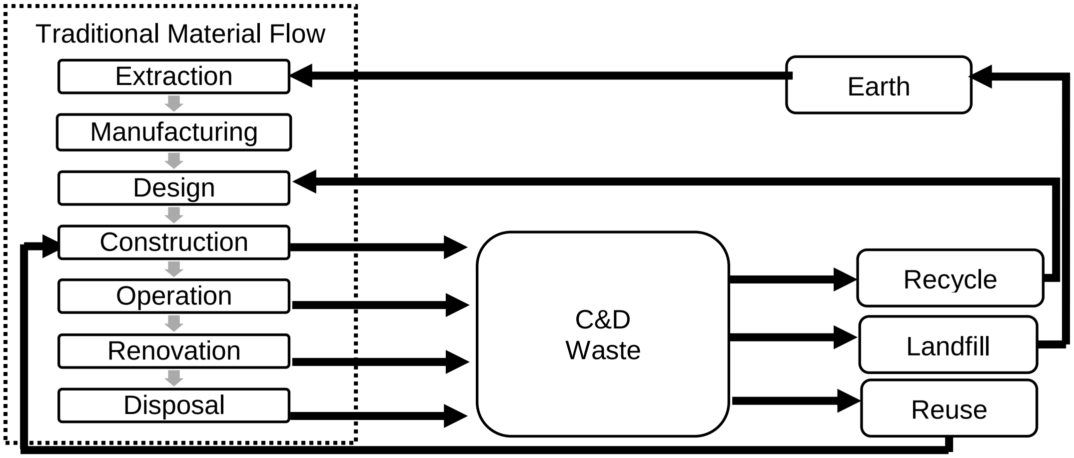


Figure 1: Advance material flow for waste management

The use of recycled products can be categorized as non-structural (self -stripping) and structural. Re-using of any building content which does not affect the structural elements of the new construction is known as non-structural deconstruction (U.S. Environmental Protection Agency (EPA) 2008). Similarly, re-use of building contents which effects on the structural elements is known as structural deconstruction (U.S. Environmental Protection Agency (EPA) 2008). According to Yeheyis et al. (2013), 3R's (Reduce, Recycle and Reuse) concept was proposed for C&D waste management (Yeheyis et al. 2013). Hence, the use of recyclable materials and use of recycled materials in construction can be considered as a sustainable approach to manage C&D waste in future. Generally, C&D waste is comprised of asphalt, wood products, concrete, steel and other construction materials (Yeheyis et al. 2013). Concrete can be identified as the highest (by weight 52%) contributor to the national C&D waste inventory (Yeheyis et al. 2013). However, concrete, steel, insulation materials, aluminum and plastic can be considered as highly recyclable materials (Yeheyis et al. 2013). Since demolished concrete is contributed a significant portion of C&D waste, recycling of concrete waste is required to reduce potential land-filling.

2.1 Recycled concrete aggregates

The Recycle Concrete Aggregate (RCA) can be generated using three major sources such as fresh concrete from ready-mix concrete returns, waste concrete from pre-cast concrete manufacturing facilities and demolition waste from the industry (World business council for sustainable development 2009). The concrete waste obtained from the above sources is known as C&D waste and the concrete content of C&D waste can be varied from 20% - 80% based on the region of the study (World business council for sustainable development 2009). There are several characteristics can be found in the recycled concrete instead of fresh concrete. There is high water absorption, less bulk density, less specific gravity, high abrasion loss, high crushability, high amount of dust particles and possibility of mixing with hazardous substances (Malešev, Radonjanin, and Marinković 2010). However, the use of recycled coarse aggregates and fine aggregates for structural and non-structural construction of residential buildings have no significant adverse impacts in terms of building strength and durability (Malešev, Radonjanin, and Marinković 2010) (Huda and Alam 2014).

