VOL. 10, NO. 2, FEBRUARY 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

SUSTAINABILITY ANALYSIS OF CONVENTIONAL AND ECO-FRIENDLY MATERIALS: A STEP TOWARDS GREEN BUILDING

Bakhoum E. S., Garas G. L. and Allam M. E.
Department of Civil Engineering, National Research Centre, Egypt
E-Mail: emaduk@gmail.com

ABSTRACT

In the construction industry, selection of sustainable structural materials during the design phase leads to move towards more sustainable construction. Therefore, there is a need to select more green building materials to be used in construction. Based on the promising vision of future needs for sustainable development this paper presents a comparative study between conventional and eco-friendly building materials using sustainability measures. A prototype of two storeys was constructed using eco- friendly building materials (integrated bricks, rice straw bales, M2 system, plain concrete, and Rockwool sandwich panels). A sustainable decision support system (SDSS) was used to compare between the structural building materials of the two structural systems. The results showed that the eco-friendly system had better sustainability rank (67%) than the conventional system (56%). In addition, the results of SDSS showed that the Eco-friendly system was better than the conventional system during the three phases of total life cycle assessment (manufacturing, construction and demolition) by 11%, 0.5% and 9%, respectively.

Keywords: rice straw, sustainable construction, eco-friendly structural materials.

INTRODUCTION

Globally, there is a need for alternative building materials that require less embodied energy than conventional materials. Using plant based materials reduces the climate change impact of building development, achieved through use of a sustainably grown renewable resource and the atmospheric CO_2 used up by the plants during their growth. Plant based materials offer other benefits, including very high levels of thermal insulation and providing healthier living spaces [1].

Efforts were undertaken to implement innovative thermal storage and insulation solutions to better control heat flows in buildings and make deep cuts in CO_2 emissions [2]. An example of plant based thermal insulating materials was rice straw building elements. The goal in forthcoming straw bale building was to improve the comfort and health of the built environment while maximizing use of renewable resources (active and passive uses), and minimizing life-cycle costs [3].

Based on the promising vision of future needs for sustainable development this paper presents a comparative study between conventional and eco-friendly building materials using sustainability measures.

Literature review

Garas *et al*, 2009 conducted several tests on high density rice straw elements plastered with cement skins. These tests covered economical benefits and mechanical properties gained by using plant based materials instead of conventional alternatives. Besides, a comparative study of the energy efficiency between typical brick construction and rice straw bale construction using energy software package- which is based on the principles and concepts developed by the International Commission of Energy- was used to measure and monitor the efficiency of using smart environmental systems and energy saving tools.

Fire tests on cement plastered straw bales specimens sustained the two hour direct fire exposure without passage of the flame or even gases hot enough to ignite the internal straw to reach the opposite side of the plastered bales. A saving of approximately 10% in the direct cost of the walls was achieved when building with straw bales. Energy efficiency using natural lighting building due to the reduction of glare, shine, and brightness levels rate by (89%) in straw bale construction was indicated due to the increase in walls thickness to the double [1, 4].

Allam *et al*, 2011 presented an intensive evaluation of recycling chopped rice straw to be used in the manufacture of cement bricks. The study resulted in producing a rice straw brick of density 25% less than the conventional cement bricks with acost saving of 25%. Fire exposure tests of chopped rice straw cement bricks revealed that produced bricks maintained temperatures even more than 800ºC for 1 hour fire exposure to comply with the Egyptian Codes of practice [5].

Ajamu and Adedeji (2013), compared between thermal insulation properties of straw bale and some other traditional construction materials. It was observed that internal temperatures in the mud-brick and straw bale buildings remained fairly stable despite external temperature fluctuations while requiring comparatively less energy to sustain thermal comfort conditions [6].

Objectives and limitations

This paper aims to illustrate the potential of some eco-friendly building materials to be integrated into novel designs for improved performance. The main objective is to compare between conventional and eco-friendly structural materials - used in the case study - based on sustainability criteria in order to select better sustainable materials in the construction industry.

