Investigation of the impact of eco-friendly building materials on carbon footprints of an affordable housing in hilly region

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Abstract. Increasing emission of carbon di-oxide in the atmosphere is becoming one of the greatest threats to the humans and the society. The combustion of fossil fuels and the manufacturing process of cement are responsible for around 75% increases in the CO2 emissions. It has become important to monitor and control the greenhouse gas emissions in the atmosphere. The carbon footprint is one such concept which is becoming popular over past few years. It helps in evaluation of mitigation measures and emissions management by identifying the important sources of greenhouse gas emissions and reducing their efficiency. In spite of development of various types of eco-friendly materials, the construction industry uses traditional materials that contribute largely to carbon emissions. This case study based research focuses to identify and quantify the carbon emissions of the most commonly used materials for construction in India. A physical model of low energy affordable house for hilly region has been constructed at CBRI Roorkee by replacing the traditionally used building materials with the eco-friendly greener materials. The carbon footprints of these eco-friendly materials were calculated using Process Analysis-LCA technique and then compared with the traditionally used building materials. The initial carbon footprint was estimated to be 4.17 tonnes of CO2 that was reduced to 3.95 tonnes, resulting in reduction of carbon footprint by 5.3%. Therefore eco-friendly greener materials can effectively help in reducing the carbon footprint of the traditionally used building materials in construction.

Keywords: Affordable house, GHG emissions, Process Analysis-LCA technique, low energy affordable house, eco-friendly materials.

1. Introduction

The climate change is now becoming a very serious issue and it is giving an indication for an early response at global level. The utilization of natural materials in cement mortar and cement concrete has led to the devastating effects on the environment [1–4]. Many research works have focused on the utilization of the industrial and agricultural waste as a replacement of either cement or sand [5–9]. The concentration of greenhouse gases, globally, has increased since 1750 whose main contributor is carbon dioxide (CO2) which by volume has increased predominantly [10]. The term Carbon footprint was tossed about a decade ago and it was identified as a tool to measure greenhouse gas (GHG) emissions from the debate on climate change [11]. The origin can also be traced back to 1996 when Wackernagel and Rees proposed it as a subset of “ecological footprint” [12]. The increasing worldwide interest in causes and consequences of climate change, and in exploring ways led to the
formation of Intergovernmental Panel on climate change (IPCC) whose role is to control GHGs emissions [13]. According to the Parliamentary Office of Science and Technology [14], “A carbon footprint is the total amount of CO₂ and other greenhouse gases, emitted over the full life cycle of a process or product. It is expressed as grams of CO₂ equivalent per kilowatt hour of generation (gCO₂eq/kWh), which accounts for the different global warming effects of other greenhouse gases.” The CF calculation helps in calculation of mitigation measures and emissions management [15]. When the emissions are calculated, the important sources of emissions can be identified and the efficiency can be increased by reducing the identified emissions. So, it not only helps in cost reduction but also ingresses the environmental efficiency of system. There are growing number of studies on calculation of embodied carbon and embodied energy for houses using LCA framework [16–19]. Many studies are principally concerned with obtaining a generalised value of embodied energy and embodied carbon (carbon footprint) in GJ/m² and KgCO₂/m² and providing a comparison in reduction of emissions by using new methodologies of construction [20–23]. There are various research works that have utilized the eco-friendly waste materials as a building material in construction [24–29]. Raymond J Cole in 1998 [30] analyzed the selection of alternative wood, steel and concrete assemblies and performed detailed examination of energy and GHGs emissions associated with its construction on site. He found that the energy required for the new construction was 26-51% higher than energy required by alternatives. Hacker et al. in 2008 [31] performed a life cycle analysis for a period of 100 year to analyze the carbon emission of a model house. He studied the embodied CO₂ balance and thermal mass by considering the thermal mass ranging from light weight to very heavy timber frame. It was concluded that the carbon content was higher by 15% in case of heavier weight cases. Wiedmann et al. in 2010 [32] calculated the CF using EIO analysis and a series of balanced IO tables were constructed for period 1992 to 2002. The results concluded that net CO2 emission increased from 4.3% in 1992 to 20% in 2002. Yan et al. in 2010 [33] examined the emission due to dwellings and present construction work in Hong Kong. It was concluded that 6-9% of total GHG emission are from consumption of construction equipment, 82-87% from embodied carbon of material and 6-8% from transportation. Monahan and Powell in 2011 [34] analyzed and compared the embodied carbon in a low energy house using panellised modular timber frame system with two different scenarios. It was concluded that timber frame resulted in 34% reducing in CF. In India there are few studies which aim at calculating the carbon footprint of physical model houses [35,36]. They suggested that the use of such construction practices that helps to reduce CO₂ emissions but did not show the physical interpretation in reduction of CO₂ emissions by using eco-friendly materials in place of conventionally used materials.