2.2 ICF concrete

Expanded polystyrene lightweight foam blocks are used to manufacture ICF blocks which include more than 20% of recycled materials (Hawks 2005). This concrete formwork is used to form the desired wall shape for the above ground concrete as well as to improve the thermal performance of the envelope ("Build Smart, Save Money, Use Eastern Ontario ICFs," n.d.). R-value of a typical ICF concrete wall is approximately 18 – 35 $m^2 \cdot K/W$ (Hawks 2005). Additionally, the aforementioned formwork will provide high wind resistance, sound proofing and high flexibility (Hawks 2005). These ICF blocks are capable of being reused due to their 75 years of lifetime ("Build Smart, Save Money, Use Eastern Ontario ICFs," n.d.). Additionally, this formwork will reduce the demand for lumber materials by reducing the use of wood framed walls for residential sector (Hawks 2005). Hence, the ICF concrete can be considered as a recycled and reusable product that reduces the long-term waste generation from building construction. However, the construction cost of ICF based wall system for a typical SFDH is more than 10% of the typical wood construction (Hawks 2005).

According to the previous studies done on C&D waste management, the environmental, economic and social factors are important in ensuring the sustainability of the C&D management process (Yeheyis et al. 2013). The eco-efficiency analysis has gained significant attention in the recent past in evaluating substitute products in terms of emissions and costs.

2.3 Eco-efficiency

Eco-efficiency is a concept which is used to measure the combined effect of environmental and economic cost and benefits of a particular product or product system through its entire life cycle (Brattebø 2005). The units of value generation per unit of environmental impacts is known as the eco-efficiency of the particular product (Brattebø 2005) (Tatari and Kucukvar 2012). Huppes and Ishikawa (2007) described a concept called "eco-efficiency ratio" to compare different alternatives and identify trade-offs to select the best alternative (Huppes and Ishikawa 2007). Eq 1 can be used to calculate the eco-efficiency ratio.

$$[1]\ \mathrm{Eco-efficiency\ Ratio} = \frac{\mathrm{LCC}}{\mathrm{LCA}}$$

Accordingly, the "economic score" has been identified based on the life cycle cost (LCC) and the "environmental score" has been identified using life cycle assessment (LCA) (Huppes and Ishikawa 2007).

2.3.1 Life cycle assessment (LCA)

LCA has become one of the most commonly applied instruments to evaluate the environmental performance of products or processes (Bianchini and Hewage 2012). According to USEPA (1995), LCA is a methodology to estimate the potential emissions of a process or a product during its life cycle, from cradle to grave. Therefore, LCA enables decision makers to improve the environmental performance of a particular product in a strategic planning process (ISO 14040:2006(en) 2006). There are several state-of-the-art software that can be used to calculate LCA of buildings. EnergyPlus (Feng and Hewage 2014) software to measure the operational energy requirement for multi-family residencies and they were used for the LCA analysis. The Building for Environmental and Economic Sustainability (BEES), Athena eco-calculator, Athena impact estimator and SimaPro are the common life cycle assessment software in North America (Han and Srebric 2011). Fawaz et. al (2016) used Athena Impact estimator (AL-Nassar et al. 2016) and Ahamed et al. (2016) used SimaPro V7.3 (Ahamed et al. 2016) to identify the LCA impacts for low-rise commercial buildings. The indicators such as global warming potential (GWP), stratospheric ozone depletion (SOD), acidification of land and water (ALW), eutrophication (EN), tropospheric ozone formation (TOF) and depletion of non-renewable energy resources (DNR) are used in identifying potential environmental impacts of the selected alternatives (Yeheyis et al. 2013) (Ahamed et al. 2016). BEES software can be used to obtain appropriate weight schemes to aggregate the above impacts and quantify the cumulative LCA for each alternative (Cooper 2007).

2.3.2 Life cycle cost (LCC)

LCC can be defined as the external and internal cost associated with a project or a process in its total life time (Warren 1994). The construction cost, repair and maintenance cost, building operation cost and building end-of-life cost are key component of the building life cycle. However, out of these, the operation cost, repair/maintenance cost and end-of-life costs are forecasted using discount interest rate and inflation of the country (Mirzadeh et al. 2013). LCC can be calculated as per the Eq 2 and the net present value for the LCC can be calculated as per Eq 3 (Megan Davis 2005).

$$[2]\ \mathrm{LCC} = \mathrm{C} + \mathrm{PV\ recurring} - \mathrm{PV\ residual} - \mathrm{value}$$

Where,

$\mathrm{PV}_{\mathrm{recurring}}$ - Present value of the all recurring costs

C - Initial investment / purchase cost

$\mathrm{PV}_{\mathrm{residual\text{-}value}}$ - Present value of the end-of-life value

$$[3]\ \mathrm{NPV(i,N)} = \sum_{\mathrm{t=0}}^{\mathrm{N}} \frac{\mathrm{R_t}}{\mathrm{(1+i)^t}}$$

Where:

NPV - Net Present Value

R_t - Net cash flow

t - Time of the cash flow

I - Discount rate

N - Study period

3 METHODOLOGY

The research methodology of this study is shown as Figure 2.