This study mainly covers the sustainability of the building materials used to build the two structural systems understudy. A Sustainable decision support system (SDSS) previously developed by Bakhoum (2011) was used to compare between the structural building materials. Three phases of materials life cycle are considered for sustainability evaluation: manufacturing, construction and demolition. Ten factors that cover the four aspects of sustainability (environmental, economical, social and technological) during the total life cycle of the material are used [7, 8].

METHODOLOGY

Field stage

A 22 m^2 prototype of two storeys was constructed using eco- friendly building materials. The materials used integrated bricks and rice straw bales for columns and walls (fig1) together with M2 system (foam and light wire mesh) for slabs, beams, and stairs (figures 2(a), 2(b) and 2(c)). Plain concrete (PC) was used in foundation as strip footings and in M2 system. Rockwool sandwich panels were used for the first floor slab.

Data collection and analysis stage

A similar building with the same area and architectural layout was drawn using conventional skeleton structural system (reinforced concrete columns, beams, slabs and stair). Table (1) presents a comparison between the different materials used in the both Eco-friendly and conventional structural systems.

Life cycle inventory (LCI) data for used materials were collected to be integrated in the sustainable decision support system (SDSS). Consequently, a comparison between both conventional and eco-friendly structural systems was done using the SDSS.

Figure-1. Bricks and rice straw bales for columns and walls.

Figure-2(a). M2 System for ground floor slabs and beams.

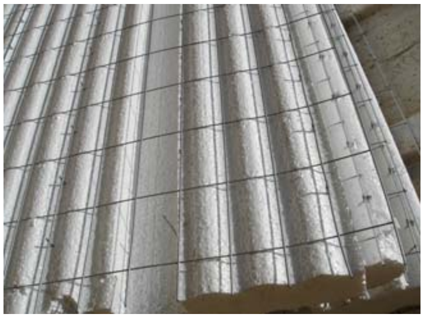


Figure-2(b). M2 Foam slab.

Figure-2(c). M2 Foam beam.

Table-1. Different materials used in the both Eco-friendly and conventional structural systems.

	Eco-friendly structural system	**Conventional structural system**
Architectural	Ground floor (5.5 x 4.0 m) first floor (3.0 x 4.0 m) Clear floor height is 2 m	Ground floor (5.5 x 4.0 m) first floor (3.0 x 4.0 m) Clear floor height is 2 m
Foundation	PC strip footing	RC Isolated footing
Columns	Cement bricks	Reinforced concrete (RC)
Slabs / beams	M2 system (G. Floor) Rockwool (F. Floor)	Reinforced concrete (RC)
Stairs	M2 system	Reinforced concrete (RC)
Walls	Rice straw bale	Cement bricks
Wall finishing	Wire mesh - cement plastering	Cement plastering

Sustainable decision support system (SDSS)

Sustainable decision support system (SDSS) includes a developed sustainable scoring system that used life cycle assessment technique to evaluate the sustainability of materials. Multi-Criteria decision analysis methods were used to ranks and select alternatives based on the sustainability scores [9, 10]. Three phases of materials life cycle have been considered for sustainability evaluation: manufacturing, construction and demolition.

Phase (I): Manufacturing: Embraces all the processes for producing the structural material and its components from extraction of raw materials till transportation and manufacturing.

Phase (II): Construction: Corresponds to the construction phase of a building including transportation of the materials and construction equipments to the construction site.

Phase (III): Demolition: Starts from the occupation of a building and lasts until the building is demolished. This phase includes material maintenance, repairing and finally demolition (reused, recycled or land filled). Transportation of demolished material is included in this phase.

A flowchart of sustainable factors - including indicators - of materials has been developed in the SDSS. It includes ten factors that cover the four aspects of sustainability (environmental, economical, social and technological) during the total life cycle of the material. The factors are divided into two groups; each group has five sustainable factors. The developed list includes the following sustainable factors and sub-factors:

Group (1): Sustainable Factors related to structural element design

a) Climate Change includes global warming (embodied CO_2 is used as an indicator to measure it)
b) Pollution includes air pollution and acidification (DALY index and acidification index are used as indicators to measure them, respectively)
c) Energy Consumption includes embodied energy (initial, induced and demolition embodied energy are used as indicators to measure it through each phase)
d) Resources and Waste includes raw materials consumption and solid waste (weight of raw materials consumption and solid waste generated through each phase are used as indicators to measure them respectively)
e) Life Cycle Cost includes cost (market price, construction/transportation, and demolition cost are used as indicators to measure it through each phase)

