Sustainable materials for low carbon buildings

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Abstract

This paper focuses on certain issues pertaining to energy, carbon emissions and sustainability of building construction with particular reference to the Indian construction industry. Use of sustainable natural materials in the past, related durability issues, and the implications of currently used energy-intensive materials on carbon emissions and sustainability are discussed. Some statistics on the Indian construction sector regarding materials produced in bulk quantities and the energy implications are discussed. Examples of low embodied energy materials are provided. An analysis of total embodied energy in conventional and alternative building systems shows nearly 50% reduction in embodied energy of buildings. Potential uses for solid wastes for building materials are presented.

Keywords: sustainable construction; embodied energy; carbon emission; low carbon material

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1 INTRODUCTION

Building materials and technologies, and building practices have evolved through ages. The art and science of building construction commenced with the use of natural materials like stones, soil, thatch/leaves, unprocessed timber, etc. Hardly any energy is spent in manufacturing and use of these natural materials for construction. Some problems associated with the durability of the natural materials like soil, thatch/leaves, timber, etc. lead to the exploration for durable building materials ever since the man started construction activity. Brick burning represents one of the earliest examples of using thermal energy to manufacture durable building materials. Metal products, lime and lime-based products represent the other manufactured energy-consuming materials used for the construction. Discovery of natural inorganic binders like pozzolanic materials resulted in lime-pozzolana (LP) cement and this paved the way for the invention of Portland cement in 1824. Portland cement and steel brought revolutionary changes in the construction practices since early part of twentieth century. Later on plastics and plastic products entered the construction industry. Thus, the journey through the developments in the building materials and technologies is traced in Table 1. As we moved away from zero energy materials to more modern materials for the construction activities, it became imminent to spend more energy and natural resources. These modern materials are energy intensive and are hauled over long distances before being used for construction. In the context of carbon emission reductions and the issues of global warming, there is a need to pay attention to use of modern building materials with reference to (i) energy intensity of materials, (ii) natural resources and raw materials consumed, (iii) recycling and safe disposal and (iv) impact on environment. Indiscriminate use of natural resources and energy-intensive process for the building materials will not lead to sustainable options. This paper focuses on certain issues pertaining to the energy, carbon emissions and sustainability of building construction with particular reference to Indian construction industry.

2 ENERGY AND MATERIAL RESOURCES IN THE INDIAN CONSTRUCTION SECTOR

Indian construction industry is one of the largest in terms of volume of raw materials/natural resources consumed and volume of construction materials/products manufactured. Large variety of materials are manufactured and consumed in the building industry. Materials produced and consumed in bulk quantities are listed in Table 2. Quantity of materials produced, their raw materials and energy expenditure are provided in the table. Quantity of materials produced and the energy consumption are based on the reports and papers [1–3, 24, 25] and some estimates. Total energy expenditure on these materials consumed in bulk quantities is 3155×10^6 GJ per annum. It has been estimated (in 1991) that 22% of green house gas (GHG) emissions is contributed by the construction sector in India [1]. Currently, GHG emissions from

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Table 1. *Energy consumption and developments in building materials.*

Prior to 4000 BC	4000 BC–1800 AD	1800 AD–to date
Soil, stones, reeds/ thatch, Sun dried bricks/adobe, unprocessed timber	Burnt clay bricks, lime, cast iron products, lime-pozzolana cement	Aluminium, steel, glass, Portland cement, plastics, other smart materials, nano-materials, etc.
Zero-energy materials	Medium-energy materials	High-energy materials

Table 2. *Construction materials produced in bulk quantities in India.*

Type of material	Annual Consumption	Raw materials	Energy
Burnt clay bricks	150×10^9 nos.	Fertile soil (500×10^6 tonnes)	600×10^6 GJ
Cement	187×10^6 tonnes	Lime stone, gypsum, oxides	650×10^6 GJ
Structural Steel	45×10^6 tonnes	Iron ore, lime stone	1800×10^6 GJ
Coarse Aggregates	250×10^6 m^3	Granite/basalt rock	30×10^6 GJ
Fine Aggregates	350×10^6 m^3	River sand/rocks	75×10^6 GJ

Table 3. *Cement production and CO_2 emissions (million tonnes per year).*

	1990	2005	2010 (projected)
Global			
Cement consumption/production	1040	2270	2800
CO_2 released	940	1700	2070
India			
Cement consumption/production	45	127	200
CO_2 released	41	94	148

construction sector could be 30%. Cement production and CO_2 emissions for global and Indian conditions are displayed in Table 3. These numbers are based on the data from [3, 25]. The figures indicate that during 20 years, the CO_2 emissions from cement/clinker production have more than doubled, inspite of improvements in energy efficiency in the manufacturing process as well as the use of blended cements.