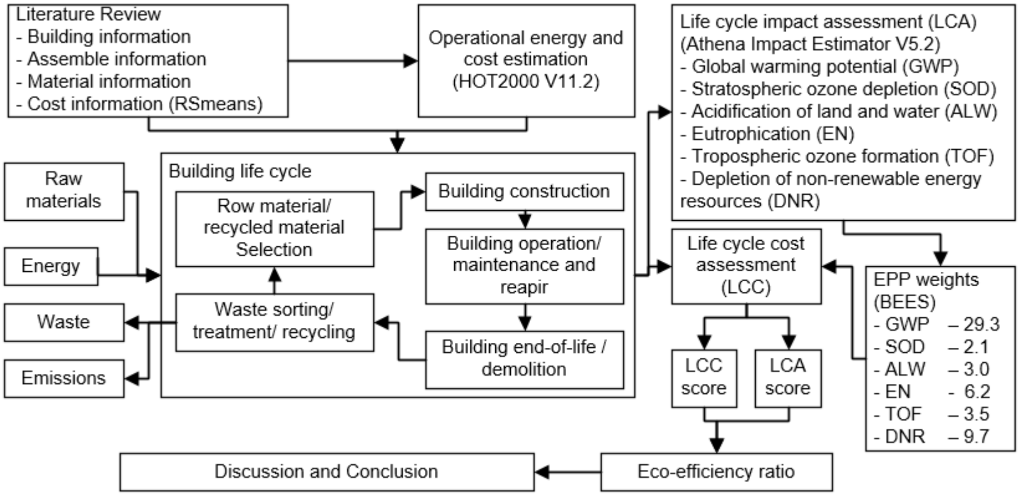


Figure 2: Research framework

This study focused on a SFDH experimental model which was constructed in Okanagan, BC. The project was comprised of material testing, energy and cost simulation, monitoring and forecasting. The floor plan of the particular SFDH is shown in Figure 3. The drawings given below were modeled with different wall materials to evaluate the use of ICF blocks and recycled concrete aggregates to reduce potential C&D waste in future. The different wall construction alternatives which was considered in this analysis are indicated in

Table 1.