Group (2): Sustainable Factors related to general material properties

a) Recyclability includes recycled content, reused material, and recycled deconstructed material (percentages) as indicators to measure it through each phase
b) Local Economic Development includes locality and employment (local material/equipment and contribution to employment and skills improvement are used as indicators to measure them respectively)
c) Health/Safety includes health and safety (environmental quality against ozone depletion effect/ toxic gases/ waste, indoor environmental quality, safety against labours accidents, and resistant to damage such as fire/flood/weather are used as indicators to measure them through each phase)
d) Human Satisfaction includes climate/culture and noise/vibration (appropriateness for culture, against dust, climate “habitability” and level of noise and vibration insulation are used as indicators to measure them)
e) Practicability includes constructability and resource depletion (degree of off-site manufacture, flexibility “ease and fast of construction/disassembly”, renewability of resources, durability “material life” and maintainability “ease and fast” are used as indicators to measure them)

Data collection and assumptions

Group (1): Sustainable factors related to structural element design

Life cycle inventory (LCI) data for used materials in the case study (concrete, steel, cement bricks, rice straw bale, foam, and rockwool) were collected from different sources to fulfil the required data of the first group of SDSS factors. Table-2 presents the collected LCI data for used materials in both Eco-friendly and conventional structural system.

a) Manufacturing phase

The life cycle inventory (LCI) data of CO_2, SO_x, NO_x, particulates, embodied energy, raw material consumption and solid waste for used structural materials and their components are based on the results of different sources as follows:

- For concrete, Portland Cement Association (PCI) report by Marceau *et al*. [11] and American Concrete Institute (ACI) study by Prusinski *et al*. [12].
- For steel, Australian Steel Institute report by Strezov and Herbertson [13] and Bath University report by Hammond and Jones [14].
- For cement bricks including mortar, ATHENA Institute report by Venta [15], Portland Cement Association (PCI) report by Marceau et al. [11] and Bath University report by Hammond and Jones [14].
- For rice straw bale, it is a waste material, therefore, it is assumed that it has no emissions, energy, or waste for manufacturing phase.
- For flexible polyurethane foam, SPINE database [16], the American Chemistry Council report [17] and Bath University report by Hammond and Jones [14].
- For Rockwool, SPINE database [16], ESU-services report by Flury and Frischknecht [18] and Bath University report by Hammond and Jones [14].
- Cost of all materials is based on actual market price in Egypt.

b) Construction phase

The construction embodied energy and greenhouse gas emissions are calculated based on the results of the study conducted by Cole [19]. It ascertained that the construction process presents a relative proportion of the total initial embodied energy and greenhouse gas emissions of manufacturing phase. In addition, there are significant differences between the structural material alternatives. The proportions of construction waste for different structural materials were defined in the report prepared by Burton and Friedrich [20]. Based on these proportions, the weights of construction waste of structural materials used are calculated. Average values of 5% for concrete, steel, polyurethane foam and rock wool, 10% for bricks and rice straw bale are assumed. Construction cost is based on actual cost or a proportion of material price (estimated 15% - 20%).

c) Demolition phase

The demolition energy of reinforced concrete and steel are calculated based on the results of ATHENA Sustainable Materials Institute report by Gordon [21]. The estimated demolition energy includes the demolition process as well as the transportation of demolished materials to landfill (or recycle). The demolition energy and its CO_2 emition of rockwool are calculated based on ESU-services Ltd., fair consulting in sustainability report by Flury and Frischknecht [18]. It presents about 2.4% of the initial embodied energy. The same proportion is assumed for polyurethane foam. On the other hand, the greenhouse gases emissions of demolition process for all used materials are estimated based on the emission factors of diesel combustion estimated by SPINE database [16] as 74.6, 0.14, 1.3 and 0.1 g/MJ for CO_2, SO_x, NO_x and particulates respectively. The solid waste of the demolished material is estimated as its non-recycled part.

