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Strategies for Cleaner Walling Material in India

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The study is one of two research components aimed at developing strategies for cleaner walling material in India. A team comprising members from Enzen Global Solutions, Greentech Knowledge Solutions and the University of Illinois, Urbana Champaign, has been involved in the second component, involving monitoring of energy and emissions from brick kilns in India and Vietnam. This project has been supported by the Shakti Sustainable Energy Foundation and coordinated by Ellen Baum, Clean Air Task Force, Boston, MA.

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Executive Summary

1.0 Background

The growth in India's economy and population coupled with urbanization has resulted in an increasing demand for residential, commercial, industrial and public buildings as well as other physical infrastructure. Various studies indicate that, out of the total constructed area existing in India in 2030, about 70% would have been constructed between 2010 and 2030. Building construction in India is estimated to grow at a rate of 6.6% per year between 2005 and 2030 (McKinsey and Company, 2009). The building stock is expected to multiply five times during this period, resulting in a continuous increase in demand for building materials. The bulk of building material is presently derived from locally available clay, soil, sand and gravel. Solid fired clay bricks are the most widely-used walling materials in the country. However, over the past few decades, the development of other materials such as solid/hollow concrete blocks, fly-ash bricks, Cement Stabilized Soil Blocks (CSSB), Fly Ash-Lime-Gypsum (FaL-G) blocks, Autoclaved Aerated Concrete (AAC) blocks, etc., has created viable alternatives to bricks and have also penetrated the market.

The building materials production industry in India, particularly when seen in the light of future demand for building materials, could have long lasting implications in terms of natural resource depletion, future energy demand, local pollution, contributions to greenhouse gas emissions as well as socio-economic conditions of a significant number of low-income workers. There is limited understanding of the broader environmental consequences of building materials that address natural resource depletion, energy, environment and socio-economic aspects. It is an imperative and urgent need to have a comprehensive plan for development of walling materials production in India.

2.0 Objective

The main objective of the study was to carry out a comprehensive assessment of materials used for wall construction encompassing the following:

- Consumption of resources and raw materials including water
- Consumption of energy for production and transportation (embodied energy)
- Operational energy of buildings resulting from material (thermal) properties
- Productivity or efficiency
- Emissions of greenhouse gas (GHG) emissions – CO_2
- Regional air pollutant emissions – Particulates, SO_2, NOx
- Socio-economics (costs; occupational health and safety)

The scope of this study has been limited to walling materials since various alternatives to brick have been introduced over the past few decades and the relative energy, environmental and social merits of these materials have so far not been assessed.

3.0 Analysis framework

The walling materials considered in this study are limited to those that can be used for load bearing and non-load bearing (partition) walls constructed with masonry units in accordance with the National Building Code of India, 2005. In this study, we have assessed common burnt clay bricks, burnt clay fly ash bricks, Fly ash-Lime-Gypsum (FaL-G) blocks, cement stabilized soil blocks (CSSB), concrete blocks (solid and hollow) and Autoclaved Cellular Concrete (ACC) blocks.

The methodology used in this study compares one square meter of constructed wall for each of the walling materials by deriving an Environmental Index from performance criteria. In this study, the Environmental Index and ranking have made use of an elementary Multi-Criteria Decision Analysis (MCDA) framework. This approach employs numerical scores on a single normalized scale developed from the performance of each wall option with respect to an individual criterion. These scores have then been aggregated into a composite Environmental Index by a summation of weighted scores.

The data for the study was largely obtained through face-to-face interviews with officials of selected production plants for each of the materials considered. The data were recorded in a structured questionnaire. In addition to data obtained from visits to production units, secondary data were obtained for certain parameters such as energy and emissions from cement and lime production.

4.0 Key findings

The Environmental Indices and ranking for load bearing and non-load bearing wall assemblies are provided in **Tables ES1 and ES2**. Important conclusions from this analysis are summarized below:

Raw materials:

- Where waste material such as fly ash is used in large quantities, such as in AAC blocks, fly ash concrete blocks and FaL-G blocks, the impact is low. Materials that use stone dust from stone crushing units also have a lower raw material impact. Rat-trap bond construction can reduce the raw material impact significantly.
- With lower densities, the quantity of raw materials required reduces as is evident in the very low density of AAC blocks resulting from the aerated nature of the material.
- With increase in block size, the raw material impact is reduced. In this study, a high correlation between RMI and volume of blocks is observed for plastered non-load bearing walls (R = -0.80).

Water:

- Cement based walling materials such as concrete blocks and FaL-G blocks require more water than other materials due to the curing process involved in their production. Clay based walling materials require the least water.

Energy:

- Clay fired bricks have higher embodied energy compared to non-fired materials irrespective of kiln efficiency. The transportation component of embodied energy is significant for all wall assemblies. Among non-fired based wall assemblies, Fal-G walls have the highest embodied energy.
- The thermal performance of non-fired based wall assemblies is also generally superior to those constructed with fired bricks as reflected in the U-values. AAC blocks wall assemblies have the lowest U-value among all wall assemblies due to the porous nature of the material.

Emissions:

- On average, walls constructed with non-fired masonry materials have lower regional and CO2 emissions than walls constructed with fired clay bricks. The variations within these two groups however are very high.

Productivity, OHS and cost:

- The use of manual labor for moulding results in significantly lower productivity compared to mechanized processes. Block size also influences construction productivity and a larger block size requires less time and effort for construction.
- Cost of walls with non-fired materials is generally lower than fired products (except for AAC block walls).
- Poor conditions for labor at brick kiln sites are reflected in a lower OHS index compared to other materials.

Overall, wall assemblies that use non-fired products as masonry units are ranked higher compared to fired masonry unit wall assemblies. Clay fired masonry wall assemblies, regardless of kiln technology and fuel type, all exhibit poorer environmental performance compared to non-fired masonry wall assemblies. The only exception to this is seen in masonry walls that use clay fired bricks from the tunnel kiln. This wall assembly performs better with respect to most environmental parameters and is comparable to the other non-fired material based wall assemblies. When Rat-trap bond wall construction is considered, the environmental performance of clay fired brick walls is significantly improved.

Table ES1: Composite Environmental Index and Ranking of load bearing plastered wall assemblies

	Normalized Scores									Composite Environmental Index	RANKING
	RMI	Water	Embodied Energy	Operational Energy	REI	CO_2 Emissions	OHS Index	Productivity Index	Cost		
Solid Concrete Block	-1.29	0.24	-0.88	1.02	0.69	-0.40	-1.19	-0.82	-0.76	-3.53	6
Hollow Concrete Block	-1.40	0.24	-0.90	0.29	0.70	-0.40	-1.19	-0.35	-1.25	-4.40	4
Fly Ash Concrete Blocks	-1.55	2.60	-1.04	0.55	-0.33	-1.03	-0.72	-1.14	0.20	-1.78	9
Fal G Bricks	-0.78	2.64	0.09	-1.67	-0.04	0.96	-0.96	-0.20	-0.14	-0.56	12
AAC Blocks	-1.67	-0.46	-0.38	-3.13	0.89	-0.42	-2.11	-1.49	3.04	-5.97	1
CSSB	0.57	0.02	-1.03	0.46	-0.11	-0.78	-0.49	0.19	-1.31	-2.05	8
Fly Ash Clay Bricks	0.02	-0.43	0.61	-0.16	-0.13	0.88	0.44	0.02	0.20	1.06	17
K1_Clay Bricks_BTK	0.89	-0.50	0.75	0.72	2.46	0.08	0.44	0.19	0.87	4.63	21
K4_Clay Bricks_BTK	1.00	-0.52	0.40	0.72	-0.53	0.71	1.13	0.02	0.87	3.71	20
K6_Clay Bricks_BTK	1.28	-0.53	0.60	0.72	1.24	-0.05	1.13	0.64	0.77	5.21	23
K2_Clay Bricks_Zigzag	0.84	-0.50	0.39	0.72	-0.99	-0.43	0.44	-0.53	0.87	1.51	18
K3_Clay Bricks_Zigzag	0.91	-0.50	0.20	0.72	0.27	0.18	1.36	1.11	0.87	4.90	22
K5_Clay Bricks_VSBK	1.46	-0.49	0.53	0.72	-0.07	0.59	-0.03	3.18	0.70	6.34	24
K7_Clay Bricks_Downdraft	1.27	-0.52	3.34	0.72	1.84	3.43	0.20	0.79	0.87	9.31	25
K8_Clay Bricks_Tunnel	0.83	-0.44	0.77	0.72	0.54	-0.02	-1.88	-0.88	0.89	0.26	16
Fly Ash Concrete Blocks_RTB	-1.69	1.65	-1.48	-0.16	-1.13	-1.42	-0.72	-1.16	-0.96	-5.80	2
Fal G Bricks_RTB	-1.16	1.68	-0.69	-2.20	-0.93	-0.03	-0.96	-0.50	-1.19	-5.50	3
Fly Ash Clay Bricks_RTB	-0.60	-0.47	-0.33	-0.83	-0.99	-0.08	0.44	-0.35	-0.96	-3.63	5
K1_Clay Bricks_BTK_RTB	0.01	-0.52	-0.23	0.01	0.82	-0.65	0.44	-0.23	-0.48	-0.92	11
K4_Clay Bricks_BTK_RTB	0.09	-0.54	-0.48	0.01	-1.27	-0.20	1.13	-0.34	-0.48	-1.36	10
K6_Clay Bricks_BTK_RTB	0.28	-0.54	-0.33	0.01	-0.04	-0.73	1.13	0.09	-0.56	-0.31	14
K2_Clay Bricks_Zigzag_RTB	-0.02	-0.52	-0.49	0.01	-1.60	-1.00	0.44	-0.73	-0.48	-3.10	7
K3_Clay Bricks_Zigzag_RTB	0.03	-0.52	-0.61	0.01	-0.71	-0.57	1.36	0.42	-0.48	-0.45	13
K5_Clay Bricks_VSBK_RTB	0.41	-0.51	-0.39	0.01	-0.95	-0.29	-0.03	1.87	-0.61	0.13	15
K7_Clay Bricks_Downdraft_RTB	0.28	-0.54	1.58	0.01	0.38	1.70	0.20	0.20	-0.48	2.29	19

Table ES2: Composite Environmental Index and Ranking of non-load bearing plastered wall assemblies

	Normalized Scores									Composite Environmental Index	RANKING
	RMI	Water	Embodied Energy	Operational Energy	REI	CO_2 Emissions	OHS Index	Productivity Index	Cost		
Solid Concrete Block	-1.39	0.55	-1.03	0.61	0.39	-0.55	-0.93	-0.32	-1.21	-3.80	3
Fly Ash Concrete Blocks	-1.63	2.24	-1.20	0.28	-0.71	-1.15	-0.51	-1.05	-0.28	-3.08	4
FaL-G Bricks	-0.93	2.28	-0.17	-1.50	-0.42	0.65	-0.72	-0.24	-0.60	-1.77	6
AAC Blocks	-1.68	-0.47	-0.47	-2.93	0.74	-0.50	-1.77	-1.54	2.38	-6.38	1
CSSB	0.00	-0.10	-1.42	0.55	-0.89	-1.11	-0.30	-0.10	-2.15	-4.51	2
Fly Ash Clay Bricks	-0.19	-0.44	0.30	-0.25	-0.51	0.58	0.54	-0.05	-0.28	-0.33	7
K1_Clay Bricks_BTK	0.61	-0.50	0.43	0.40	2.12	-0.15	0.54	0.10	0.36	2.93	10
K4_Clay Bricks_BTK	0.71	-0.52	0.10	0.40	-0.92	0.42	1.17	-0.05	0.36	1.93	9
K6_Clay Bricks_BTK	0.97	-0.53	0.29	0.40	0.87	-0.26	1.17	0.49	0.26	3.36	12
K2_Clay Bricks_Zigzag	0.57	-0.51	0.10	0.40	-1.39	-0.60	0.54	-0.53	0.36	-0.06	8
K3_Clay Bricks_Zigzag	0.63	-0.51	-0.07	0.40	-0.10	-0.05	1.38	0.90	0.36	3.02	11
K5_Clay Bricks_VSBK	1.07	-0.50	0.17	0.40	-0.51	0.26	0.12	2.62	0.11	3.89	13
K7_Clay Bricks_Downdraft	0.96	-0.52	2.79	0.40	1.49	2.88	0.33	0.62	0.36	7.12	14
K8_Clay Bricks_Tunnel	0.31	-0.46	0.17	0.40	-0.15	-0.42	-1.56	-0.86	-0.02	-2.32	5

5.0 Strategies for cleaner walling material in India

Broad strategies that have the least impact on natural resources, energy and water, and which also promote more efficient production are outlined below:

- Promoting the use of non-fired masonry materials
- Promoting mechanization in production units
- Encouraging year round production of masonry units
- Promoting the production and use of larger sized low-density masonry units
- Promoting further use of fly ash in masonry material production
- Encouraging alternative construction practices
- Establishing a quality control mechanism for masonry unit manufacturers

Specifically, an Action Plan at the National, State and local levels to facilitate development and production of non-fired masonry materials is delineated below:

National level:

Drafting a building materials policy for India

- The Ministry of Urban Development and Poverty Alleviation could draft a building materials policy that sets targets to increase the production and use of non-fired masonry materials (e.g., from current levels of 8% to 30% by 2030)[1].
- Targets could also be set in the policy to increase fly ash utilization in bricks and block production. Guidelines could be issued by the MoEF/MoP to thermal power plants mandating a fly ash processing facility at thermal power plants near major demand centers to make graded fly ash available to end users. This would provide an impetus for AAC block manufacturers as well as for CLC block making, which require fly ash of a certain grade.
- The policy needs to promote mechanization by providing incentives to manufacturers (e.g., tax benefits for equipment and machinery, financing options, etc.; financing units with proposals for year-round production) and to also encourage further use of fly ash (and other 'waste' material) in masonry materials production.
- Alternate construction techniques such as the Rat-trap bond also need to be promoted under the policy.
- The policy also needs to encourage the development and production of low-density, larger sized masonry units. BMTPC in collaboration with research and academic institutes could play an important role in the development of such masonry units as well as the development of other 'waste' material based masonry blocks of low density and larger size.