This study is based on calculation of carbon footprint of a low energy affordable house constructed in year 2015 at Central Building Research Institute, Roorkee in India. Estimation for all the materials used in the construction is done and then total carbon footprint is estimated for the house. In addition to the Case Study, further scenario is studied by replacing the originally used building material by eco-friendly greener materials to provide a comparison in carbon footprint of both houses. The contribution of this paper is to the growing researches on environmental impacts of commonly used Indian building materials by comparing the carbon footprint and embodied energy of low cost affordable house constructed at CSIR-CBRI, Roorkee, with identical model houses if constructed using suitably replaceable eco-friendly materials already been developed in India. Further, the investigation assesses that whether the replacement of commonly used building material by eco-friendly material can contribute towards national carbon reduction goals or not, and if it can, then to how much extent.

2. Methodology and Description of Study

This research focuses to identify the materials that are used most commonly in India and to quantify the total carbon emissions through their use. To analyze those commonly used building materials, a physical model affordable house forms the basis of study, the case study presented here is based on calculation of carbon footprint of low energy affordable house constructed in year 2015 at Central
Building Research Institute, Roorkee in India. Additionally, a further scenario was studied by replacing the originally used building material by eco-friendly materials to compare affordable houses built using conventional material and eco-friendly materials. The reduction in percentage of CF is observed. CF in all cases is calculated by Process Analysis-LCA technique. The case study boundary is limited to analysis of building materials used in construction. The cradle to site emissions generated from building materials are calculated. The inventory used to obtain carbon factors and embodied energy factor of different materials is The Inventory of Carbon & Energy- (ICE) [37].

2.1. Affordable house for hilly region using conventional materials

The house constructed for hilly region mainly utilizes the locally available material such as rock. Total internal floor area is 23.4 m² as shown in Figure 1. Figure 2, 3, 4 shows the top view section, front view section and side view section of affordable house in hilly region while Figure 5 shows the front elevation of affordable house in hilly region. Mainly used materials are stones, lime, GI sheets, cement etc. Foundation is constructed using stones laid above PCC. Plinth band is provided to avoid crack in walls above due to settlement of foundations, to make them safe for earthquake and to avoid water absorption. The walls of superstructure are constructed using stones blocks also called as stonecrete blocks. Sills and lintels are also provided. The floor consists of tiles and roof on drawing room is made of galvanized iron sheets fixed to walls and by using angles. Total length of GI sheet is 3.048 m and width is 3.03 m. The roof in kitchen and bathroom consists of RC plank, roof of toilet is made from RBC and roof of loft consists of brick panels. Actual Photograph of house is shown in Figure 6.
The amount of each material used is obtained from contractor and architects of CBRI and the remaining data was estimated manually. Embodied energy and carbon footprint is calculated for different materials using the PA-LCA technique as shown in Table 1. The boundary is limited to analysis of building materials only. The inventory used to obtain carbon factors and embodied energy factor of different materials is the Inventory of Carbon & Energy (ICE) – main data tables.