Table-2. Life Cycle Inventory (LCI) data for used materials.

	Life Cycle Phase	**Concrete**	**Steel**	**Cement bricks**	**Rice straw bale**	**Rockwool**	**Polyurethane Foam**
CO_2 **(**Kg/ton)	*Phase I*	130	770	122	0	1047	2564
	Phase II	26	35	24	0	47	115
	Phase III	19	44	19	0	10	127
SO_x (g/ton)	*Phase I*	241	180	72	0	500	1497
	Phase II	48	8	14	0	23	67
	Phase III	35	82	35	0	55	238
NO_x **(**g/ton)	*Phase I*	368	440	546	0	300	4613
	Phase II	74	20	109	0	14	208
	Phase III	329	763	329	0	507	2213
Particulates (g/ton)	*Phase I*	439	1500	340	0	3000	1383
	Phase II	88	68	68	0	135	62
	Phase III	25	59	25	0	39	170
Energy **(**MJ/ton)	*Phase I*	788	11560	1040	0	16233	70917
	Phase II	142	405	187	0	568	2482
	Phase III	253	587	253	0	390	1702
Raw material consumption **(**Kg/ton)	*Phase I*	1130	2500	1093	1000	1649	1019
Solid waste **(**Kg/ton)	*Phase I*	16	120	2	0	460	156
	Phase II	50	50	100	100	50	50
	Phase III	250	250	250	0	990	700

Group (2): Sustainable factors related to general material properties

- **Recyclability**

It is assumed that 100% of steel reinforcement bars are manufactured from recycled scrap [22]. In addition, rice straw bale - as a waste material - is considered as recycled contents of 100%. The recycled content of Rockwool manufacturing is considered as 23% as stated in the Imperial College report [23]. The recycled content of Polyurethane foam is considered as 10% as stated in Polyurethane Foam Association [24]. It is assumed that concrete and bricks have no recycled content. The recycled deconstructed reinforced concrete and bricks are considered 75% as stated in the institution of civil engineers (ICE) standard demolition recovery indices (DRI) in the demolition protocol [25]. Only 1% of deconstructed Rockwool and 30% of Polyurethane foam can be recycled [18, 26].

- **Local economic development**

All materials used are local materials except a part of Rockwool production. Therefore, the proportion of locality and employment sub-factors are assumed to be 100% for all materials and 90% for Rockwool.

- **Health and safety**

The proportion of environmental quality against ozone depletion effects (phase I) and against toxic gases or waste (phase II) is assumed 100% for all used structural materials. Indoor environmental quality (phase III) is assumed 90% for concrete, steel and bricks and 100% for rice straw bale, Rockwool and foam for their better insulation. The proportion of safety against labours accidents (phases I and II) is assumed 100% for all used materials. Resistant to fire, flood and weather conditions (phase III) is assumed 100% for all used materials except rice straw bale that assumed 90% for its lower resistant.

- **Human Satisfaction**

Appropriateness for culture (phase I) is assumed 100% for all used materials. Appropriateness against dust and odorants emissions and appropriateness for climate (phases I and II) are assumed 90% for reinforced concrete and cement bricks and 100% for rice straw bale, Rockwool and PUR foam for their clean/dry construction, dust free and thermal insulation. Level of noise and vibration insulation (phases I, II and III) is assumed 80% for reinforced concrete and cement bricks and 100% for rice straw bale, Rockwool and polyurethane foam for their better performance.

- **Practicability**

For the materials that fabricated in manufactories such as Rockwool, polyurethane foam and rice straw bale the degree of off-site manufacture (phase I) is assumed 90%. For reinforced concrete and bricks, it is assumed 70%. However, the degree of flexibility (phases II and III) is assumed 90% for all used materials for their similarity performance in fast construction and ease of disassembly. Rice straw bale is only the renewable material of used materials. Therefore, its renewability (phase I) assumed 100%. For other materials, it is assumed 25%, as they are not virgin materials. All used structural materials have long service life for buildings. Therefore, the durability and maintainability (phases II and III) are assumed 100% for all used materials.