Energy and raw materials are essential for the production of building materials and products. Basic raw material resources include soil, stones, sand, timber/tree products, minerals, chemicals, etc. Energy resources include electricity, coal, oil and gas, biomass, etc. Energy consumption in the manufacturing and transportation of building materials is directly related to GHG emissions and the related environmental consequences. Indian construction industry is growing at an alarming rate (>8% per annum). Apart from meeting the energy demand, the material resources for the sustainable growth is another important aspect. It has been estimated that 300 mm depth of fertile top soil of the entire county will be consumed for burnt clay brick production in about 60 years (assuming a compounded growth rate of 5%) [2]. This is an alarming situation. Similar arguments arise for the case of aggregates (both coarse and fine aggregates) where natural stones and rocky outcrops as well as river beds are exploited indiscriminately. Sustainability of the present mode of production and consumption of building materials and currently adopted construction practices is questionable.

Over exploitation of raw material resources and extensive use of energy-intensive materials can drain the energy and material resources, and can adversely affect the environment. On the other hand, it is difficult to meet the ever-growing demand for buildings by adopting only energy efficient traditional materials (like mud, thatch, timber, etc.) and construction methods. There is a need for energy efficient, environment friendly and sustainable building alternatives. To achieve such objectives, optimum utilization of available energy resources and raw materials becomes imminent. Some of the guiding principles in developing the sustainable alternative building technologies are: (a) energy conservation, (b) minimizing the use of high-energy materials, (c) minimize transportation and maximize the use of local materials and resources, (d) decentralized production and maximum use of local skills, (e) utilization of industrial and mine wastes for the production of building materials, (f) recycling of building wastes and (g) use of renewable energy sources. Building technologies manufactured by meeting these guiding principles could become sustainable and facilitate sharing the resources especially energy resources more efficiently, causing minimum damage to the environment.

3 EXAMPLES OF LOW CARBON BUILDING MATERIALS AND TECHNOLOGIES

Ideal building materials from the consideration of low carbon emissions, least carbon footprint and potential for recycling and reuse are the natural materials like soil, stones and timber/biomass. Unprocessed or least processed natural materials have limitations particularly with reference to strength and durability aspects. Processing and transport of the natural materials involves energy expenditure resulting in carbon emissions. To minimize carbon emissions it will become essential to device technologies to produce building materials and products with minimum amount of energy expenditure. Brief details of some building materials and techniques are discussed below.

3.1 Blended cements

These are cements containing a high volume of one or more complementary cementing materials (CCM), such as coal fly ash, granulated slag, silica fume and reactive rice-husk ash. A large volume of CO_2 is directly emitted during the cement manufacturing process (0.9 tonnes/tonne of clinker). Reduction in the quantity of clinker by substituting with CCM results in lesser CO_2 emissions. There is a considerable amount of ongoing R&D in the direction of using CCM in Portland cements and up to 40% substitution by CCM is possible.

Mehta [3] presented a roadmap for sustainability of the global concrete industry. He predicted CO_2 emissions from cement/concrete industry to reduce drastically by 2030. CO_2 emissions will be at 940×10^6 tonnes by 2030, which is same as that for the year 1990 though there will be a considerable increase in the total volume of concrete consumed.