Skill upgradation and technical support

- Organizations such as Housing and Urban Development Corporation (HUDCO) could take the lead role in setting up entrepreneurship training and technical support centers for establishment of non-fired masonry industries (and fly ash based masonry block industries) in major demand centers; providing guidance on choosing appropriate machinery and equipment for mechanization; skill upgradation for masons on alternative construction techniques (Rat-trap bond construction).

Quality control of masonry products

- The Bureau of Indian Standards could be entrusted with the task of establishing a quality control mechanism for masonry unit manufacturers to ensure products adhere to IS.

Creating demand for alternative materials and practices

[1] The actual targets could be set once a reliable inventory of materials production is developed.

- Specification of non-fired masonry material (and other proven alternative masonry blocks with low environmental impact) in large building construction projects by the Central Public Works Department (CPWD).
- Specification of unplastered walls for large building projects using better / appropriate quality masonry material.
- Specification of alternative construction techniques (Rat-trap bond) in large building projects.
- Modifying building rating systems such as GRIHA and LEED to provide additional incentives for the use of non-fired masonry material.

State and local level:

Policy

- Identification of regional level strategies and policies based on demand and resources available in that geographical context – (for instance, land budgets could be defined for brick production in each state in order to protect agricultural land using a GIS based decision support system. The same decision support system could be used to prioritize walling material use and production in a particular region; a higher clay mining royalty combined with fly ash transportation subsidies could be explored to encourage greater fly ash utilization in existing brick making units). The Urban Development departments of each state could initiate such action together with other relevant departments such as the Mining Department.
- Earmark land for building materials production near high demand centers. The decision support system could be used by the Department of Industries in each state to identify suitable land that has easy access to demand centers as well as raw material sources; Provide incentives to entrepreneurs for establishment of non-fired masonry materials, e.g., tax benefits for equipment and machinery, financing options, land approvals, etc.
- Ensuring continuous power supply for (semi) mechanized masonry industries.
- Providing incentives for biomass based power generation for (semi) mechanized masonry industries.

Creating demand for alternative materials and practices

- Modifying building byelaws by Urban Local Bodies and Urban Development Agencies to encourage non-fired masonry materials.
- Specification of non-fired masonry material (and other proven alternative masonry blocks with low environmental impact) in large building construction projects. State Public Works Departments could play an instrumental role in this.
- Specification of unplastered walls for large building projects using better / appropriate quality masonry material.
- Specification of alternative construction techniques (Rat-trap bond) in large building projects.

Skill upgradation and technical support

- Awareness creation on benefits of non-fired masonry use among developers and other individual building construction proposers; on exposed masonry using better quality masonry units; and on alternative construction techniques (Rat-trap bond construction). The state level Building Centers or 'Nirmithi Kendras' could also provide such support taking into account local considerations.

Chapter 1: Introduction

1.1 Building material demand in India

The Indian economy has been growing at a rate of between 7-8% since 2001. In an approach paper prepared by the Planning Commission of India in 2006, it is stated that the 11th five year plan (2007-2012) targets a higher economic growth of around 9% with an objective to double real per capita income in next 10 years. The rate of urbanization in India has also been rapid with a decennial growth rate of 31.3% between 1991 and 2001 (Census of India, 1991; 2001). The overall urban population increased from 217.17 million to 285.35 million during this period. The numbers of towns and cities have also increased from 4,689 to 5,161 between 1991 and 2001. The growth in the economy and population coupled with urbanization has resulted in an increasing demand for residential, commercial, industrial and public buildings as well as other physical infrastructure.

The country's housing shortage was estimated to be as high as 24.7 million units at the end of the 10th five year plan of which about 70% is in rural areas (Government of India, 2007). About 99% of the housing shortage pertains to the Economically Weaker Sections (EWS) and Low Income Groups (LIG) sectors. Various studies indicate that, out of the total constructed area existing in India in 2030, about 70% would have been constructed between 2010 and 2030. Building construction in India is estimated to grow at a rate of 6.6% per year from 8.0 billion sm in 2005 to 41.0 billion sm in 2030 (McKinsey and Company, 2009). The building stock is expected to multiply five times during this period, resulting in a continuous increase in demand for building materials.

It is quite evident that India requires massive quantities of construction material over the next two decades. The bulk of building material is presently derived from locally available clay, soil, sand and gravel. Solid fired clay bricks are the most widely-used walling materials in the country. However, over the past few decades, the development of other materials such as solid/hollow concrete blocks, fly-ash bricks, Cement Stabilized Soil Blocks (CSSB), Fly Ash-Lime-Gypsum (FaL-G) blocks, Autoclaved Aerated Concrete (AAC) blocks, etc., has created viable alternatives to bricks and have also penetrated the market.

Based on discussions with several manufacturers and experts in the field, we have estimated the share of each of the major walling materials in India in 2011[2]. Fired clay bricks (including fly ash based fired bricks) dominate current use of walling material and account for 92.2% of 151.83[3] billion brick equivalent masonry units produced annually in the country. Concrete blocks have penetrated urban and rural markets over the past few decades and account for 5.9% of all brick equivalent masonry units. AAC and FaL-G blocks have also been gaining in popularity in certain regions across the country over the past decade and are estimated to have a share of 0.2% and 1.6% respectively. Other materials such as CSSB, sand-lime bricks, etc., are expected to have a 0.1% share. A 6.6% annual growth rate in construction activity would increase the annual demand for walling material to 511.38 billion brick equivalent masonry units in 2030. Given present labor constraints and increasing raw material costs that are proving to be barriers for brick making, alternate materials (such as concrete blocks, FaL-G, AAC, etc.) that are comparable in cost are gaining acceptance for construction and it is likely that the demand for these alternate materials would increase. Assuming an annual increase in demand of 10.0% for alternate material such as concrete blocks, FaL-G blocks, AAC blocks, etc., the share of fired bricks is estimated to fall marginally to 85.9% in 2030.

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2 There are presently no reliable estimates of production of walling materials or production units in India and the estimates presented here could be significantly different from actual numbers

3 We have estimated that 9.0 billion brick equivalent concrete block units, 2.4 billion FAL-G bricks, 0.33 billion brick equivalent AAC blocks and 0.1 billion brick equivalent other material in addition to 140.0 billion fired clay bricks are produced annually in India. Several broad assumptions have been made in arriving at these estimates and an inventory of production is required to more accurately estimate share of each material.

1.2 Issues related to building material use

Raw materials and water

The built environment has a major determining role to play on the environment. It is a significant consumer of land and resources in the production of material required for construction, second only to the food industry (Berge, 2009). Raw materials used in the construction of buildings consume 40% of the stone, sand and gravel, 25% of the timber and 16% of the water used annually in the world according to data from the Worldwatch Institute (Arena and de Rosa, 2003). The growth in the demand for natural resources over the past few decades has accelerated to the extent that it is now widely considered a serious threat to the functioning of economies and societies due to associated environmental problems such as climate change, biodiversity loss, desertification, and ecosystem degradation. The rapidly growing demands for food, fresh water, fibre and fuel have resulted in a substantial and largely irreversible loss in the diversity of life on Earth; ecosystems have changed more rapidly and extensively over the past 50 years than in any comparable period in human history as a result (The Millennium Ecosystem Assessment Synthesis Report, 2005). Behrens et al (2007) have shown that annual resource consumption of the world economy increased by about one third between 1980 and 2002. Their regional analysis shows the increasing importance of Asia and Latin America in global resource extraction.

Water is another vital resource that is in shortage is several regions and is likely to become a critical issue especially in the context of projected climate change scenarios. Fertile soils are also considered vital and their rate of exploitation or depletion is now in some cases so rapid that there is a danger that critical thresholds will be crossed (Berge, 2009). This is closely linked to both increased extraction of resources and increased water use.

One of the key sustainability challenges for the coming decades will thus be to improve the management of natural resources and water in order to reduce current levels of anthropogenic environmental pressures. In the context of the projected demand for construction material in India over the next few decades and in particular the use of bricks as the major walling material, it is likely that natural resources, including water, will come under tremendous pressure if adequate and timely measures are not taken to ensure more sustainable management of resources and more responsible consumption.

Energy

Apart from having a large environmental footprint in terms of raw material use, the production of building materials also requires an enormous amount of energy. The amount of energy consumed in the extraction of raw material, the manufacturing processes to produce a finished product, the associated transportation energy as well as the energy for construction and ultimate demolition, accounts for 10-20% of a building's life cycle energy, while 80-90% of the energy a building uses during its entire life cycle is consumed for heating, cooling, lighting, and other appliances (Cheng et al, 2008). The building envelope plays a key role as a key climate moderator between the internal and external environments. The envelope is exposed to the elements and has a major impact not only on the energy utilization within the space it controls but also on the quality of comfort. With buildings accounting for 30-40% of energy use worldwide, reducing embodied energy as well as operational energy in buildings assumes enormous importance. This is very relevant in the context of the current power shortage facing India, and where demand for power is likely to increase more than five-fold from 700 terawatt hours (TWh) in 2005 to 3,870 TWh by 2030 (McKinsey and Company, 2009).

Incorporating energy efficiency concepts into new buildings has special significance for developing economies. Construction booms in fast-growing economies, such as China, India, and some Latin American countries, have substantially boosted energy demand in the building sector. Due to the long life cycle of buildings and the projected new demand for public and private construction, energy consumption in the building sector is expected to continue to grow dramatically over the next 30 years (World Business Council for Sustainable Development, 2007; Levine, 2007).

Pollution

Pollution relates closely to the amount and source of energy used in the production of materials. Transport both of raw materials and finished products could be a major factor in materials that are not locally produced or for materials that source raw materials from large distances. Energy pollution from combustion of fuels and electricity use in the manufacturing process and from transportation refers to regional air pollutant emissions as well as greenhouse gas emissions.

In India, the use of coal and other biomass for brick production results in regional environmental pollution through emissions of particulate matter (PM) including Black Carbon (BC), sulphur dioxide (SO_2), oxides of nitrogen (NOx) and carbon monoxide (CO). BC emissions and carbon dioxide (CO_2) are the most significant drivers of climate change from the brick production process.

Occupational risks and safety

The production of building materials also has a socio-economic dimension. In India, the building materials production industry is largely an informal sector employing a very large number of workers. Although the sector is a major source of employment, especially for poor families, the working conditions endured by workers of this unregulated sector impact health and compromise safety and are a cause for concern. This calls for attention and intervention by policy makers.

1.3 The need for a building materials policy for India

Several developing countries such as China and Vietnam where building construction is growing at a fast pace have already identified sustainable building materials production as one of the key areas and have policies and programmes in place for building materials production. The issue of upgradation of the brick industry is an important component of these programmes. For example, the Vietnamese policy is aimed at promoting hollow clay fired bricks produced in tunnel kilns over solid clay fired bricks produced in traditional kilns. It also advocates a gradual shift to non-fired building materials, particularly AAC blocks, which have the added advantages of being lightweight and with better insulating properties. India currently does not have any such policy and programme.