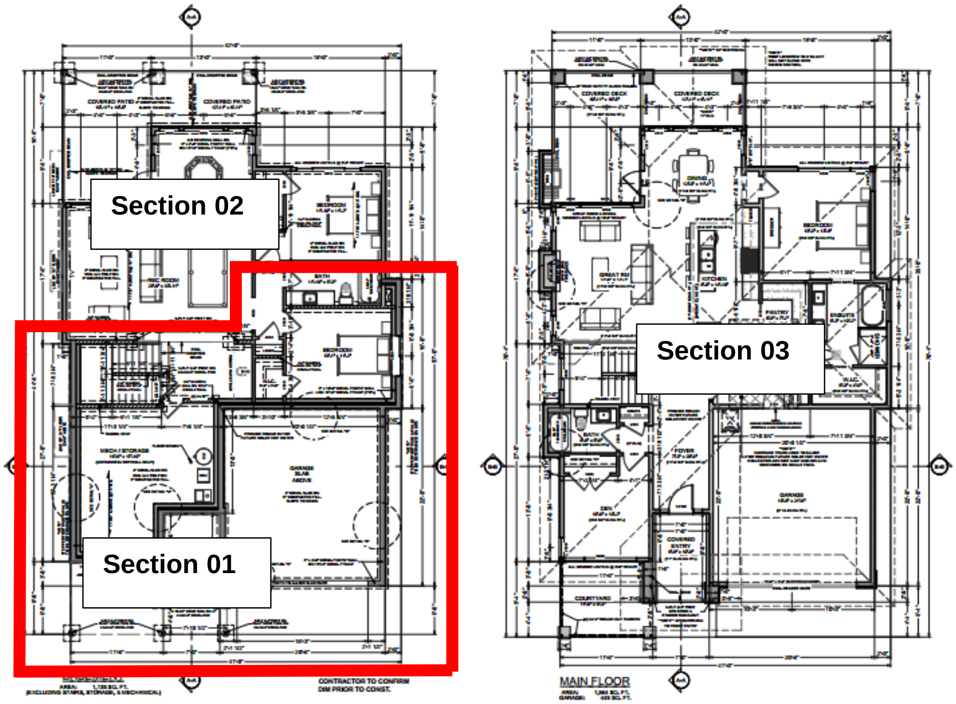


Figure 3: SFDH experimental model floor plan

Table 1: SFDH construction alternatives

	Alternative 1 (A1)	Alternative 2 (A2)	Alternative 3 (A3)
Foundation	8” reinforced concrete	8” reinforced concrete	8” reinforced concrete
Basement slab	4” concrete	4” concrete	4” concrete
Exterior wall (Section 1)	8” reinforced concrete	ICF blocks, 8” RCA reinforced concrete	ICF blocks, 8” RCA reinforced
Exterior wall (Section 2 &3)	2”×6” wood studs @ 24” OC, 3/8” OSB sheathing, R20 insulation, ½” drywall	2”×6” wood studs @ 24” OC, 3/8” OSB sheathing, R20 insulation, ½” drywall	ICF blocks, 6” RCA reinforced
Interior wall	2”×4” wood studs, ½” drywall	2”×4” wood studs, ½” drywall	2”×4” wood studs, ½” drywall
Ground floor	Engineered I joist 11 7/8” @ 19.2” OC, ¾” plywood	Engineered I joist 11 7/8” @ 19.2” OC, ¾” plywood	Engineered I joist 11 7/8” @ 19.2” OC, ¾” plywood
Celling	R50 insulation, ½” drywall	R50 insulation, ½” drywall	R50 insulation, ½” drywall
Roof	Engineered trusses (wood), 1/2” OSB sheathing, Asphalt	Engineered trusses (wood), 1/2” OSB sheathing, Asphalt	Engineered trusses (wood), 1/2” OSB sheathing, Asphalt
Construction Cost (CAD)	461,822	462,592	463,362

End-of-life cost[i] (CAD) (Demolition)	3,000	3,000	3,000

[1] Based on the demolishing calculator given in http://www.buildingjournal.com/commercial-construction-estimating-demolition.html (The exchange factor is assumed as USD1:CAD1.28)

The software HOT2000 V11.2 which was developed by Natural Resources Canada, was used to analyze operational energy requirement for the three alternatives. The results obtained from energy models were used to estimate the life cycle emissions of these three alternatives. Athena impact estimator V5.2 was used for the emission estimation. The building envelope characteristics given in Table 1 and operational energy estimations were used for calculating the carbon footprint, human health impacts, global warming etc. Product stage, construction process stage, use stage, end-of-life stage and recycle/reuse stage (A to D) were considered in defining the system boundary for building LCA.

Following assumptions were made to model the energy performances, LCA and LCC of above three alternatives.

- The end-of-life cost for all three alternatives were assumed to be proportionate to the building floor area.
- The front orientation of above alternatives was assumed to be northwest.
- Occupancy is assumed to be two adults and one child and they will be in the house for 50% of the day.
- Summerland, BC meteorological data were considered.
- According to the BC building code, the night time and day time heating temperature are assumed as 18^{0}C and 21^{0}C and the cooling temperature was assumed as 25^{0}C. (Night time set back duration was 8hrs)
- The appliances were assumed as standard appliances with energy star rating (stove, refrigerator, dish washer, clothes washer and dryer)
- Extra electricity used beyond the standard appliances were assumed as 12KWh/day.
- All windows were assumed to be double glazed soft coated air and doors were assumed to be fiberglass exterior doors with 50% glazing and hollow core wood interior doors.
- Heat, Ventilation, Air Conditioning (HVAC) system of the above alternatives were assumed according to the data presented in Table 2.