3.2 Stabilized mud blocks for masonry

Burnt clay bricks are basically manufactured by burning (at high temperature) of processed clay. Clay minerals experience irreversible changes imparting strength to the brick at the cost of high-energy input. Here, conservation of energy as well as clay mineral resources are important from the environmental angle. Stabilized mud blocks (SMB) are energy efficient eco-friendly alternatives to burnt clay bricks. These are solid blocks manufactured by compacting a mixture of soil, sand, stabilizer (cement/lime) and water. After 28 days curing, these blocks are used for wall construction. Compressive strength of the block greatly depends upon the soil composition, density of the block and percentage of stabilizer (cement/lime). Major advantages of SMB are: (a) energy efficient, do not require burning, 60–70% energy saving when compared with burnt clay bricks, (b) decentralized production, production on site is possible, (c) utilization of other industrial solid wastes like stone quarry dust, fly ash etc. and (d) easy to adjust the block strength by adjusting stabilizer content. More information on SMB can be found in the literature [4–11]. Figure 1 shows a load-bearing SMB masonry building.

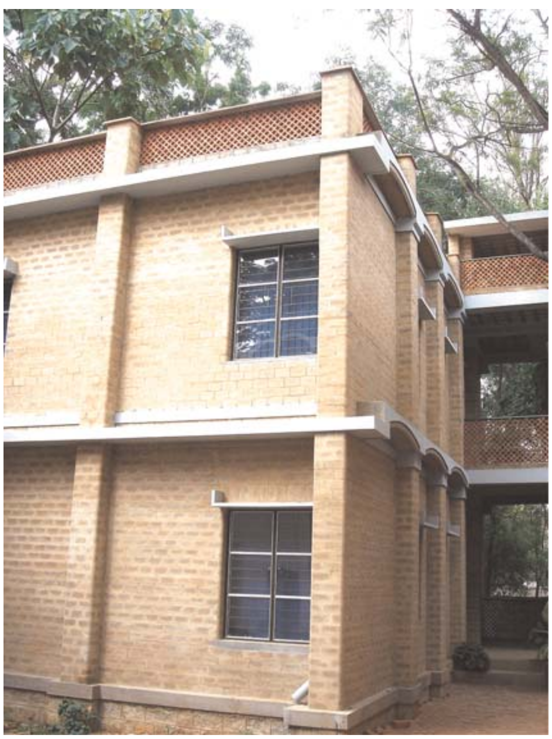

Figure 1. *Load-bearing SMB masonry building.*

3.3 Compacted fly ash blocks

A mixture of lime, fly ash and stone crusher dust can be compacted into a high-density block. Lime reacts with fly ash minerals forming water insoluble bonds imparting strength to the block. These reactions are slow at ambient temperatures (~30°C) and can be accelerated by either low-temperature steam curing [12, 13] or by using additives like phosphogypsum [14] (an industrial waste product). Block strength depends upon the composition of the mix, density and percentage of stabilizer/additives. Some advantages of the technology are: (a) decentralized production in tiny scale industries, (b) utilization of industrial waste products and (c) energy efficient and environment friendly. Figure 2 shows a small-scale compacted fly ash block manufacturing unit.

3.4 Rammed earth walls

Rammed earth is a technique of forming solid walls by compacting processed soil in progressive layers in a temporary formwork. There are two types of rammed earth constructions: stabilized rammed earth and un-stabilized rammed earth. Unstabilized rammed earth is made from mainly soil, sand and gravel. Whereas stabilized rammed earth contains additives like cement or lime in addition to soil, sand and gravel. Unstabilized rammed earth walls are nearly zero carbon options but with some drawbacks like (a) loss of strength on saturation and (b) erosion due to wind-driven rain. Generally, unstabilized rammed walls are thicker (400 mm or more) and need good protection from exposure to moisture. The use of inorganic additives like cement for rammed earth walls has been in practice since the last 5–6 decades. Examples of successful use of cement-stabilized rammed earth for walls can be seen in Australia, USA, Europe, Asia and many other countries [15–20]. Some of the advantages of rammed earth construction include: (a) low energy intensity, (b) materials used are recyclable and bulk of the materials are locally available, (c) rammed earth offers wide variety of textures and finishes, (d) flexibility in plan forms for the buildings and (e) strength and wall thickness can easily be adjusted in case of stabilized rammed earth walls. Figure 3 shows a load-bearing stabilized rammed earth structure.

3.5 Low energy intensity floor and roofing systems

Floor and roofing systems are an assembly of two or more building materials or products. For example the most commonly used reinforced concrete (RC) slab is made up of reinforcing steel, concrete and other non-structural elements like floor finish, renderings and paints. Energy intensity of RC slab arises from the energy intensity of its various component materials. Composite masonry jack-arch roof or floor system, RC filler slab, unreiforced masonry vaults, etc. represent some of the low energy intensity options for floor and roof slabs. Figures 4–6 show some of these alternative floor or roofing systems. Brief technical details of these roofing systems can be found in [2].