The building materials production industry in India, particularly when seen in the light of future demand for building materials, could have long lasting implications in terms of natural resource depletion, future energy demand, local pollution, contributions to greenhouse gas emissions as well as socio-economic conditions of a significant number of low-income workers. There is limited understanding of the broader environmental consequences of building materials that address natural resource depletion, energy, environment and socio-economic aspects. It is an imperative and urgent need to have a comprehensive plan for development of walling materials production in India.

Chapter 2: Study Objectives and Methodology

2.1 Study objectives

Building materials have so far been assessed largely in terms of energy consumption during the manufacture of materials or in terms of thermal behavior of wall elements. For example, Buchanan and Honey (2004), Suzuki and Oka (1998), Reddy and Jagadish (2003), etc., estimate embodied energy of building materials and most of these studies have shown that steel, cement, glass and other newer material are more energy intensive when compared to alternative material such as wood or earth. Vijayalakshmi et al (2006) have assessed the thermal properties of different opaque wall materials in India. Other case studies have estimated life-cycle energy use that includes embodied energy and operational energy, e.g., Keoleian et al (2001), Kofoworala and Gheewala (2009), Scheuer et al (2003), Utama and Gheewala (2008), Dimoudi and Tompa (2008), etc. A few of these studies have also estimated CO_2 emissions resulting from such energy use.

While assessments of embodied energy and operational energy have been carried out for certain building materials in India, there is limited literature available on the relative impacts of building material use on natural resource depletion or on environmental emissions. Literature on the social and economic impacts of building material use, particularly in the material production stage, is also limited. Given the need to develop strategies and policies for building material development based on the issues discussed in Chapter 1, the objective of the study was to carry out a comprehensive assessment of materials used for wall construction encompassing the following:

- Consumption of resources and raw materials including water
- Consumption of energy for production and transportation (embodied energy)
- Operational energy of buildings resulting from material (thermal) properties
- Productivity or efficiency
- Emissions of greenhouse gas (GHG) emissions – CO_2
- Regional air pollutant emissions – Particulates, SO_2, NOx
- Socio-economics (costs; occupational health and safety)

The scope of this study has been limited to walling materials since various alternatives to brick as walling materials have been introduced over the past few decades and the relative energy, environmental and social merits of these materials have so far not been assessed. Roofing and flooring materials have fewer options and have therefore not been considered in this study. A second objective of the study was to develop strategies for cleaner walling material in India taking into account their overall energy, environmental and social impacts.

This report forms one of two components of a larger study to develop strategies for cleaner walling materials in India. The other component involved environmental and energy monitoring of selected kilns across India and two kilns in Vietnam and data from this component is used in this report where appropriate.

2.2 Walling materials assessed in this study

Masonry construction is the predominant type of construction in India. The walling materials considered in this study are therefore limited to those that can be used for load bearing and non-load bearing (partition) walls constructed with masonry units in accordance with the National Building Code of India, 2005. The following masonry walls are most widely used or gaining in popularity in India and have been assessed in this study:

- Common burnt clay bricks
- Burnt clay fly ash bricks
- Fly ash-Lime-Gypsum (FaL-G) blocks
- Cement Stabilized Soil Blocks (CSSB)

- Concrete blocks (solid and hollow)
- Autoclaved Cellular Concrete (ACC) blocks

Other materials such as concrete stone masonry blocks, pulverized fuel ash lime bricks, sand-lime bricks and lime based blocks for which IS Codes exist, have not been included in the study either because they are not commonly used or because appropriate case studies could not be identified. Gypsum partition blocks have not been included since this material can only be used for internal partition walls.

Since burnt clay bricks are the most commonly used walling material in the country, the assessment also covers different types of brick firing technologies and fuels to provide some insight into their relative performance. Three Bulls Trench Kilns (BTK), two zigzag kilns (a forced draft and a natural draft), a Downdraft kiln and a Vertical Shaft Brick Kiln (VSBK) in India were monitored for energy and environmental performance as part of the second component of this project. Another VSBK and a tunnel kiln in Vietnam were also monitored. Since this component of the study focuses on India, only kilns monitored in India were used in the analysis to compare kiln technologies. However, the tunnel kiln in Vietnam was also included since this type of kiln was not monitored in India.

2.3 Analysis framework

A wide range of methods and tools to assess materials has been used in the literature. Life Cycle Assessments (LCA) have commonly been used for assessing materials using economic, energy and/or environmental data (e.g., Frenette et al, 2010; Blengini and DeCarlo, 2010; Huberman and Pearlmutter, 2008; De Meester et al, 2009; etc.). These have found to be valuable for building databases or making comparisons for simple systems and are appropriate when comparing materials when quantitative evaluation parameters are used. However, the use of LCA using both quantitative and qualitative parameters in a multi-criteria analysis is limited.

An Environmental Suitability Index (ESI) based on embodied energy, life-cycle cost and re-usability of five of the most commonly used walling materials in Sri Lanka has been developed in an analysis to rank environmental performance of each of the five materials (Emmanuel, 2004). Esin (2007) has used a points-based system to analyze the environmental aspects and ecological criteria of the building materials production process that involves allocation of points for previously defined endorsements.

The methodology used in this study compares one square meter of constructed wall for each of the materials listed in Section 2.3 by deriving an Environmental Index from performance criteria discussed in Section 2.5. In this study, the environmental index and ranking have made use of an elementary Multi-Criteria Decision Analysis (MCDA) framework. This approach employs numerical scores on a single normalized scale developed from the performance of each wall option with respect to an individual criterion. These scores have then been aggregated into a composite Environmental Index by a summation of weighted scores.

The final Environmental Index (EI) for each walling material M_i is given as:

$$EI(M_i) = \sum_{k=1}^{C} Z_k(M_i) \times w(C_k) \qquad \text{- eq (1)}$$

where $Z_k(M_i)$ is the normalized score of option M_i under criterion C and $w(C_k)$ is the weight for criterion C_k

This provides a systematic analytical approach for an integrated evaluation and ranking of alternatives.

The analysis has been carried out for load bearing and non-load bearing walls separately and inferences have been drawn accordingly. The properties of materials used to define the design of each of the walling systems (such as compressive strength) reflect average values for materials produced and available in

India and conform to the appropriate Bureau of Indian Standards. In this study, load bearing walls have been defined as walls that are capable of being used for a two-storied structure. Any structure beyond two stories is likely to be designed as a Reinforced Cement Concrete (RCC) framed structure with infill (non-load bearing) panels. A non-load bearing wall has been defined as a wall of one story or part story in height. A minimum compressive strength of 3.5 MPa and a design life of 50 years for load bearing walls have been considered as a basic requirement for all wall materials.

The quantity of mortar required to construct one square meter of wall would vary depending on the size of the masonry unit. This unit of analysis therefore adequately captures this variation and provides a true assessment of the total raw materials, energy, emissions, costs and occupational risks associated with a particular material wall assembly taking into account the size of the masonry unit. The analysis also provides a comparison of the commonly practiced English bond with an alternative Rat-Trap Bond form of load bearing masonry construction for materials of a standard brick size (230 mm x 115 mm x 75 mm). More details on Rat-Trap bond construction is provided in **Annexure 1**. A comparison of non-load bearing walls would provide the relative merits and demerits of a particular masonry material while a comparison of load bearing walls would show the benefits of an alternative construction technique.

2.4 Metrics and boundaries

The following metrics have been used for each of the evaluation criteria:

Raw materials

The quantity of each raw material used to produce a single block or brick was estimated using data from each of the production units. Based on the block size, the number of blocks required to construct one square meter of wall was estimated taking into account a standard mortar thickness of 10 mm. The quantity of cement and sand required for the mortar was also estimated considering a mix proportion of one part cement and five parts sand by volume as given by the National Building Code of India, 2005, for M1 mortar grade. A mix proportion of one part cement and six parts sand by volume has been considered for partition walls. The use of lime in mortars has not been considered in the analysis. The quantity of raw materials required to construct one square meter of wall area thus includes the raw materials required to produce the masonry units as well as the quantity of cement and sand required for preparation of the mortar.

The analysis has been carried out for plastered and unplastered walls and the raw materials required for plastering both surfaces of the wall have been estimated using a plaster thickness of 12 mm on one surface (internal face) and 15 mm on the other surface (external surface). The mix proportion considered for plaster is one part of cement to four parts of sand by volume for load bearing walls and one part of cement to six parts of sand for non-load bearing walls. Load bearing walls used as external walls would require a richer plaster mix to prevent water seepage. The finishes for the wall surfaces have not been included in the analysis.

The main raw materials used for the materials assessed are clay, sand, stone dust, lime, fly ash, cement and sand. The quantity of each of these materials required to construct one square meter of wall has been added after weighting each to arrive at a Raw Material Index (RMI) for each material. A maximum weight of 2 has been given to clay since soil from where this material is usually obtained is a natural resource that is limited, has implications for the country's food security, impacts the soil regime, drainage and hydrology of the region from where it is mined, and the impact is irreversible when used for fired building materials. Although the impact is less where clay is sourced from the silt accumulated in lakes and tanks, this practice is not generally prevalent across the country and is limited to a few specific regions. Sand is another limited resource that can have a significant environmental impact on the region from where it is mined. Since the impacts are not as significant as clay, a weight of 1 has been assigned. Similarly, the extraction of lime can have significant local and regional environmental impacts and has been assigned a weight of 1. Cement is mainly produced from limestone and a weight of 1 has been assigned for this material. However, since about 1.45 tons of dry raw materials are required to produce one ton of cement (Infrastructure Leasing and Financial Services, 2007), the estimation of total quantity of raw material required has taken this into account. Stone dust used in the construction industry is sourced from stone crushing units and is a waste material. Fly ash is also a waste material and the weights assigned for these two materials are 0, implying no environmental impact from their use.

Water

The quantity of water used for producing one brick or block was estimated using data obtained from the production unit. The quantity of water used in the mortar and plaster needed to construct one square meter of wall took into account 0.5 parts by volume of water in the mortar mix. In addition, the quantity of water required for curing the wall was assumed as 200 l/m^2 for an unplastered wall and 400 l/m^2 for a plastered wall. The quantity of water consumed for constructing one square meter of wall in this assessment includes the water used to produce the number of blocks required in unit area of wall as well as the water required to construct and cure the wall.

Embodied energy

The energy required to produce one block or brick was estimated using the energy content of all fuels and electricity used in the manufacturing process as well as the embodied energy of certain raw materials like cement[4] and lime[5]. The energy required for the transportation of raw materials to the manufacturing plant and the energy required for the transportation of the finished product to the end user[6] was also included as a component of the embodied energy. This transportation component of the embodied energy was also estimated for each masonry unit. For fired clay brick, where a more detailed assessment of embodied energy was carried out, the energy used in the production process was estimated using the calorific content of the fuels used[7].

The embodied energy in the number of masonry units required in one square meter of wall was then estimated. The energy used in the production of unit weight of cement as well as the transportation energy required for cement and sand in the mortar and plaster were also added to arrive at the total energy embodied in one square meter of constructed wall area. The metric to quantify embodied energy in this study is mega joule per square meter (MJ/m^2).

Operational energy

The choice of walling material partially contributes to the operational energy of an enclosed space required for thermal comfort. The other contributing factors being the type and design of the roof, spatial arrangement of spaces, internal loads, ambient conditions (climate), and other factors related to the operation and use of internal spaces. In India, the insulation is a major determinant of the energy needed for space cooling or heating and a material with better insulation properties would be most preferred. Thus, the thermal transmittance or U-value of the wall, which is a measure of this property, has been used in this analysis as a metric. The units of this measure are in $W/m^2.K$, which uses one square meter of wall surface as the reference unit. Data to compute the U-values of wall assemblies (plaster and masonry wall) using thermal conductance values were obtained from the literature.

Productivity

The person-hours spent in producing one block was estimated using data from individual production units. This was used to estimate the total person-hours associated with block production for one square meter of wall area. The labor required to construct one square meter of wall with and without plastering was also estimated. The construction labor requirements factored in the time saved due to larger block sizes.