**Table 1. Summarized Inventory for Hilly Region Using Conventional Materials**

| Material      | Quantity (Kg) | Embodied Carbon Factor | Carbon Emission (KgCO₂) |
|---------------|---------------|------------------------|-------------------------|
| Steel         | 42            | 1.77                   | 74.34                   |
| Iron          | 145           | 1.91                   | 276.95                  |
| Stone         | 37500         | 0.056                  | 2100                    |
| Cement        | 2690          | 0.136                  | 365.84                  |
| Concrete      | 8750          | 0.13                   | 1137.5                  |
| Bitumen       | 93.6          | 0.48                   | 44.92                   |
| Wood Varnish  | 1             | 5.35                   | 5.35                    |
| Lime          | 22.36         | 0.75                   | 16.77                   |
| PVC           | 58.38         | 2.5                    | 145.95                  |
| **TOTAL**     | **4.17 tonnes of CO₂** |                        |                         |

Hence, the total embodied energy of affordable house for Hilly region using conventional materials is 61.63 GJ and carbon footprint is 4.17 tonnes CO₂

**2.2. Affordable house for hilly region using eco-friendly materials**

The CF of hilly region house is mainly due to stones and cement usage. Stones are the locally available material and is used in large quantity but still it’s per unit CF is very less as compared to any other material. The replacement is done for GI sheets used in terracing by bamboo mat corrugated roofing sheets and outer and inner plaster by mud phuska. Bamboo mat corrugated roofing sheet is a suitable replacement for GI sheets. It is environment friendly, light weight, strong and possess food thermal and sound insulation. Load bearing capacity is also comparable to GI sheets. Its other advantages are that it is water and termite proof, resistant to face, aesthetically good and is suitable for disaster prone and heavy rainfall areas [38,39]. More extensive research for bamboo mat corrugated roofing sheet is done by Sujatha et al. [40] and its CF is 1.308 and density is 400 kg/m³. Figure 7 shows the bamboo mat roof sheets.
The amount of each material used is obtained from contractor and architects of CBRI and the remaining data was estimated manually. Embodied energy and carbon footprint is calculated for different materials using the PA-LCA technique as shown in Table 2. The boundary is limited to analysis of building materials only. The inventory used to obtain carbon factors and embodied energy factor of different materials is The Inventory of Carbon & Energy (ICE) – main data tables.

### Table 2. Summarized Inventory for Hilly Region Using Eco-Friendly Materials

| Material                          | Quantity (Kg) | Embodied Carbon Factor | Carbon Emission (KgCO₂) |
|----------------------------------|---------------|------------------------|-------------------------|
| Steel                            | 42            | 1.77                   | 74.34                   |
| Iron                             | 48.2          | 1.91                   | 276.95                  |
| Stone                            | 37500         | 0.056                  | 2100                    |
| Cement                           | 1340          | 0.136                  | 182.24                  |
| Concrete                         | 8750          | 0.13                   | 1137.5                  |
| Bitumen                          | 93.6          | 0.48                   | 44.92                   |
| Bamboo                           | 30            | 1.308                  | 39.42                   |
| Non-Erodible Mud Plaster         | 237           | 0.48                   | 113.76                  |
| Wood Varnish                     | 1             | 50                     | 50                      |
| Lime                             | 22.36         | 5.3                    | 118.5                   |
| PVC                              | 58.38         | 67.5                   | 3490.65                 |
| **TOTAL**                        | **3.95 tonnes** |                       | **CO₂**                |

Hence, the total carbon footprint of affordable house for hilly region using Eco-Friendly materials is 3.95 tonnes CO₂.