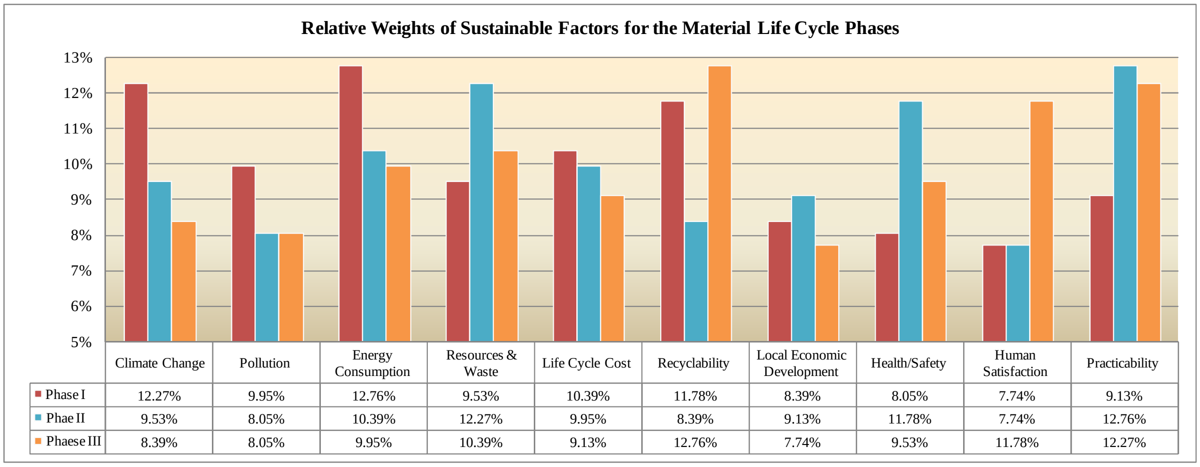
RESULTS AND DISCUSSIONS

Based on estimated materials' quantities - as presented in Table-3 - and collected/assumed data for used structural materials, the SDSS was used to compare between the sustainability of Eco-friendly structural system and the conventional structural system in order to determine which one is more sustainable.

Table-3. Quantities of materials used in both Eco-friendly and conventional structural systems.

Materials	**Eco-friendly structural system**		**Conventional structural system**	
	Weight (kg)	**%**	**Weight** (kg)	**%**
Concrete	14,016	49.03%	42,432	56%
Steel *	548	1.92%	1,903	3%
Cement bricks	7,700	26.94%	31,350	41%
Rice straw bale	6,000	20.99%	0	0%
Polyurethane Foam**	260	0.91%	0	0%
Rockwool	60	0.21%	0	0%
TOTAL	**28,584**	**100%**	**75,685**	**100%**
***** Steel reinforcement for RC & M2 system as well as wire mesh for walls ** Polyurethane foam used for M2 system				

The default relative weights of sustainable factors of SDSS - as presented in Figure-3 - were used.



	Climate Change	Pollution	Energy Consumption	Resources & Waste	Life Cycle Cost	Recyclability	Local Economic Development	Health/Safety	Human Satisfaction	Practicability
🟥 Phase I	12.27%	9.95%	12.76%	9.53%	10.39%	11.78%	8.39%	8.05%	7.74%	9.13%
🟦 Phae II	9.53%	8.05%	10.39%	12.27%	9.95%	8.39%	9.13%	11.78%	7.74%	12.76%
🟧 Phaese III	8.39%	8.05%	9.95%	10.39%	9.13%	12.76%	7.74%	9.53%	11.78%	12.27%

Figure-3. Relative weights of sustainable factors.

The results of SDSS showed that the Eco-friendly system was better than the conventional system during the three phases of total life cycle assessment. It can be seen that the Eco-friendly system had sustainability ranks 64.7%, 64.4% and 84.6% while conventional system ranks 54%, 63.9% and 75.7% for the three phases (manufacturing, construction and demolition), respectively as presented in Figure-4.