Productivity in the context of this study is a measure of human energy spent in the production and construction process and is considered as a separate parameter in addition to embodied and operational energy. This parameter, expressed as person-hours/m^2, is also a measure of the employment generation

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[4] The embodied energy of cement of 4.2 MJ/kg used in the analysis was estimated using the thermal energy (723 Kcal/kg clinker) and electrical energy (82 kWh/tonne of cement) used in the production of cement and assuming a cement to clinker ratio of 0.88 (Infrastructure Leasing and Financial Services, 2009)

[5] Embodied energy of lime = 6.5 MJ/kg (Chani et al , 2003)

[6] The 'end-user' refers to the final destination and does not accurately capture the distance to the construction site.

[7] Please refer to the 'Cleaner Brick Industry for India' study report for additional details.

potential. However, since labor shortages were seen to be a major issue facing most production units, a higher productivity (or lower value) for this parameter was considered favorable in this study.

Where the production process uses a higher level of mechanization, particularly in the moulding process, the productivity is higher. The quality of the product is also superior with less variation in physical characteristics such as dimensions and strength. A quality score of 'High = 1', 'Medium = 2' or 'Low = 3' was assigned to each material based on the variations in physical characteristics observed. This score was used to weight the productivity parameter to add the dimension of quality in the analysis.

Emissions

Emissions of PM, NO_X, SO_2 and CO_2 for each material have been estimated per block using fuel and electricity use data obtained from the production units. Transportation emissions have also been estimated for raw materials brought to the production unit and for the finished goods transported to the end user. Appropriate emission factors have been used from literature or have been derived to estimate emissions. For fired clay bricks where emissions have been monitored[8], the emissions from the production process have been estimated using the emission factors computed from the monitoring results. Emissions associated with cement production have been used to estimate the total emissions of cement used in mortar and plaster to construct one square meter of wall area. Transportation related emissions of cement and sand used have also been estimated. The total quantity of emissions due to the construction of one square meter of wall, as for embodied energy, thus includes the production and transportation components of masonry unit production, mortar and plaster. The emission factors used in the analysis are provided in **Annexure 2**.

The emissions of PM, NO_X and SO_2, expressed in grams per square meter (g/m^2), have been summed to arrive at a Regional Pollutant Emissions Index. Weights have not been assigned to any pollutant. CO_2 emissions have not been included in this index but treated as a separate parameter since this is a GHG and not considered a regional pollutant. The magnitude of CO_2 emissions in relation to the other pollutants is also very high and adding this pollutant in the index would skew the index disproportionately in favor of CO_2.

Cost

This parameter reflects the cost of the masonry units that go into the construction of one square meter of wall, the cost of materials for mortar and plaster, as well as the cost of labor to construct the wall. The costs of masonry units, cement and sand are the average landed cost of the materials at a construction site that includes transportation costs. These costs are prevalent market rates at various locations across the country obtained from discussions with architects and civil engineers.

Occupational health and safety

Occupational risks related to exposure to dust, exposure to heat, exposure to air pollutants, risk of falling (working at heights), and manual handling risks have been assessed as 'High = 3', 'Moderate = 2' and 'Low = 1' for each of the materials based on observations at the production units. The availability of housing facilities for temporary workers, sanitation facilities, drinking water and protective gear at the production units was assessed as 'Available = 1', 'Inadequate = 2' and 'Not available = 3'. For production units that did not have to provide housing facilities for temporary workers because the workers lived close to the plant (usually for plants located in or near urban areas), a 'Not applicable = 0' was used. The sum of scores for all these nine sub-parameters was used to define the Occupational Health and Safety (OHS) Index.

2.5 Data

The data for the study was largely obtained through face-to-face interviews with officials of selected production plants for each of the materials considered. The data were recorded in a structured questionnaire. Information was collected on annual production, the quantity of raw materials used, the origin of raw materials and their transportation, fuels and their usage (including electricity), water consumption, and costs (capital and operational) involved in production. The questionnaire also captured

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[8] Please refer to the 'Cleaner Brick Industry for India' study report for additional details.

occupational risks that workers face and amenities available at the plant. The occupational risks and amenities were scored on a rating scale based on visual observations during visits to the plants and are described more fully in Section 2.5.

In addition to data obtained from visits to production units, secondary data was obtained for certain parameters such as energy and emissions from cement production. For materials such as CSSB, where blocks are produced at the construction site and not in any manufacturing unit, secondary data was used from available literature.

The analysis framework and parameters for the assessment of walls was first presented at a Stakeholder Workshop in New Delhi on 17th March 2011. Inputs on these were solicited from representatives of the government, industry, industry experts, research/academic institutes and NGOs working in this area. The analysis framework and metrics were refined based on inputs received at this workshop. The findings of the study were subsequently presented at a second Stakeholder Workshop in New Delhi on 9th September 2011. A draft of this report was also reviewed by two independent experts. Feedback from the stakeholder workshop and from the reviewers was incorporated in this final report.

Chapters 3-8 provide a summary of the production of the materials studied. Details of walling assemblies are also provided, which form the basis for the comparative assessment in Chapter 9. A summary of the assessment and strategies for cleaner walling material in India are then presented in Chapter 10.

Chapter 3: Cement Concrete Blocks

3.1 Overview

Cement is a collective name for mineral binders in powder form, which sets to become solid when mixed with water. Cement reacts with water in a hydrating process. The cement most usually used in building today is Portland cement. The main constituent of Portland cement is limestone (65%), which is broken up and ground with quartz sand and clay or just clay. The mixture is calcined in kilns at 1400–1500 °C and sintered to small pellets called cement clinker. After firing, the mass is ground again with additives such as gypsum to regulate setting. The cement industry is an energy intensive industry with total energy cost typically accounting for 40-45% of production costs. At present, about 96% of India's cement production is from dry process kilns, which is considerably less energy intensive than wet process kilns (Infrastructure Leasing and Financial Services, 2009).

The manufacture of concrete blocks is based on the principle of densification of a lean concrete mix to make a regular shaped, uniform, high performance masonry unit. Blocks typically manufactured are solid or hollow and are available in sizes of 400 mm x 200 mm x 200 mm, 400 mm x 200 mm x 150 mm, and 400 mm x 200 mm x 100 mm. The material has high potential in areas where fired bricks are not easily available or are of poor quality. In large scale construction such as apartments and commercial complexes, concrete blocks have found favor among developers primarily because of the advantages of faster construction with the larger sized blocks and also due to costs being comparable with fired clay bricks. The slightly lower width of concrete blocks in relation to standard-size fired clay bricks also offers a higher usable area of constructed space. The demand for concrete blocks has therefore grown considerably in urban areas and small production units have been established around towns and cities in India. However, the quality of blocks produced at these units has not been consistent and is a cause for concern. Certain large developers have established their own cement concrete block manufacturing units to overcome this issue. The demand for cement concrete blocks has been growing rapidly over the past decade and has also been gaining in acceptance for use in residential buildings both in urban as well as semi-urban areas.

3.2 Production of cement concrete blocks

The basic raw materials for the manufacture of cement concrete blocks are cement, fine aggregate and coarse aggregate. Wastes generated by stone crushers, quarrying and stone processing units can also be used as aggregates and has now become increasingly common.

Concrete blocks are usually produced using a semi-mechanized stationary type machine. Although manual moulding requiring hand tamping is an alternative method that does not require electrically operated machinery, this process is low in productivity and often with high variation in quality of the product. A fully mechanized system which combines compression and vibration is also used in a few instances but these are large scale units that require significant investments.

Adequate vibration of the mix, best obtained in high quality machines, can lower the cement content substantially without compromising on the strength of the block. Mechanization in the moulding process provides adequate compaction of the mix and can yield uniform dimensions of blocks. Very little water is used in the mix where compaction and vibration is mechanized. Blocks need to be cured for a period of 10-14 days and this part of the production process results in a high level of water consumption overall.

A case study of a concrete block unit in Bangalore that uses a semi-mechanized production process was carried out as part of this study. The mixing of the raw materials is done using a concrete mixer and a concrete block making machine is used for moulding. The annual production of this unit is equivalent to 459,000 blocks of 400 mm x 200 mm x 200 mm size. The quantity of sand, cement and stone dust used to produce one block of this size was estimated to be 5.80 kg (25%), 3.48 kg (15%) and 13.92 kg (60%) respectively. The total water used in the mix and for curing the blocks was estimated to be 33.0 liters. Sand and stone dust are transported to the unit from a distance of about 40 km and 10 km respectively. Although a semi-mechanized process has been adopted, it was observed that the quantities of raw materials mixed are not adequately controlled. This could lead to non-uniform compressive strengths that vary by batch of mixes.

Figure 1: Fully mechanized cement concrete block making unit

Electricity is primarily used in the production process to operate the equipment. About 26,400 kWh of electricity are used annually. Due to frequent power outages, a back-up diesel generator is also used. On average, 3600 liters of diesel are used annually. The unit employs 23 persons and operates throughout the year. The final product is transported on average over a distance of 40 km to the end user. A summary of raw materials, water, embodied energy (including transportation), and productivity for each block of size 400 mm x 200 mm x 200 mm is provided in **Table 1** below:

Table 1: Cement concrete blocks - Raw materials, embodied energy & production productivity

	Solid concrete block	**Hollow concrete block**
Weight of block (kg)	23.20	17.79
Size of block (mm)	400 x 200 x 200	400 x 200 x 200
Raw materials		
Sand (%)	25	20
Cement (%)	15	20
Stone dust (%)	60	60
Water (including curing) (l/block)	33.0	33.0
Embodied Energy[9]		
Total (MJ/block)	22.41	21.96
Excluding raw material transportation (MJ/block)	15.43	15.92
Production productivity (person-hours/block)	0.15	0.18

[9] Energy content of diesel = 35.74 MJ/l; energy content of grid electricity = 9.28 MJ/kWh (derived assuming 0.7 kg/kWh of coal consumption, calorific value of coal of 6000 Kcal/kg and 52.8% mix of thermal power in the grid); and energy content of cement = 4.20 MJ/kg

3.3 Wall assembly

Certain studies have reported compressive strengths of 2.8-5.4 MPa for hollow concrete blocks with a bulk density of about 1300 kg/m^3, while other studies on commercially manufactured blocks using quarry dust containing significant amount of silt like fines with low cement content report lower compressive strengths of about 2.0 MPa, just adequate to meet the minimum prescribed strength of the Bureau of Indian Standards (Jagadish et al, 2007). However, a greater control over the production process and selection of raw materials can result in good quality blocks with high compressive strength and low coefficient of variation as seen in certain large fully mechanized units.

The compressive strengths of the blocks from the case study have not been tested as part of this study. However, we expect that the compressive strength of these blocks is in the range of 3.5 MPa based on block density. The sizes of blocks produced at the plant are as indicated in **Section 2.1**. A 400 mm x 200 mm x 200 mm block size with a compressive strength of 3.5 MPa can be used to construct a load bearing wall of two stories. The wall thickness of this wall would be 200 mm excluding plaster thickness. A non-load bearing wall of 100 mm thickness excluding plaster thickness can be constructed with blocks of size 400 mm x 200 mm x 100 mm. Solid and hollow concrete blocks are used to construct load bearing walls. Since blocks produced are typically of larger size compared to burnt bricks, fewer number of mortar joints are required for unit wall area resulting in higher wall strength. For partition walls, hollow concrete blocks are generally not used since nails driven through the wall tend to cause damage and weaken the entire wall. Most production units do not manufacture hollow concrete blocks of 100 mm thickness and this has been excluded from the analysis.

The number of blocks required to construct one square meter of load bearing and non-load bearing walls with concrete blocks is given in **Table 2**. The estimated quantities of raw material, embodied energy, U-value, emissions, productivity, and cost for one square meter of these walls are provided in **Annexures 3-7**.

Table 2: Cement concrete block wall assembly

	Load bearing	**Non-load bearing**
Block size (mm)	400 x 200 x 200	400 x 200 x 100
Wall thickness (mm)[10]	200	100
Blocks/m^2	11.6	11.6

[10] Excluding plaster thickness

Chapter 4: Fly ash Concrete Blocks

4.1 Overview

Fly ash is a residue from the combustion process of thermal power stations using coal or lignite. The total installed capacity of coal based thermal power in India is 96,743.38 MW (54.66%) of the total installed capacity of 1,76,990.40 MW in 2011 according to the Ministry of Power, Government of India. Coal resources in the country are abundant and coal based thermal power stations are presently the mainstay of power development. This is likely to be so in the immediate future also, considering the present status of projects and various constraints in the development of hydro and nuclear power. The demand for coal, driven primarily by the coal power sector, has been outstripping the pace of extraction. Over the past few years, many power plants have restricted generation or have partially shut down because of coal supply shortages despite increasing levels of coal imports (Chikkatur, 2008). Although low in sulphur content, Indian coals contain high ash content of between 35-45% resulting in enormous quantities of fly ash generation. The annual generation of fly ash was estimated at 112 million tonnes in 2005 and is expected to reach about 170 million tonnes by 2012 and 225 million tonnes by 2017 (Kumar et al, 2005).