Table 2: HVAC system for energy simulation

	Type / Fuel	Characteristics	Efficiency
Space heating	Duel fuel (Natural Gas & electric) heating system	56000 BTU/hr, switching temperature 35^{0}F	EF - 92.1%
	Natural gas fireplace	2kW, 6824.28 BTU/hr	30% SS
Space cooling	Central split system, electric	14SEER, 10kW	COP 3
Water heating	Natural gas heat pump	N/A	1.00EF
Ventilation	HRV certified by Home ventilation institute	Air flow rate: 158.92 cfm	75%

Moreover, life cycle cost calculation was formulated using the present cost factors identified through the existing literature and RSMeans2016 cost database. The EPP environmental impact weights (given in Figure 2) were used to calculate the environmental score. Then the economical score was obtained from the present value of LCC. The eco-efficiency for three alternatives were calculated by Eq 1 using the calculated environmental score and economical score. Based on the results obtained from above simulations, the eco-efficiency of use of recycled RCA based concrete and recyclable ICF block use in construction of SFDH was discussed.

4 RESULTS AND DISCUSSION

In the initial phase of the analysis, operational energy simulation was conducted for the three alternatives. Based on the HOT2000 analysis, operational energy and operational costs for three alternatives are shown in Table 3.

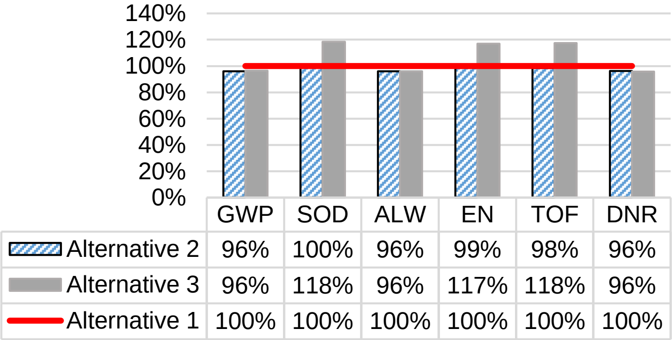
Table 3: HOT2000 based operational energy for three alternatives

	Alternative 1	Alternative 2	Alternative 3
Operational Energy:			
Electricity (kWh/year)	18111.6	17388.3	16460.8
Natural Gas (m^3/year)	1342.6	1271.8	1161.0
Operational Costs:			
Electricity (CAD/year)	2055.68	1957.20	1832.06
Natural Gas (CAD/year)	500.13	481.24	451.69

The R-value (Thermal performance) of ICF foam concrete wall is considerably higher than the typical 2”×6” wooden frame walls. Hence, the thermal loss through the wall should be higher in conventional walls compared to the ICF concrete walls. Accordingly, Table 3 shows that Alternative 3 has the lowest operational energy consumption which leads to lowest operational costs per year.

4.1.1 Environmental Scores

The operational energy was used as an input for LCA analysis. Environmental impacts were calculated using Athena Impact Estimator V5.2. The results obtained from the software is given in Appendix B. Figure 4 shows the percentage differences of environmental indicators with reference to the conventional construction practices. According to Figure 4, the SOD, EN and TOF has extensively increased in Alternative 3. However, Alternative 2 shows the minimum levels of EN and TOF. Nevertheless, the actual environmental impact depends on the environment impact weightage.



	GWP	SOD	ALW	EN	TOF	DNR
▨ Alternative 2	96%	100%	96%	99%	98%	96%
■ Alternative 3	96%	118%	96%	117%	118%	96%
— Alternative 1	100%	100%	100%	100%	100%	100%

Figure 4: Percent environmental impacts of proposed alternatives (A2 and A3) with reference to conventional construction (A1)

The environmental impact weightages for GWP, SOP, ALW, EN, TOF and DNR are 29.3, 2.1, 3.0, 6.2, 3.5 and 9.7 respectively. Hence, the total environmental scores for each of the three alternatives are shown in Table 4. Accordingly, the environmental scores of Alternative 1 is 1.095×10^6, Alternative 2 is 1.053×10^6 and Alternative 3 is 1.051×10^6.

Table 4: Environmental score calculation

Environment Impact	Weight	Alternative 1	Alternative 2	Alternative 3
Global warming potential	2.93E+01	1.22E+07	1.17E+07	1.18E+07
Stratospheric ozone depletion	2.10E+00	2.07E-03	2.07E-03	2.46E-03
Acidification of land and water	3.00E+00	5.85E+03	5.61E+03	5.61E+03
Eutrophication	6.20E+00	3.04E+02	2.99E+02	3.55E+02
Tropospheric ozone formation	3.50E+00	4.20E+04	4.13E+04	4.94E+04
Depletion of non-renewable energy resources	9.70E+00	4.67E+07	4.49E+07	4.47E+07

Total Weight	5.38E+01	5.89E+07	5.67E+07	5.66E+07
Environmental score		1.10E+06	1.05E+06	1.05E+06

4.1.2 Economical Scores

The economical score was calculated as Table 5 using Eq.2 and Eq.3. The net present value of the three alternatives were assumed as economical score. The maintenance and repair cost for all three alternatives were assumed to be negligible due to limited availability of data. Accordingly, the economical scores of Alternative 1 is 5.352×10^5, Alternative 2 is 5.326×10^5 and Alternative 3 is 5.290×10^5.