Figure 2. *Small-scale compacted fly ash block manufacturing unit.*

Figure 3. *Load-bearing stabilized rammed earth building.*

Figure 4. *Composite masonry jack-arch roof system.*

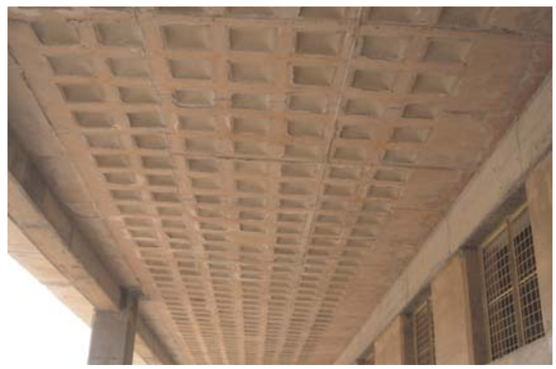

Figure 5. *Ceiling of an SMB filler slab floor.*

Figure 6. *Unreinforced SMB masonry vault roof.*

4 ENERGY IN BUILDING MATERIALS AND BUILDING SYSTEMS

Energy in buildings comprises of two components: (i) primary energy (embodied energy) that goes into materials and assembling of the building and (ii) energy for the maintenance/servicing of a building during its useful life. The second one greatly depends on the climatic variations in a particular region. The first one is a one-time investment, which can vary over wide limits depending upon choice of building materials and techniques. The main focus of the present study is on

Table 4. *Embodied energy in various walling and floor/roofing systems.*

Type of building element	Energy per unit (GJ)
Burnt clay brick masonry (m^3)	2.00–3.40
SMB masonry (m^3)	0.50–0.60
Fly ash block masonry (m^3)	1.00–1.35
Stabilized rammed earth wall (m^3)	0.45–0.60
Unstabilized rammed earth wall (m^3)	0.00–0.18
Reinforced concrete slab (m^2)	0.80–0.85
Composite SMB masonry jack-arch (m^2)	0.45–0.55
SMB filler slab (m^2)	0.60–0.70
Unreinforced masonry vault roof (m^2)	0.45–0.60

Table 5. *Total embodied energy in load bearing masonry buildings.*

Type of building	No. of storeyes and built-up area	Total Embodied energy (GJ / m^2)
Conventional building		
Load-bearing brickwork, RC solid slab floor and roof, concrete tile flooring	2 and 150 m^2	2.95
Building with alternative technologies		
Stabilized mud block masonry, SMB filler slab floor and roof, terracotta tile flooring	2 and 161 m^2	1.53

primary energy and the related carbon emissions. Specific energy consumption values (of basic materials) of 4, 5.75 and 42 MJ/kg of cement, lime and steel, respectively, was considered in assessing the primary energy consumption in building technologies and building systems. Embodied energy in various walling and floor/roofing systems are given in Table 4. The following observations can be made from the energy values given in Table 4.

(a) Alternative options like SMB masonry and rammed earth walls have considerably lower embodied energy values when compared with energy of burnt clay brick masonry. Energy content of SMB masonry and stabilized rammed earth wall is about 20–25% of the burnt clay brick masonry energy. Fly ash block masonry shows reduction of 40–50% in the embodied energy values when compared with the energy in burnt clay brick masonry
(b) Composite masonry jack-arch roofing system shows 40–50% reduction in embodied energy when compared with RC slab. The use of SMB filler slab results in 20–25% savings in embodied energy when compared with energy in RC slab.

Studies of Buchanan and Honey [21], Suzuki et al. [22], Debnath et al. [23] and Venkatarama Reddy and Jagadish [24] emphasize shift in construction from bricks, steel, concrete and aluminium to other low-energy alternative materials in order to save energy costs and reducing carbon emissions in the construction of buildings. The alternative materials discussed above fall into the class of energy-saving options in the construction of buildings.