Fly ash collected by electro static precipitators of thermal power plants consists of very fine particles and accounts for about 80% of the total ash generated. The remaining 20% of the ash is collected at the bottom of the boiler (bottom ash) and is carried to ash ponds as a water slurry. The disposal of fly ash poses a significant challenge for thermal power plants. Efforts of government stakeholders (with the focused thrust provided by Fly Ash Mission (FAM), Technology Information, Forecasting and Assessment Council (TIFAC), Department of Science & Technology, Government of India), research and development organizations, academic institutes and industry to utilize fly ash for various purposes since the mid-1990s has since resulted in utilization of about 45 million tonnes during 2005. Various policies implemented by the Ministry of Environment and Forests (MoEF), Ministry of Power (MoP) and the Ministry of Finance have been instrumental in this effort to increase utilization of fly ash.

A Gazette notification issued by the MoEF in 1999, stipulated that existing power stations have to achieve 20% ash utilization within three years and 100% utilization within 15 years from the date of notification. New stations have to achieve 100% utilization within 4 years of operation. The MoEF has also amended this notification in 2003 and 2008 containing directives for greater fly ash utilization. In these notifications, manufacturers of bricks/blocks/tiles within a radius of 100 km from coal or lignite based thermal power plants, are required to use at least 25% of ash in their products. In addition, all construction agencies engaged in the construction of buildings within a radius of 50 to 100 km of a thermal power plant have to use 100% fly ash based bricks/blocks in their construction projects by August 2007. For projects within 50 km of a thermal power plant, the deadline for use of 100% fly ash based bricks/blocks (any brick/block containing more than 25% fly ash) was end of August 2005. A summary of these regulations is provided in **Annexure 9**.

The utilization of fly ash for brick / block making in and around a few thermal power plants as shown in **Table 3** varies significantly across the country. Where manufacturing units are well connected to major demand centers the utilization of fly ash for brick/block making is higher. Large urban areas are major demand centers and fired clay bricks alone are not able to match demand. Moreover, large scale construction projects necessitate faster construction and alternate larger sized building material such as concrete blocks offer this advantage over smaller fired bricks. Distance to thermal power plants also affects utilization of fly ash for brick/block making and it appears that a distance beyond 25 km is uneconomical to transport fly ash to manufacturing units. An exception to this is seen in Maharashtra where the black cotton soil by itself is not conducive for brick making. Mixing fly ash to the soil improves the quality of bricks and therefore making larger distances viable. Overall, it appears that fly ash utilization for building materials has gained momentum in the country over the past decade through efforts by the government to enforce regulation as well as awareness creation, although there are significant differences across the country.

Table 3: Fly ash utilization around thermal power plants in India

Plant	Annual fly ash generation (tonnes)	Ash collection system	Fly ash utilized (%)	Fly ash applications	Distance (km)
Neyveli Lignite Corporation Limited, Tamil Nadu (250 MW)	1,357,298	Silos	1.2%	Bricks & blocks (0.2%) Cement (1.1%) Earth filling (0.8%)	Na 45-200 Na
Tamil Nadu SEB, North Chennai (630 MW)	1,319,860	Pressurized dense Fly ash conveying system with PLC & silos	26.6%	Bricks & blocks (2.42%) Cement (22.48%) Concrete mortar (1.68%)	25 125-275 Na
Maharashtra SEB, Bhusawal (483 MW)	773,371	Wet and dry	47.0%	Bricks & blocks (30.0%) Cement (4.0%) Agriculture (13.0%)	100 25 50
Maharashtra SEB, Parli (690 MW)	1,146,260	Dry fly ash collected in jumbo bags	29%	Bricks & blocks (1.9%) Cement (6.61%) Agriculture (0.50%) Land development (19.92%)	15 220-370 Na Na
Thane District BSES, Dahanu (500 MW)	565,917	Manually operated wet system	20%	Bricks and blocks (0.72%) Agriculture Land development	Na Na Na
Rayalseema Thermal Power Station, Kadapa (420 MW)	893,063	Wet system and silos for dry ash	51%	Bricks & blocks (11.5%) Cement (39.9%)	Na Na
Renukoot Hindalco Industries Ltd. Renusagar (UP) (619MW)	1,689,320	Wet and dry system	48%	Bricks & blocks (0.6%) Cement (8.5%) Land development (13.9%) Ash dyke (25.0%)	Na 225 Na Na
NTPC Rihand, Sonebhadra District (UP) (1000MW)	Na	Dry ash collection	35%	Bricks & blocks (2.0%) Cement (1.3%) Land development (6.7%) Ash dyke (25.0%)	Na Na Na Na

Source: *Fly ash status summary report in India*, (Undated), prepared by International Centre for Sustainable Development of Cement and Concrete (ICON), CANMET, Natural Resources Canada, and Confederation of Indian Industry (CII)

Fly ash consists of inorganic materials, mainly silica and alumina, with some amount of organic material in the form of unburnt carbon. Its fineness is comparable to cement, although some particles are smaller than 1 micron in equivalent diameter. In presence of moisture, fly ash reacts with lime at ordinary temperature to form a compound possessing cementitious properties (pozzolanic property). Fly ash can therefore be used as pozzolana and admixture in cement, mortar and concrete. Fly ash can also be used in lime pozzolana mixtures to produce blocks, which does not require stringent parameter quality control. Bottom ash or pond ash can be used for sintered applications, geotechnical applications, structural fills, fired clay-fly ash bricks, agricultural applications, etc. (Jha and Prasad, 2008).

The utilization of fly ash has increased from 3% in 1994 to 42 million tons (38%) of 112 million tons produced during 2004-05. Presently, cement manufacturing (49%) and road construction (21%) account for the largest consumption while brick manufacturing is only 2% (Dhadse et al, 2008). While efforts by the government have yielded good results, there is still considerable potential to increase the utilization of fly ash for brick/block making. Providing incentives for setting up new fly ash based manufacturing plants in areas that are in close proximity to both major demand centers and thermal power plants could be one way of doing so. Fly ash concrete blocks, like cement concrete blocks, are favored by developers and builders of large residential and commercial buildings wherever they are available. In cities like Bangalore, where fly ash based blocks are not produced, the costs of transporting fly ash blocks is uneconomical.

4.2 Production of fly ash concrete blocks

The production of fly ash concrete blocks is similar to that of concrete blocks discussed in Chapter 3. The primary difference between the two is in the use of raw materials where fly ash is used in place of sand. Here too, the blocks are typically produced using a semi-mechanized stationary type machine. However, the unit chosen as part of this study has a fully mechanized system which combines compression and vibration. This enables some comparisons between the semi-mechanized and fully mechanized systems in terms of productivity.

The fly ash concrete block unit chosen as a case study is on the outskirts of Nagpur city, Maharashtra, and is located within 10 km of a thermal power plant.

The annual production of this unit is equivalent to 14,640,000 blocks of 230 mm x 115 mm x 75 mm size. Other block sizes are also produced but this is the commonly produced size. The quantity of fly ash, cement and stone dust used to produce one block of this size was estimated to be 0.85 kg (24%), 0.12 kg (4%) and 2.53 kg (72%) respectively. The use of fly ash in the mix requires a smaller proportion of cement compared to the mix used for cement concrete block production. The total water used in the mix and for curing the blocks was estimated to be 15.3 liters. Fly ash and stone dust are transported to the unit from a distance of about 10 km and 40 km respectively. The quantities of raw materials mixed are adequately controlled resulting in uniform compressive strengths that do not vary by batch of mixes.

Figure 2: Fully mechanized fly ash concrete block making unit

Electricity is primarily used in the production process to operate the equipment. About 238,000 kWh of electricity are used annually (14 kWh/1000 blocks). Since the electricity supply for the unit is through an independent feeder, the unit does not experience any power outages and does not use any back-up diesel generator. Diesel used at the plant is for the operation of a fork lift for stacking pallets of raw blocks at the stocking yard. About 5000 liters of diesel are used annually at the plant.

Figure 3: Curing of fly ash concrete blocks

The unit employs 10 persons in each of two shifts and operates throughout the year. The final product is transported on average over a distance of 40 km to the end user. A summary of raw materials, water, embodied energy (including transportation), and productivity for each block is provided in **Table 4** below:

Table 4: Fly ash concrete blocks - Raw materials, embodied energy & production productivity

	Fly ash concrete block
Weight of block (kg)	3.50
Size of block (mm)	230 x 115 x 75
Raw materials	
Fly ash (%)	24
Cement (%)	4
Stone dust (%)	72
Water (including curing) (l/block)	15.3
Embodied Energy[11]	
Total (MJ/block)	1.51
Excluding transportation (MJ/block)	0.66
Production productivity (person-hours/block)	0.003

4.3 Wall assembly

A 230 mm x 115 mm x 75 mm block size with a compressive strength of 3.5 MPa can be used to construct a load bearing wall of two stories using English bond or Rat-Trap bond. The wall thickness using this size of brick would be 230 mm excluding plaster thickness. A non-load bearing wall of 115 mm wall thickness excluding plaster thickness can be constructed with blocks of the same size.

[11] Energy content of diesel = 35.74 MJ/l; energy content of grid electricity = 9.28 MJ/kWh; and energy content of cement = 4.20 MJ/kg

The number of blocks required to construct one square meter of load bearing and non-load bearing walls with fly ash concrete blocks is given in **Table 5**. The estimated quantities of raw material, embodied energy, U-value, emissions, productivity, and cost for one square meter of these walls are provided in **Annexures 3-7**.

Table 5: Fly ash concrete block wall assembly

	Load bearing (English bond)	**Load bearing (Rat-Trap bond)**	**Non-load bearing**
Block size (mm)	230 x 115 x 75	230 x 115 x 75	230 x 115 x 75
Wall thickness (mm)[12]	230	230	115
Blocks/m^2	98.0	68.6	49.0

[12] Excluding plaster thickness

Chapter 5: Fly ash-Lime-Gypsum (FaL-G) Blocks

5.1 Overview

Fly ash reacts with lime in the presence of moisture at ordinary temperature to form a compound possessing cementitious properties. This reaction between lime and fly ash results in the formation of calcium silicate hydrates (CSH) which impart high strength to the material. Blocks made by mixing lime and fly ash are, therefore, chemically bonded bricks. In the case of fly ash-lime-gypsum (FaL-G) mixes, the early strengths are imparted by calcium alumina-sulphate hydrates (CASH) supplemented by CSH for late-age and ultimate strengths. The production of FaL-G blocks does not involve any sintering process.

Several clusters of FaL-G units have emerged in close proximity to thermal power plants in several states. There are an estimated 1200 units across the country with a production capacity ranging from 2.0-6.0 million FaL-G bricks annually. This material has been seen as an alternative to fired clay bricks due to similar size. Its use has grown mainly in small residential construction due to its lower cost. Its use in large scale construction projects has been limited due to its smaller size.

5.2 Production of FaL-G blocks

Fly ash, lime, sand and gypsum are manually fed into a pan mixer where water is added in the required proportion for intimate mixing. The mixture is then compacted into blocks under vibration or hydraulic compression depending on the equipment used. The pressed blocks are moved to an open area where they are dried and water cured for 10-14 days.

The FaL-G block unit chosen as a case study is adjacent to the fly ash concrete block unit on the outskirts of Nagpur city, Maharashtra, discussed in Chapter 4. This unit has a mechanized system for mixing and hydraulic compression for compaction of blocks.

Figure 4: FaL-G block production unit

The annual production of this unit is equivalent to 3,750,000 blocks of 230 mm x 115 mm x 75 mm size. The quantity of fly ash, sand, and lime used to produce one block of this size was estimated to be 0.93 kg (33%), 1.40 kg (50%) and 0.47 kg (17%) respectively. The quantity of gypsum added is very small (less than 1%). The total water used in the mix and for curing the blocks was estimated to be 15.5 liters. Fly ash and sand are transported to the unit from a distance of about 10 km and 15 km respectively. Lime is sourced from a distance of 250 km. The quantities of raw materials mixed were observed to not be adequately controlled which could result in non-uniform compressive strengths that vary by batch of mixes.