Table 5: Economic score calculation

		Alternative 1	Alternative 2	Alternative 3
Construction Cost	CAD	461,822	462,592	463,362
End-of-life cost (Demolition)	CAD	3,000	3,000	3,000
Maintenance/Repair cost	CAD/ year	Negligible	Negligible	Negligible
Electricity (CAD/year)	CAD/ year	2055.68	1957.2	1832.06
Natural Gas (CAD/year)	CAD/ year	500.13	481.24	451.69
Present Value (PV)				
Construction Cost	CAD	461,822	462,592	463,362
End-of-life cost (Demolition)	CAD	872.8266	872.8266	872.8266
Operational Costs:	CAD	72488.68	69159.8	64772.43
Economical score (NPV)	CAD	535,184	532,625	529,007

4.1.3 Eco-efficiency ratio

The environmental scores and economical scores which were calculated in Section 4.1.1 and Section 4.1.2, respectively, were considered in calculating the eco-efficiency of the three alternatives. Eq 1 was used for the calculations. Accordingly, the eco-efficiency of Alternative 1 is 0.489, Alternative 2 is 0.506 and Alternative 3 is 0.503. Based on the design characteristics and assumptions, Alternative 2 can be identified as the optimum construction mix of ICF foam concrete and RCA based concrete among the selected alternatives. Consequently, the ICF foam concrete, RCA concrete and conventional wall system collectively achieved the highest eco-efficiency ratio. Therefore, the optimum eco-efficiency level of the wall construction alternatives is a mix of ICF foam concrete, RCA concrete and conventional 2”×6” wooden frame wall systems. Moreover, the optimum wall mixer will vary with building characterizes, material and energy cost variations, material selections, and climatic variations of the area. However, as future research, a decision support tool can be developed using the same methodology to identify the optimum material mix for a household based on consumer budget, climate conditions, house characteristics and cost factors.

There is a natural tendency to select Alternative 03, due to low environmental impacts and lowest life cycle cost. Therefore, this research has shows a limitation in eco-efficiency concept where the highest eco-efficient alternative has not been achieved the lowest LCA and LCC. Therefore, this has to be further analysis using another comparison method to validate the above methodology. As a limitation of this research, the study considered only environmental and economical performance of the building. However, the social aspects such as aesthetic view, durability of materials etc. of the building are also important for the decision making perspective. The detailed process analysis for ICF and RCA based concrete were not formulated due to limited data availability. However, a detailed study based on SimaPro library can be simulated to analyze material level, component level (wall) and building level LCA to obtain more accurate results (Han and Srebric 2011). Moreover, actual thermal resistance values and energy consumptions of above alternatives can vary with the consumer behaviour, material properties and manufacturing process. Hence, the data uncertainty needs to be considered.

5 CONCLUSIONS

Consumption of recyclable and recycled materials has gained extensive attention in recent past due to the scarcity of raw materials and adverse impacts of C&D waste. Moreover, building energy performance, LCA and LCC varies with the material used in the construction. Hence, a systematic approach is needed to identify the high performance material mix with low LCC and LCA. Eco-efficiency approach has been developed recently to compare different alternatives using the LCC and LCA of those alternatives.

This study has focused on three alternatives with different wall systems and similar building characteristics. Alternative 1 used conventional wall system, Alternative 2 used conventional with ICF and RCA concrete walls and Alternative 3 used ICF and RCA concrete wall system. These alternatives were modeled using HOT2000 V11.2 for energy modelling and Athena Impact estimator V5.2 for LCA. Simultaneously, LCC of each alternative was calculated using RSMeans2016 database. The environmental and economical scores were calculated using aforementioned LCC and LCA. The eco-efficiency of each alternative was calculated and compared with each other to select the most appropriate wall system out of the selected alternatives. According to the design characteristics and assumptions made on this study, alternative 2 has been selected as the most suitable alternative. Therefore, the optimum eco-efficiency level of the wall construction alternatives can be considered as a mix of ICF foam concrete, RCA concrete and conventional 2”×6” wooden frame wall systems. Moreover, this methodology can be extended to develop a decision support tool to identify different material mixtures for a selected household. Hence, this tool will be valuable for building developers, potential building owners, practitioners, researchers, public and private institutes to select building material mixes according to their budget, expected building performances and to minimize the emissions.