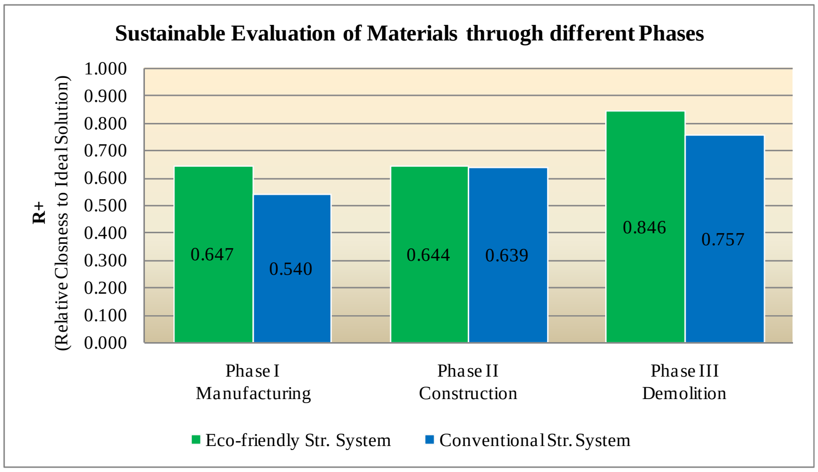


Figure-4. Sustainable evaluation of Eco-friendly and conventional systems through the different phases.

It is clear that the bigger difference between the two systems in the manufacturing phase (11%) then in the demolition phase (9%). Conversely, in the construction phase, there is no significant difference (less than 1%). It means that manufacturing of the selected materials in the Eco-friendly system has the most significant sustainability effect on the comparison. Consequently, the Entropy method in the SDSS produced the weights of the three phases as 72.73%, 0.14% and 27.13% as presented in Figure-5.

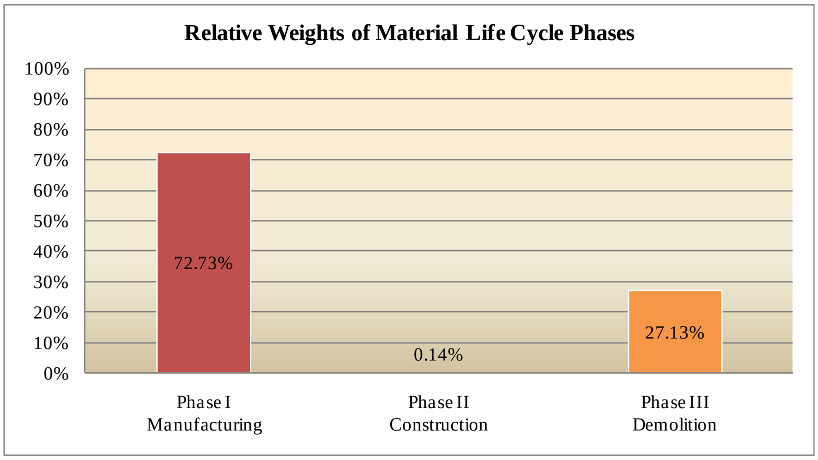


Figure-5. Relative weights of material life phases.

Based on the presented results shown in Figure-5 which indicates that phase I (manufacturing) has got the highest relative weight, an example of SDSS results for Sustainable factors' scores for the two compared systems are illustrated in Figure-6. It can be noticed that the Eco-friendly system had higher sustainable scores than the conventional system for all sustainable factors due to the larger masses of materials used in the second system (i.e., the quantities of the conventional materials are more than 2.5 times the eco-friendly materials as presented in Table-3). The bigger difference in the sustainable scores between the two systems is about 42% in the recyclability factor. For the factors of life cycle cost, resources/waste and practicability; the differences were about 10% to 12%. For other factors the differences were only about 0% to 4%.

The resources/waste factor score of Eco-friendly system was higher than the conventional system by 9% for phase II and 35% for phase III (maximum difference in these phases). However, the recyclability factor score of Eco-friendly system was lower than the conventional system by 6% for phase III.