Figure 5: FaL-G blocks stacked for curing

Electricity is primarily used in the production process to operate the equipment. About 119,000 kWh of electricity are used annually (7.0 kWh/1000 blocks). The electricity supply for this unit is also through an independent feeder obviating the need for on-site back-up power supply. Diesel used at the plant is for the operation of a fork lift for stacking pallets of raw blocks at the stocking yard and about 5000 liters of diesel are used annually at the plant.

The unit employs 15 persons in each of two shifts and operates throughout the year. The final product is transported on average over a distance of 40 km to the end user. A summary of raw materials, water, embodied energy (including transportation), and productivity for each block is provided in **Table 6** below:

Table 6: FaL-G blocks - Raw materials, embodied energy & production productivity

	FaL-G block
Weight of block (kg)	2.80
Size of block (mm)	230 x 115 x 75
Raw materials	
Fly ash (%)	33
Sand (%)	50
Lime (%)	17
Water (including curing) (l/block)	15.5
Embodied Energy[13]	
Total (MJ/block)	3.92
Excluding transportation (MJ/block)	3.15

[13] Energy content of diesel = 35.74 MJ/l; energy content of grid electricity = 9.28 MJ/kWh; and energy content of lime = 6.5 MJ/kg

Production productivity (person-hours/block)	0.02

5.3 Wall assembly

The size of FaL-G blocks produced in this unit can be used to construct a load bearing wall of two stories using English bond or Rat-Trap bond. The wall thickness using this size of brick would be 230 mm excluding plaster thickness. A non-load bearing wall of 115 mm wall thickness excluding plaster thickness can be constructed with blocks of the same size.

The number of blocks required to construct one square meter of load bearing and non-load bearing walls with FaL-G blocks is as for similar sized fly ash concrete blocks given in **Table 5**. The estimated quantities of raw material, embodied energy, U-value, emissions, productivity, and cost for one square meter of these walls are provided in **Annexures 3-7**.

Chapter 6: Autoclaved Aerated Concrete Blocks

6.1 Overview

Aerated concrete is produced by mixing finely powdered quartz (about 50% by weight) with lime, gypsum, cement, and water, along with a small proportion (about 0.1%) of aluminum powder, which reacts to release hydrogen (Berge, 2009). Fly ash can replace some of the lime. When the substance is almost stiff, it is cut into blocks and slabs that are hardened in an autoclave at 180°C. Prefabricated slabs are usually reinforced with steel. Autoclaved Aerated Concrete (AAC) is effectively low density concrete (about 500 kg/m^3) with closed air pockets and is the only commercial pure mineral block with good structural properties combined with high thermal insulation value. Aerated concrete normally has good moisture regulating properties and does not have any negative effects on the indoor climate.

AAC blocks have been manufactured in India since the 1980s but the high costs have been a major barrier for their adoption. More recently however, the superior thermal performance of these blocks in terms of its high insulation property has seen the blocks gaining in popularity – large scale developments with high energy efficiency targets with the objective of achieving a higher rating under LEED or GRIHA building rating systems[14] have been the driving force behind this. The blocks have also been used for high rise residential buildings, including high rise housing for low-income households, where the savings resulting from reduced concrete and steel in the structure offset the incremental costs of using this higher cost material. The added benefit of using AAC blocks is the savings in mortar and faster construction due to the large size of blocks.

6.2 Production of AAC blocks

AAC blocks are typically manufactured in large scale plants requiring heavy investment. The blocks are produced in a highly controlled mechanized environment and are regular shaped, uniform, high performance masonry units. Blocks typically manufactured are available in sizes of 650 mm x 240 mm and in widths of 75 mm, 100 mm, 125 mm, 150 mm and 200 mm.

An AAC block unit in Pune, Maharashtra, was chosen as a case study. The annual production of this unit is equivalent to 11,500,000 blocks of 650 mm x 240 mm x 200 mm size. The main raw materials used in the production process are fly ash, cement and sand, along with small quantities of other additives such as aluminum. A block of 650 mm x 240 mm x 200 mm requires 9.57 kg (61%) of fly ash, 4.78 kg (31%) of cement and 1.25 kg (8%) of sand. Fly ash and sand are sourced from a distance of 200 km. The large distances over which raw materials are sourced is one of the main reasons for the high costs of AAC masonry units.

The raw materials are mixed with water to form a slurry. A small quantity of aluminum powder is added, careful regulation of which gives accurate control over the density of the final product. Large moulds (about 3.0 m x 1.5 m x 1.0 m) are partly filled with the slurry which then expands in a controlled reaction to fill the moulds. The expansion is due to the hydrogen gas released by the reaction between the aluminum powder and the alkaline slurry. When the mass has sufficiently hardened, the moulds are removed and the block is wire cut into standard rectangular units. The units are then placed in an autoclave for steam curing at high temperature and pressure. The total water used in the mix and for steam curing each block was estimated to be 8.0 liters. The chemical reactions that produce the final calcium silicate hydrate take place in the autoclave. The units are ready for use on site as soon as they have cooled to ambient temperature and milled to profile as necessary.

[14] The Leadership in Energy and Environmental Design (LEED) and Green Rating for Integrated Habitat Assessment (GRIHA) are the two most popular building rating systems in India

Figure 6: Autoclaves in the AAC block plant

The manufacturing of AAC blocks is subject to a tight quality and process control. All raw materials are thoroughly tested at the plant laboratory before entering the warehouse and the final products have very little variation in dimensions or other characteristics.

The equipment and machinery for mixing, lifting, and cutting in the plant is mainly electrically operated. On average, 15.0 kWh of electricity is used to produce 1.0 m^3 of finished product. Steam for the autoclave is generated using boilers with furnace oil as fuel. About 10.0 kg of furnace oil is used to produce 1.0 m^3 of finished product.

The unit employs 225 at the plant persons in three shifts and operates throughout the year. In addition, about 110 staff is employed for administration and other functions. The final product is transported on average over a distance of 300 km to the end user. A summary of raw materials, water, embodied energy (including transportation), and productivity for each block is provided in **Table 7** below:

Table 7: AAC blocks - Raw materials, embodied energy & production productivity

	AAC block
Weight of block (kg)	15.60
Size of block (mm)	650 x 240 x 200
Raw materials	
Fly ash (%)	61
Cement (%)	31
Sand (%)	8
Water (including curing) (l/block)	8.0
Embodied Energy[15]	
Total (MJ/block)	62.28
Excluding transportation (MJ/block)	37.62
Production productivity (person-hours/block)	0.058

6.3 Wall assembly

The sizes of blocks produced at the plant are as indicated in **Section 6.1**. A 650 mm x 240 mm x 200 mm block size with a compressive strength of 3.5 MPa can be used to construct a load bearing wall of two stories. The wall thickness of this wall would be 200 mm excluding plaster thickness. A non-load bearing

[15] Energy content of furnace oil = 42.25 MJ/l; energy content of grid electricity = 9.28 MJ/kWh; and energy content of cement = 4.20 MJ/kg

wall of 100 mm thickness excluding plaster thickness can be constructed with blocks of size 650 mm x 240 mm x 100 mm. Since these blocks are significantly larger in size compared to burnt bricks, fewer number of mortar joints are required for unit wall area.

The number of blocks required to construct one square meter of load bearing and non-load bearing walls with AAC blocks is given in **Table 8**. The estimated quantities of raw material, embodied energy, U-value, emissions, productivity, and cost for one square meter of these walls are provided in **Annexures 3-7**.

Table 8: AAC block wall assembly

	Load bearing	**Non-load bearing**
Block size (mm)	650 x 240 x 200	650 x 240 x 100
Wall thickness (mm)[16]	200	100
Blocks/m^2	6.1	6.1

[16] Excluding plaster thickness

Chapter 7: Cement Stabilized Soil Blocks

7.1 Overview of technology and block production

Earth has widely been used as a material for building with significant variations resulting from topography and climatic differences. The common methods used for earth construction are cob, wattle and daub, rammed earth, and adobe. Earth based construction has several limitations such as water penetration, erosion at lower levels due to splashing of water and attack by termites. Cement Stabilized Soil Blocks (CSSB) overcomes these limitations by an increase in block density through compaction using a mechanical press. The strength obtained at the optimum moisture content is stabilized by using an additive such as cement or lime in the mixture. The water content required in the soil is low for compaction as compared to puddle clay required for mud bricks, which ensures much greater dimensional stability.

CSSBs are dense solid blocks produced by compacting a mixture of soil, sand, stabilizer (cement/lime) and water using a machine. The blocks are cured for 21 days before being used for wall construction. Typical block sizes of 305 × 143 × 100 mm and 230 × 190 × 100 mm are produced using a soil compaction press (Reddy, 2004). The compressive strength of the block greatly depends upon the soil composition, density of the block and percentage of stabilizer (cement/lime). Therefore, careful consideration of clay-sand percentages in soil is required to ensure adequate block strength. Cement content of 6-7% cement and clay content of about 15% can yield blocks having wet compressive strength of 3.0 MPa, sufficient for two storied buildings (Jagadish et al, 2007). Higher strength for the block can be obtained by increasing the quantity of stabilizer.

CSSBs are economical and easy to manufacture locally and have been produced in certain areas using soil excavated at the construction site. Their use in India has been more popular for small scale construction projects with blocks being produced using a manual press. Although motorized hydraulic presses are available, their use has been limited in India. Since CSSBs are produced at site and there is no production unit in India, information on production was obtained from literature and discussions with practitioners of this technology. CSSBs have been used predominantly in small scale residential construction and in regions such as Karnataka, Pondicherry, Gujarat, Haryana and West Bengal, where research and dissemination activities have been concentrated. Although this form of construction is economical, the production of blocks requires technical expertise to assess soil characteristics and the appropriate mix of cement. This has been a barrier for its adoption. The perceptions of this material having a very small quantity of cement and thus not having adequate strength have also been impediments.

The process of producing CSSBs first involves sieving soil and mixing sand or quarry dust to achieve the correct clay-sand percentages. Cement and/or lime is then added and mixed with water to obtain optimum moisture content. The correct amount of soil is weighed and compacted in a press. The block is then stacked and cured before being used for construction. A block of 305 mm x 143 mm x 100 mm requires 1.52 kg (17%) of clay, 0.54 kg (6%) of cement, 5.81 kg (65%) of sand and 1.07 kg (12%) of silt.

Where clay and sand are sourced from other locations and not from excavated earth at site, they are transported to the site from an average distance of about 40 km. The quantities of raw materials mixed are carefully controlled and the production of the blocks is supervised to ensure uniform compressive strengths. The total water used in the mix and for curing the blocks was estimated to be 6.0 liters. Since the mixing and moulding processes are manual, electricity or fuel is not used in the production process. About 350 blocks can be produced in a day employing six persons. The blocks are typically produced and used at the construction site and have no transportation requirement for the finished blocks.

A summary of raw materials, water, embodied energy (including transportation), and productivity for each block is provided in **Table 9**:

Table 9: CSSB - Raw materials, embodied energy & production productivity

	CSSB
Weight of block (kg)	8.94
Size of block (mm)	305 x 143 x 100
Raw materials	
Sand (%)	65
Silt (%)	12
Clay (%)	17
Cement (%)	6
Water (including curing) (l/block)	6.0
Embodied Energy[17]	
Total (MJ/block)	3.73
Excluding transportation (MJ/block)	2.25
Production productivity (person-hours/block)	0.206

7.2 Wall assembly

The sizes of blocks typically produced are as indicated in **Section 7.1**. A 230 mm x 190 mm x 100 mm block size with a compressive strength of 3.5 MPa can be used to construct a load bearing wall of two stories. The wall thickness of this wall would be 230 mm excluding plaster thickness. A non-load bearing wall of 100 mm thickness excluding plaster thickness can be constructed with blocks of size 305 mm x 143 mm x 100 mm. Since these blocks are significantly larger in size compared to burnt bricks, fewer number of mortar joints are required for unit wall area.

The number of blocks required to construct one square meter of load bearing and non-load bearing CSSB walls is given in **Table 10** The estimated quantities of raw material, embodied energy, U-value, emissions, productivity, and cost for one square meter of these walls are provided in **Annexures 3-7**.

Table 10: CSSB wall assembly

	Load bearing	Non-load bearing
Block size (mm)	230 x 190 x 100	305 x 143 x 100
Wall thickness (mm)[18]	230	100
Blocks/m^2	45.9	20.8

[17] Energy content of cement = 4.20 MJ/kg
[18] Excluding plaster thickness

Chapter 8: Fired bricks

8.1 Overview

Fired clay bricks are one of the most important building materials used in India and the country is the second largest producer of bricks, representing over 10% of global production. There is no reliable inventory of brick kilns or of brick production in the country and estimates vary significantly by organizations reporting these numbers. Singh and Asgher (2005) have reported an estimated 100,000 operating units producing about 140 billion bricks annually in India while a more recent Central Pollution Control Board estimate reports 150,000 brick kilns operating in the country in 2008. Coal is the main fuel used for firing bricks. The annual consumption of coal in brick kilns is estimated to be around 25 million tonnes.