3. RESULTS AND DISCUSSIONS

The need to calculate CF so as to monitor and control the carbon emissions and various methods to calculate CF has been understood while PA-LCA is used to calculate the CF for case study. The boundary is limited to analysis of building materials only. The inventory used to obtain carbon factors and embodied energy factor of different materials is The Inventory of Carbon & Energy (ICE) – main data tables.
3.1. Affordable house for hilly region using conventional materials

Fig. 8 Material Proportionate CF of Conventional Materials for Hilly Region

i. This model house required a total of 61.63 GJ of embodied/primary energy to construct. This equates to primary energy of approximately 2.63 GJ per m$^2$ of area.

ii. The total carbon footprint of house accounts to 4.17 tonnes of CO$_2$ which equates to carbon footprint of 178 KgCO$_2$ per m$^2$.

iii. Stone is the main contributor to both embodied energy and carbon emission.

iv. Out of all the materials considered stone, cement, concrete and bitumen were found to be the most significant and accounts to 87% of total emitted carbon.

v. The major part of structure that contributes most to carbon emissions is super structure.

3.2. Affordable house for hilly region using eco-friendly materials

Fig. 9 Material Proportionate CF of EFM Materials for Hilly Region

i. The total carbon footprint of house accounts to 3.95 tonnes of CO$_2$. This equates to carbon footprint of 168.8 KgCO$_2$ per m$^2$.

ii. Out of all the materials that are considered, minerals are found to be the most significant category that accounts to 91% of total emitted carbon.

iii. Use of bamboo mat corrugated roofing sheets resulted in less consumption of iron in structural assembly and thus lowers down the carbon emissions produced by iron.

iv. The use of non-erodible mud plaster on walls helps in less consumption of cement usage and thus lowers down the emissions due to cement.
3.3. Comparison between carbon footprint generated by conventional and eco-friendly materials

A direct comparison in carbon footprint production by using conventional and eco-friendly materials is shown in Figure 10. For hilly region the carbon footprint generated by use of conventional materials is 4.17 tonnes of CO\(_2\) while carbon footprint generated by use of eco-friendly materials is 3.95 tonnes of CO\(_2\). The use of bamboo mat corrugated roof sheets and mud phuska resulted in decrease of carbon emission by 5.3%.

![Comparison of carbon footprints between conventional and eco-friendly materials](image)

By learning the need for calculation of the carbon footprints and applicability of several approaches, PA-LCA technique was used to calculate the cradle to site emissions. The following conclusions can be derived from the comparative analysis:

i. For the case of affordable house for hilly region, stone and concrete are utilized most resulting in total emission of 3.2 tonnes of CO\(_2\) and therefore these two materials needs to be monitored to control the emissions. But as stone is the low cost and most locally available material available in hilly region, it cannot be substituted for any other material, so, replacement should be done for other materials being used to reduce the emissions.

ii. By replacing the GI sheets by bamboo mat corrugated roof sheets and using non-erodible mud plaster for plastering of walls for house constructed for hilly region also helped in reduction of emission. The initial CF was estimated to be 4.17 tonnes of CO\(_2\) that was reduced to 3.95 tonnes, resulting in reduction of CF by 5.3%.

iii. The use of greener Eco-Friendly suitable materials resulted in lowering down of emissions significantly. The total replacement of clay bricks by fly ash bricks and outer cement plaster by
non-erodible mud plaster in house for plain region was the key factor in reduction of emissions. The initial CF was 17.5 tonnes of CO$_2$ that dropped down to 9.7 tonnes, resulting in reduction of CF by 44.6%.

iv. As stated above, the replacement of conventional used building materials with new greener eco-friendly materials resulted in considerable reduction of carbon footprint, it can be finally concluded that for production of energy efficient buildings, new developed eco-friendly materials should be used, they not only provides adequate strength to the structure but also their impact to environment and surroundings is lesser as compared to traditionally used building materials.

4. CONCLUSION

The study focused on the analysis and determination of the energy consumed and total carbon emission produced by building materials incorporated in construction of model house. Two separate designs for plain and hilly regions of India were examined for the emissions and also suggestions are made to follow such construction practice that motivates the use of greener Eco-Friendly materials which helps in reduction of carbon emissions.

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