Acknowledgements

The authors gratefully acknowledge the financial contributions of Natural Sciences and Engineering Research Council (NSERC) through Collaborative Research and Development (CRD) grant program, and Blenk Development Corporation for conducting this research. Acknowledgements are also due to AuthenTech Homes Ltd and Geotility Geothermal Systems Corporation for providing their valuable input in this research. Last but not the least, the authors sincerely acknowledge Mr. Scott Tyerman, Owner of AuthenTech Homes Ltd and Karin Eger-Blenk, Director of Blenk Development Corporation for providing cost data.

References

Ahamed, A., K. Yin, B. J H Ng, F. Ren, V. W C Chang, and J. Y. Wang. 2016. “Life Cycle Assessment of the Present and Proposed Food Waste Management Technologies from Environmental and Economic Impact Perspectives.” *Journal of Cleaner Production* 131: 607–14. doi:10.1016/j.jclepro.2016.04.127.

AL-Nassar, Fawaz, Rajeev Ruparathna, Gyan Chhipi-Shrestha, Husnain Haider, Kasun Hewage, and Rehan Sadiq. 2016. “Sustainability Assessment Framework for Low Rise Commercial Buildings: Life Cycle Impact Index-Based Approach.” *Clean Technologies and Environmental Policy* 18 (8). Springer Berlin Heidelberg: 2579–90. doi:10.1007/s10098-016-1168-1.

Bianchini, Fabricio, and Kasun Hewage. 2012. “How ‘green’ Are the Green Roofs? Lifecycle Analysis of Green Roof Materials.” *Building and Environment* 48. Elsevier Ltd: 57–65. doi:10.1016/j.buildenv.2011.08.019.

Bontoux, Laurent, and Fabio Leone. 1997. “The Legal Definition of Waste and Its Impact on Waste Management in Europe,” no. November. file:///C:/Users/Violet pc/Desktop/Waste Management/Definition of Waste Management/The Legal definition of waste and its impact on waste management in Europe.pdf.

Brattebø, Helge. 2005. “Toward a Methods. Framework for Eco-Efficiency Analysis?” *Journal of Industrial Ecology* 9 (4): 9–11. doi:10.1162/108819805775247837.

“Build Smart, Save Money, Use Eastern Ontario ICFs.” n.d. *Eastern Ontario ICFs*.

Cooper, Jennifer. 2007. “Life Cycle Impact Assessment Weights to Support Environmentally Preferable Purchasing in the United.”

Feng, H., and K. Hewage. 2014. “Energy Saving Performance of Green Vegetation on LEED Certified Buildings.” *Energy and Buildings* 75 (June): 281–89. doi:10.1016/j.enbuild.2013.10.039.

Giroux Environmental Consulting. 2014. “State of Waste Management in Canada.” *Canadian Council of Ministers of Environment*.

Han, Guiyuan, and Jelena Srebric. 2011. “Life-Cycle Assessment Tools for Building Analysis.” *Engr.Psu.Edu*, no. Lcc: 7. http://www.engr.psu.edu/phrc/Publications/RB0511-Life-cycle assessment tools for bldg analysis .pdf.

Hawks, Leona K. 2005. “Energy Smarts : Insulating Concrete Forms (Icfs),” 1–3.

Huda, Sumaiya Binte, and M. Shahria Alam. 2014. “Mechanical Behavior of Three Generations of 100% Repeated Recycled Coarse Aggregate Concrete.” *Construction and Building Materials* 65 (August 2014). Elsevier Ltd: 574–82. doi:10.1016/j.conbuildmat.2014.05.010.

Huppes, Gjalt, and Masanobu Ishikawa. 2007. *Quantified Eco-Efficiency: An Introduction with Applications*.

Springer Science & Business Media.