The majority of brick production takes place in the unorganized, small-scale/micro sector. Brick making in India is a traditional, unorganized industry generally confined to the rural and peri-urban areas. A major proportion of bricks are made using very basic tools and techniques. Primitive brick kilns have been recognized as having large environmental, health, and a range of social problems. Historically, fired clay brick has been the material of choice for small residential construction in rural and urban areas and is expected to remain the primary choice even for the next two decades. More recently however, the availability of good quality bricks has been on the decline and demand has been growing due to increasing construction activity. The perception among end users on alternate walling material is also gradually changing and masonry material such as concrete blocks is gaining acceptance. Although brick manufacturers face several barriers in labor and input costs, and alternate material have been gradually filling the demand gap and entering the mainstream, bricks are still expected to dominate the walling material landscape over the next two decades.

The brick industry in the Gangetic plain differs from the brick industry in peninsular and coastal India. The Gangetic plains of North India account for about 65% of total brick production. Punjab, Haryana, Uttar Pradesh, Bihar and West Bengal are the major brick producing states in this region. Brick kilns, generally of medium and large production capacities (2–10 million bricks per year), are located in clusters around major towns and cities (Singh and Asgher, 2005). The availability of good fertile alluvium soils in north India has caused the fringe areas of cities in this region to be dotted with brick kilns and consequently is a significant force in bringing about land use/ landcover changes around cities. Peninsular and coastal India accounts for the remaining 35% of the brick production. In this region bricks are produced in numerous small units (production capacities generally range from 0.1 to 3 million bricks per year). Gujarat, Orissa, Madhya Pradesh, Maharashtra and Tamil Nadu are important brick producing states in the peninsular plateau and coastal India. Apart from coal, a variety of biomass fuels such as firewood, dry dung, rice husk are used for firing bricks.

8.2 Brick production

The primary material used in the production of bricks is clay. Argillaceous materials used are mixed well with sand to improve the workability. Clay is relatively easy to extract as it does not usually lie too deep in the ground. After the top soil has been removed and the clay extracted, it is sieved, blended and mixed well with water, either manually or with mechanical mixers. The forming of bricks with the prepared clay is done manually or by moulding machines.

Hand moulding is done a four sided mould using a soft mud process where soil with high moisture content is used to facilitate easier pressing. The moulding is done on level ground and the wet brick is sun dried. A five sided mould is used to shape a relatively stiffer mud into a brick. The wet brick is released onto a level platform by turning the brick upside down. These bricks generally have a frog on one of the faces. Wire cut bricks are produced by a mechanized operation. The selected soil is plugged adequately and then extruded into a continuous slab of clay. This slab is then sliced by a wire frame into a number of bricks.

The green bricks are stacked and allowed to dry in a covered area until the moisture content is reduced to about 2%. This generally is a natural drying process. When clay is heated up to boiling point the water in the pores evaporates, and at 200–300 °C the hydrate water evaporates. After this change, the clay will not revert to soft clay with the addition of water, unlike an air-dried earth block.

In India, the Bull's Trench Kiln (BTK) accounts for around 70% of brick production and is prevalent in the Indo-Gangetic plains as well as in certain pockets around the country. Clamps are temporary firing structures adopted to manufacture bricks on a small scale and used widely all over peninsular India. Down-draught kilns, Vertical Shaft Brick Kilns (VSBK), Hoffmann kilns, and zig-zag kilns are some of the other types of kilns used but make up less than 5% of all kilns in the country. The energy and environmental performance of different types of kiln technologies using different types of fuels was monitored in the second component of this study. Seven kilns across India and one tunnel kiln in Vietnam have been assessed. These kilns all use clay (99.5% with 0.5% sand) as the raw material to produce bricks. A more detailed description of these kilns is provided in the 'Cleaner Brick Industry for India' study report. A summary of water, embodied energy (including transportation), and productivity for bricks produced in these kilns is provided in **Table 11** below:

Table 11: Fired clay bricks[19] – Water, embodied energy & production productivity

	K1	K2	K3	K4	K5	K6	K7	K8
Weight of brick (kg)	2.79	2.74	2.81	2.91	3.67	3.34	3.21	1.66
Size of brick (mm)	230 x 115 x 75	230 x 115 x 75	230 x 115 x 75	230 x 115 x 75	255 x 125 x 75	242 x 120 x 75	230 x 115 x 75	210 x 95 x 54
Annual production (million)	5.0	8.8	4.5	5.7	1.0	3.0	2.5	25.0
Water (l/brick)	0.30	0.27	0.28	0.18	0.37	0.14	0.18	0.35
Kiln type	BTK	Zigzag Natural Draft	Zigzag Fixed Draft	BTK	VSBK	BTK	Down draft	Tunnel
Location	Hapur	Varanasi	Varanasi	Ludhiana	Arah	Arah	Malur	Vietnam
Fuel used	Mixed	Coal	Coal	Coal	Coal	Coal	Biomass	Coal
Embodied Energy								
Total (MJ/brick)	5.32	4.54	4.15	4.56	5.13	5.17	10.82	3.21
Excluding transportation (MJ/brick)	4.07	3.32	2.89	3.26	3.49	3.67	9.34	2.47
Production productivity (person-hours/brick)	0.042	0.040	0.046	0.037	0.096	0.058	0.060	0.012

In addition to these kilns, a fly ash based fired brick unit in Akola, Maharashtra, was also selected as a case study to assess the relative environmental performance when fly ash is used in the clay mix. This is a large scale unit with three BTKs operating together. The annual production of this unit is equivalent to 17,600,000 bricks of 230 mm x 115 mm x 75 mm size. The bricks have a fly ash content of 30%. The fly ash is sourced from a thermal power plant located about 10 km away. Clay is also sourced from a river about 10 km away from the plant.

The unit uses partial mechanization for clay mixing. Electricity used in this process is about 20,000 kWh over the four month moulding period. Diesel used at the plant is for the operation of earth moving equipment and loaders. About 500 liters of diesel are used every day at the plant during the moulding process.

The unit employs about 500 persons during the production period. Since the operation of the kiln is only for a six month period in a year, a majority of the workers are seasonal, and usually migrant labor from other States in India. The final product is transported on average over large distances of about 250 km to the end user. A summary of raw materials, water, embodied energy (including transportation), and productivity for each block is provided in **Table 12.**

[19] Please refer to 'Cleaner Brick Industry for India' study report for more details

Table 12: Fired clay fly ash bricks - Raw materials, embodied energy & production productivity

	Fired clay fly ash brick
Weight of block (kg)	2.60
Size of block (mm)	230 x 115 x 75
Raw materials	
Fly ash (%)	30
Clay (%)	70
Water (l/block)	0.65
Embodied Energy[20]	
Total (MJ/block)	5.01
Excluding transportation (MJ/block)	3.09
Production productivity (person-hours/block)	0.037

8.3 Wall assembly

The size of fired clay bricks and the fly ash clay bricks (230 mm x 115 mm x 75 mm) can be used to construct a load bearing wall of two stories using English bond or Rat-Trap bond. The wall thickness using this size of brick would be 230 mm excluding plaster thickness. A non-load bearing wall of 115 mm wall thickness excluding plaster thickness can be constructed with blocks of the same size. The number of bricks required to construct one square meter of load bearing and non-load bearing walls with fired clay (and fly ash clay) bricks is as for similar sized fly ash concrete blocks given in **Table 5**. The estimated quantities of raw material, embodied energy, U-value, emissions, productivity, and cost for one square meter of these walls are provided in **Annexures 3-7**. For brick sizes produced in K5, K6 and K8, the estimated quantity of cement, sand and water (excluding) curing required in mortar and plaster to construct one square meter of wall have factored in the different sizes.

[20] Energy content of diesel = 35.74 MJ/l; energy content of grid electricity = 9.28 MJ/kWh

Chapter 9: Comparative Assessment of Walling Systems

9.1 Raw materials and water

The raw materials required to produce blocks in one square meter of wall as well as the raw materials required for the mortar and plaster (cement and sand) to construct the wall for each material discussed in the previous chapters have been estimated. Weights have been assigned to each raw material as described in Section 2.5 to arrive at a Raw Material Index (RMI). The Index has been normalized for each wall assembly using the mean and the standard deviation for the load bearing (including for Rat-trap bond construction) and non-load bearing groups separately. The normalized RMI is a relative measure of the raw material impact. Since the index has been normalized with respect to the mean and the standard deviation of the group, a negative value for a wall assembly would indicate that the raw material impact of that wall assembly is lower than the mean for the group. The wall assembly with the lowest normalized RMI would therefore have a lower environmental impact compared to a wall assembly with a higher value when raw material alone is considered. A summary of raw materials for each wall assembly, the RMI and the normalized RMI are provided in **Annexure 3**. The normalized RMIs for plastered load bearing and non-load bearing wall assemblies are presented in **Figures 7 and 8**. AAC walls, fly ash concrete walls followed by concrete blocks have the least raw material impact among all walls compared.

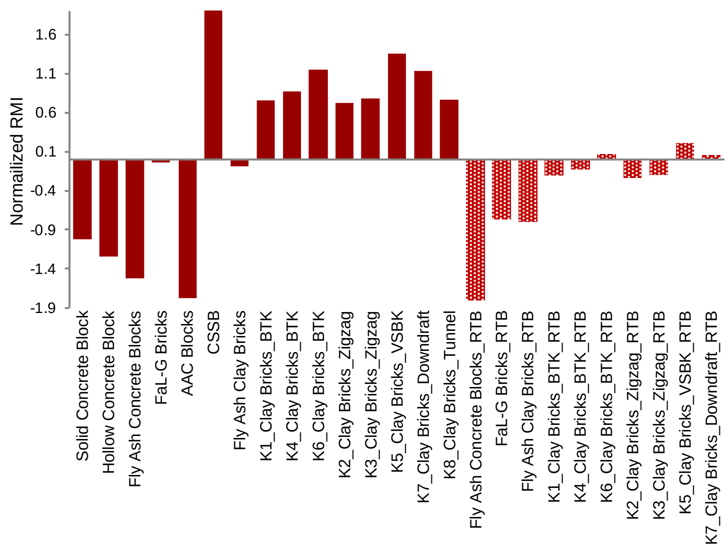

Figure 7: Normalized Raw Material Index for load bearing wall assemblies

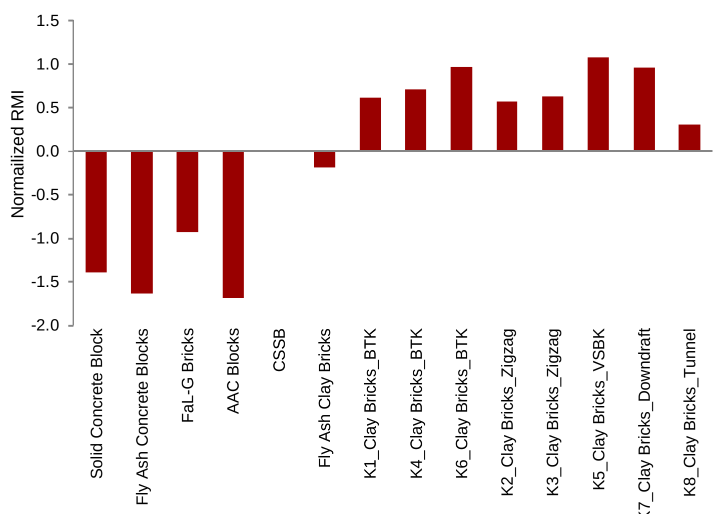

Figure 8: Normalized Raw Material Index for non-load bearing wall assemblies

The estimated quantity of water required for production of blocks and for construction of one square meter of wall is provided in **Annexure 4**. The normalized values are also provided in the table. The normalized water scores for plastered load bearing and non-load bearing wall assemblies are presented in **Figures 9 and 10**. Clay fired bricks and AAC blocks perform better than other cement based wall assemblies – cement based products require water for curing blocks.