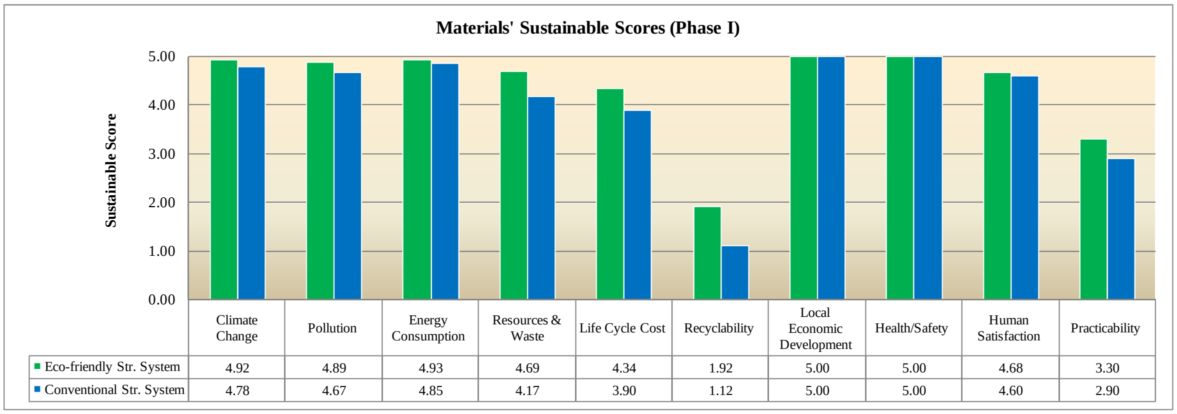


Figure-6. Sustainable factors scores for Eco-friendly and conventional systems (Phase I).

Overall, the Eco-friendly system had better sustainability rank (67%) than the conventional system (56%) according to SDSS results as presented in Figure-7.

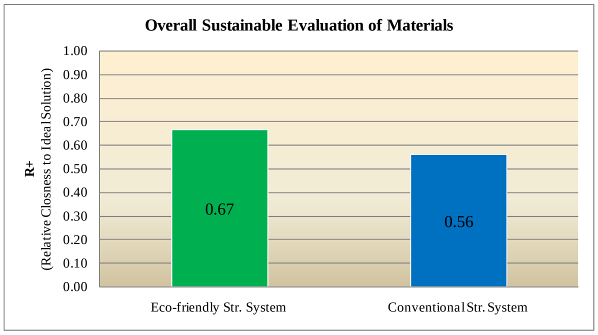


Figure-7. Overall sustainable evaluation for eco-friendly and conventional systems.

CONCLUSIONS

This paper presents a comparative study between two structural systems using conventional and eco-friendly building materials in order to evaluate the sustainability of each type. A prototype of two storeys was constructed using eco- friendly building materials (integrated bricks, rice straw bales, M2 system, plain concrete, and Rockwool sandwich panels). A similar building with the same area and architectural layout was virtually estimated using conventional skeleton structural system (reinforced concrete and bricks). A sustainable decision support system (SDSS) software was used to compare between the two systems using sustainability measurements, life cycle assessment method, and multi-criteria decision analysis technique. This paper presents, via a simple case study, an illustration of the potential of some eco-friendly building materials to be integrated into novel designs for improved performance.

Results showed that the eco-friendly system had better overall sustainability rank than the conventional system by about 11% (67% for eco-friendly system and 56% for conventional system). In addition, the results of SDSS indicated that the eco-friendly system was better than the conventional system during the three phases of total life cycle assessment (manufacturing, construction and demolition) by 11%, 0.5% and 9%, respectively.

On the other hand, the results illustrated that the manufacturing phase (phase I) has the most significant sustainability effect on the comparison study. Recyclability and resource/waste sustainable factors had the bigger difference in the sustainability scores between the two compared systems.

REFERENCES

[1] P. Walker. 2010. Low Carbon Buildings and Traditional Materials. Proceedings of International Conference on Sustainable Built Environment (ICSBE-2010) Kandy.

[2] G. Susman and M. Dowson. 2012. Innovative Use of PCM and Aerogel in Low Energy Buildings. Proceedings of Greenbuild 2012 International Conference and Expo, November 14-16, San Francisco, CA.

[3] Garas G., Allam M. and El Dessuky R. 2009. Straw Bale Construction as an Economic Environmental Building Alternative- A Case Study. ARPN Journal of Engineering and Applied Sciences. 4(9): 54-59.