5 EMBODIED ENERGY IN BUILDINGS

Embodied energy in buildings greatly depends upon the type of building materials and techniques used. RC-framed structures with infill walls is the most common and popular method of creating buildings. Glass and aluminium is profusely used for the openings and the building claddings. Embodied energy in such buildings can vary between 5 and 10 GJ/m^2 [22, 24]. Embodied energy in load-bearing brick masonry buildings (2–3 storeyed) for residential purposes is in the range of 3–5 GJ/m^2 [23, 24].

Embodied energy contents of different building materials and technologies were discussed in the previous sections. Total embodied energy of two types of buildings is presented in Table 5. The table gives details of the building specifications, number of storeyes and built-up area, and the total embodied energy. A conventional two storey load-bearing brick masonry building and a two storeyed SMB masonry building were considered for the purposes of comparison. Embodied energy of the two buildings given in Table 5 is based on the actual quantities of materials used for the construction of these buildings. Energy content of doors and windows are not considered for the embodied energy calculations, because they are made from wood and timber products.

Total embodied energy of the load bearing conventional two storeyed brickwork building is 2.95 GJ/m^2. For the two storeyed building using alternative building materials like SMB walls, SMB filler slab roof, etc., embodied energy is 1.53 GJ/m^2, which is nearly half of the conventional brick wall building. This clearly indicates that the use of alternative low-energy building technologies results in a considerable amount of reduction ($\sim$50%) in embodied energy, thus paving the way for efficient utilization of energy resources and simultaneously reducing GHG emissions.

6 POTENTIAL OF INDUSTRIAL AND MINE SOLID WASTES FOR BUILDING MATERIALS AND PRODUCTS

Apart from reduction in energy and carbon emissions, the need for conserving the raw material resources was emphasized in the earlier sections. Manufacturing of building materials consumed in bulk quantities (bricks, cement, steel, aggregates) puts great pressure on natural raw material resources. In order to meet the demand for new constructions and to sustain the construction activity, it becomes inevitable to explore the use of industrial/mine solid wastes for the manufacture of building materials. Asokan Pappu et al. [26] have compiled the data on inorganic solid wastes generated by industries and mines in

Table 6. *Inorganic industrial/mine solid wastes in India (Source: Asokan Pappu et al. [26]).*

Type of solid waste	$\times 10^6$ tonnes/ year
Fly ash	112
Coal mine wastes	60
Lime stone waste	18
Construction waste	15
Blast furnace slag	11
Iron ore tailings	11
Copper mine tailings	4
Marble dust	6
Red mud, lime sludge, phospho-gypsum, zinc tailings, kiln dust, gold mine tailings etc	20
Inorganic industrial/mine solid wastes (total)	257

India as given Table 6. Large-scale mining, industries and thermal power plants generate solid wastes in bulk quantities. Red-mud, coal ash, slag, fly ash, ore tailings, etc. represent such wastes *unutilized* for several decades. Hundreds of millions of tonnes unutilized wastes are stored in heaps and dams, causing environmental and pollution hazards. For example 200×10^6 tonnes of iron ore tailings are stored in a dam at Kudremukh in India. Such wastes can be utilized for the manufacture of bricks/blocks, substitute for fine aggregates in concrete, partial replacement of cement in concrete, lime-pozzolana cements, etc. There are attempts to utilize mine wastes for the building materials [27, 28]. Reuse and recycling of demolished building wastes is another nearly unexplored area of research. Recycling of materials like steel, stone and timber from demolished structures takes place to some extent. But the materials like broken bricks/blocks, concrete, aggregates, mortar, etc. is still not done in an organized fashion. Such materials can be crushed and processed to utilize them in new constructions.

7 CONCLUDING REMARKS

Certain issues concerning embodied energy in buildings, carbon emissions and sustainability of currently used methods of construction were discussed in detail. Problems of specific energy consumption in the construction sector and the need for conserving raw material resources were highlighted. It is difficult to sustain the building activity to meet the future demand for buildings using the currently available energy-intensive materials and building techniques/technologies. Some examples of alternative low-energy materials were discussed and the embodied energy analysis of a building using such materials was compared with that of a conventional building. The analysis shows that embodied energy of buildings using the low-energy materials and techniques results in 50% savings in total embodied energy. There is a large potential and scope for utilizing the industrial and mine solid wastes for the manufacture of building materials for promoting sustainable construction practices.

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