ISO 14040:2006(en). 2006. “Environmental Management — Life Cycle Assessment — Principles and Framework.” *ISO 14040:2006*.

Jeffery, Colin. 2011. “Construction and Demolition Waste Recycling A Literature Review,” 1–30.

Malešev, Mirjana, Vlastimir Radonjanin, and Snežana Marinković. 2010. “Recycled Concrete as Aggregate for Structural Concrete Production.” *Sustainability* 2 (5): 1204–25. doi:10.3390/su2051204.

Megan Davis. 2005. “GUIDELINES FOR LIFE CYCLE COST ANALYSIS.” Stanford University Land and Buildings.

Metro-Vancouver Regioanl Destrict. 2008. “Metro Vancouver’s Demolition, Land Clearing & Construction (DLC) Waste Management Toolkit.” http://www.metrovancouver.org/services/solid-waste/SolidWastePublications/DLCToolkit.pdf.

Mirzadeh, Iman, Ali Azhar Butt, Susanna Toller, and Björn Birgisson. 2013. “Life Cycle Cost Analysis Based on the Fundamental Cost Contributors for Asphalt Pavements.” *Structure and Infrastructure Engineering* 10 (12): 1638–47. doi:10.1080/15732479.2013.837494.

Muir, Cameron, and Brendon Ogmundson. 2016. “Housing Forecast.”

Okanagan Valley Economic Development Society. 2013. “2013 Economic Profile Okanagan Valley.”

Statistics Canada. 2013. “Waste Management Industry Survey: Business and Government Sectors: 2010.” *Ministrer of Industry*, no. 16: ii – 38. doi:16F0023X.

———. 2015. “Human Activities and the Environment: Section 03-Solid Waste.” *Government of Canada*. http://www.statcan.gc.ca/pub/16-201-x/2012000/part-partie3-eng.htm.

Tatari, Omer, and Murat Kucukvar. 2012. “Eco-Efficiency of Construction Materials: Data Envelopment Analysis.” *Journal of Construction Engineering and Management © Asce / June 2012 / 733* 138(6) (February 2017): 733–41. doi:10.1061/(ASCE)CO.1943-7862.0000484.

U.S. Environmental Protection Agency (EPA). 2008. “Lifecycle Construction Resource Guide.” *Construction*.

Warren, J.L. 1994. “Development of an Integrated Life-Cycle Cost Assessment Model.” *Electronics and the Environment, 1994. ISEE 1994*, 155–63. doi:10.1109/ISEE.1994.337306.

World business council for sustainable development. 2009. “The Cement Sustainability Initiative: Recycled Concrete.” http://www.cement.ca/images/stories/recyclingconcrete_summary_csi.pdf.

Yeheyis, Muluken, Kasun Hewage, M. Shahria Alam, Cigdem Eskicioglu, and Rehan Sadiq. 2013. “An Overview of Construction and Demolition Waste Management in Canada: A Lifecycle Analysis Approach to Sustainability.” *Clean Technologies and Environmental Policy* 15 (1): 81–91. doi:10.1007/s10098-012-0481-6.

Appendices

Appendix A: Typical construction materials used in Canadian SFDH construction

Foundation	**8” reinforced concrete**
Basement slab (Exposed floor)	4” concrete
Exterior wall	2”×6” wood studs @ 24” OC, 3/8” OSB sheathing, R20 insulation, ½” drywall
Interior wall	2”×4” wood studs, ½” drywall
Ground floor	Engineered I joist 117/8” @ 19.2” OC, ¾” plywood
Celling	R44 insulation, ½” drywall
Roof	Engineered trusses

Source: BC building code (2012)

Appendix B: Environmental emission results obtained from Athena Impact Estimator

Environment Impact	Unit	Alternative 1	Alternative 2	Alternative 3
Global warming potential	kg CO_2 eq	4.17E+05	4.00E+05	4.02E+05
Stratospheric ozone depletion	kg CFC-11 eq	9.88E-04	9.85E-04	1.17E-03
Acidification of land and water	kg SO_2 eq	1.95E+03	1.87E+03	1.87E+03
Eutrophication	kg N eq	4.90E+01	4.83E+01	5.73E+01

Tropospheric ozone formation	kg O_3 eq	1.20E+04	1.18E+04	1.41E+04
Depletion of non-renewable energy resources	MJ	4.81E+06	4.63E+06	4.61E+06