[4] G. Garas, M. Allam and K. Mamdouh. 2009. Straw Bale Fire Test on Cement Plaster Mixes. International Conference of Safety and Security Engineering III Proceeding, Rome, Italy.

[5] Mostafa E. Allam, Gihan L. Garas and Hala G. El Kady. 2011. Recycled Chopped Rice Straw- Cement Bricks: Mechanical, Fire Resistance and Economical Assessment. Australian Journal of Basic and Applied Sciences.

[6] O. Ajamu and A. A. Adedeji. 2013. Investigating the Bearing Capacity of Straw Bale Masonry in

Compression and Thermal Loads. Webs Journal of Science and Engineering Application. 2(1): 50-58.

[7] Bakhoum E.S. 2011. A decision support system for evaluation and selection of structural materials on a sustainability basis, Thesis (PhD). University of Southampton.

[8] Bakhoum E. and Brown D. 2014. An automated decision support system for sustainable selection of structural materials. International Journal of Sustainable Engineering. pp. 1-13. Taylor and Francis.

[9] Bakhoum E. and Brown D. 2012. A Developed Sustainable Scoring System for Structural Materials Evaluation. Journal of Construction Engineering and Management (ASCE). 138: 110-119.

[10] Bakhoum E. and Brown D. 2012. A hybrid approach using AHP–TOPSIS–entropy methods for sustainable ranking of structural materials. International Journal of Sustainable Engineering. 6 (3): 212-224. Taylor and Francis

[11] Marceau M.L., Nisbet M.A. and VanGeem M.G. 2007. Life Cycle Inventory of Portland Cement Concrete. Portland Cement Association (PCA).

[12] Prusinski J.R., Marceau M.L. and VanGeem M.G. 2004. Life Cycle Inventory of slag cement concrete. In:8th CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete.

[13] Strezov L. and Herbertson J. 2006. A Life Cycle Prospective on Steel Building Materials. Australian Steel Institute.

[14] Hammond G. and Jones C. 2008. Inventory of Carbon and Energy (ICE) Version 1.6a. UK: University of Bath.

[15] Venta G.J. 1998. Life Cycle Analysis of Bricks and Mortar Products. Ottawa, Canada: ATHENA Sustainable Materials Institute.

[16] SPINE database. CPM LCA DATABASE. [Online] Available at: www.lifecyclecenter.se.

[17] Franklin Associates. 2011. Cradle-to-gate life cycle inventory of nine plastic resins and four polyurethane precursors. A Division of Eastern Research Group, Inc. Prairie Village, Kansas. For The Plastics Division of the American Chemistry Council.

[18] Flury K. and Frischknecht R. 2012. Life Cycle Assessment of Rock Wool Insulation. ESU-services Ltd., fair consulting in sustainability. [Online] Available at: www.esu-services.ch.

[19] Cole R.J. 1999. Energy and greenhouse gas emissions associated with the construction of alternative structural systems. Building and Environment. (23): 335-48.

[20] Burton E. and Friedrich N. 2008. Net Waste Tool, Guide to reference data,version 1.0. Material change for a better environment (WRAP).

[21] Gordon M. 1997. Demolition Energy Analysis of Office Buildings Structural Systems. ATHENA Sustainable Materials Institute.

[22] Porritt J. 2009. The concrete industry sustainability performance report. First report. The concrete centre.

[23] Richard J. M. and Norton, A. 2008. Life Cycle Assessments of Natural Fibre Insulation Materials. London: Imperial College.

[24] Sikorski M. 2000. New Development in Low VOC Flexible Polyurethane Foams. Proceedings of the Polyurethane Foam Association.

[25] Menzies B., Hay D. and Gribble N. 2008. Demolition Protocol. Institution of Civil Engineers (ICE).

[26] Nikje M. M. 2012. High Lights in Industrialization of Polyurethane Foam Wastes Chemical Recycling: Economical Roots to Polyol Recovery, Application and Market Studies. [Online] Available at: http://waste.ua/eco/2012/municipal-waste/polyurethane.