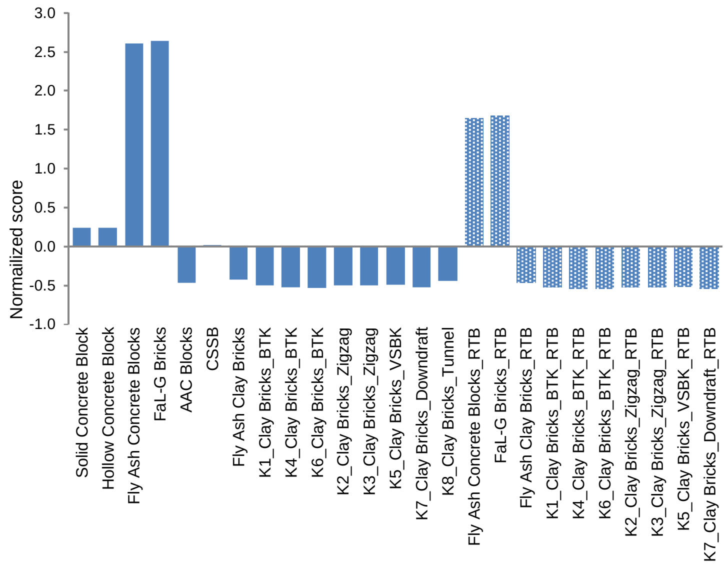

Figure 9: Normalized water score for load bearing wall assemblies

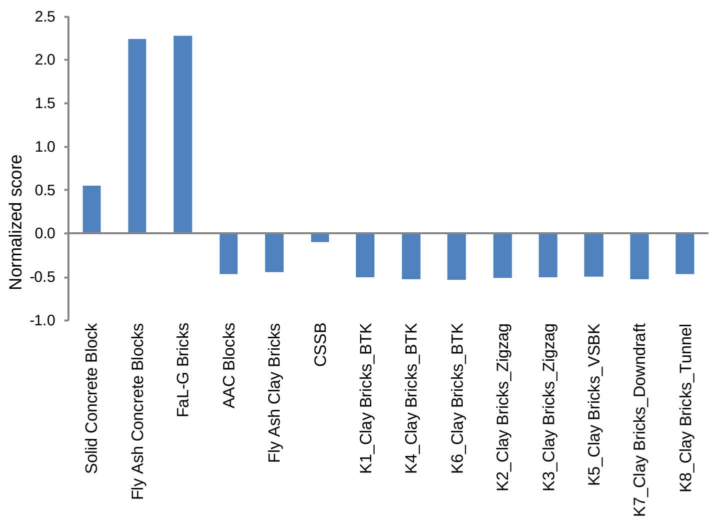

Figure 10: Normalized water score for non-load bearing wall assemblies

9.2 Energy

Embodied energy content in one square meter of wall has been estimated separately for block production, the transportation of raw materials and the finished product to the construction site, the energy content of mortar and plaster, and the transportation component of cement to the construction site. These are presented in **Annexure 5**. The total embodied energy including the transportation component for plastered wall assemblies and the normalized scores are also provided in the table. The U-value of each wall assembly, which is representative of the operational energy impact, is listed along with its normalized score in the table.

The normalized embodied energy scores and the normalized operational energy scores for plastered load bearing and non-load bearing wall assemblies are presented in **Figures 11-14**. As expected, wall assemblies with materials that are not fired, including AAC block wall assemblies, have a lower embodied energy content (average of 464 MJ/m^2 for plastered load bearing walls) compared to fired materials (702 MJ/m^2 for the same category of wall). However, when Rat-trap bond construction is used, the embodied energy content of fired material based wall assemblies is comparable to the non-fired based material assemblies.

The insulation properties of AAC block and FaL-G block wall assemblies are superior to all other assemblies and are reflected in the operational energy scores.

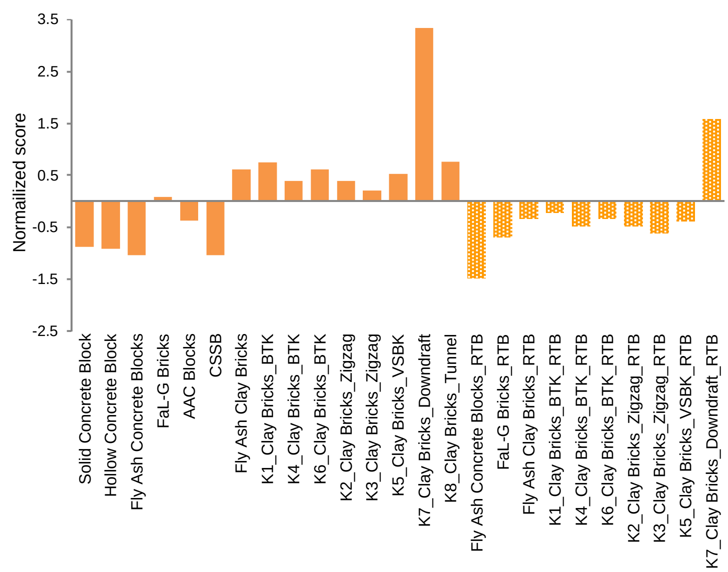

Figure 11: Normalized Embodied Energy score for load bearing wall assemblies

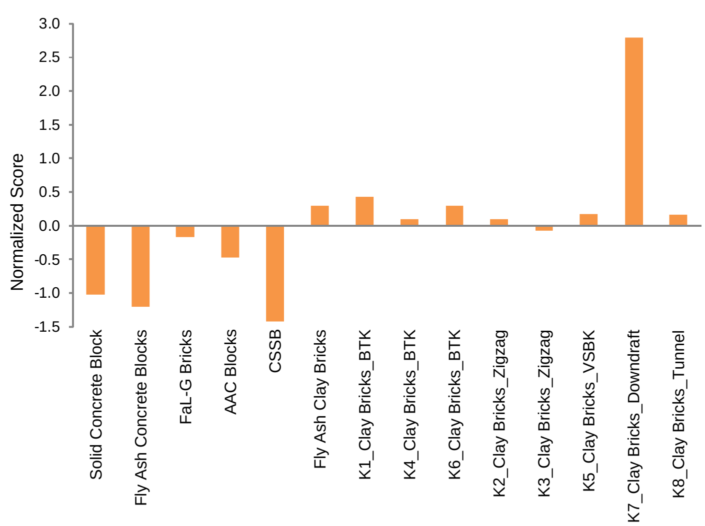

Figure 12: Normalized Embodied Energy score for non-load bearing wall assemblies

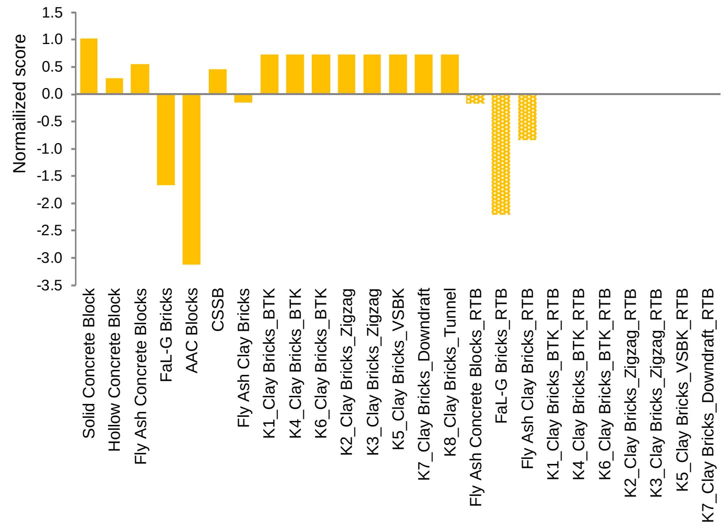

Figure 13: Normalized Operational Energy score for load bearing wall assemblies

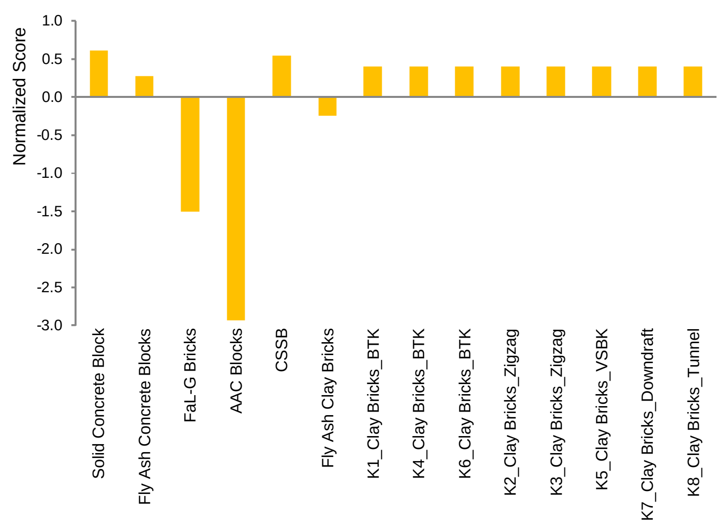

Figure 14: Normalized Operational Energy score for non-load bearing wall assemblies

9.3 Emissions

Emissions resulting from one square meter of wall have been estimated separately for the materials used in the production and in the transportation components. These are presented in **Annexure 6**. The total emissions including the transportation component for plastered wall assemblies are also provided.

Regional pollutants included in this study – PM, NOx and SO_2 – have been grouped together to form a Regional Emissions Index (REI). The REI for plastered wall assemblies and the normalized REI are also provided. CO_2 emissions have been accounted for as a separate global pollutant and the normalized score for CO_2 emissions are also provided.

The normalized REI and normalized CO_2 emission scores for plastered load bearing and non-load bearing wall assemblies are presented in **Figures 15-18**.

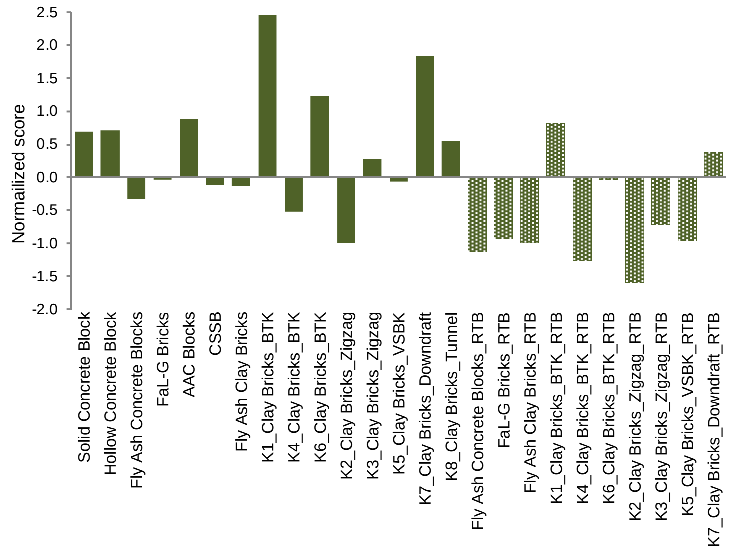

Figure 15: Normalized REI score for load bearing wall assemblies

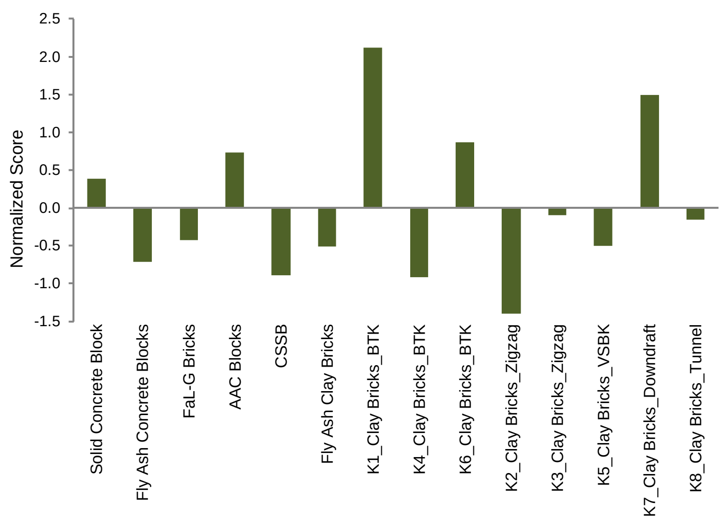

Figure 16: Normalized REI score for non-load bearing wall assemblies

The average REI is 687 g/m^2 for load bearing wall assemblies with non-fired masonry units (346 g/m^2 for non-load bearing plastered walls) and 725 g/m^2 for walls with fired masonry units (371 g/m^2 for non-load bearing plastered walls). A similar trend is observed for CO_2 emissions. The average CO_2 emissions are 68,582 g/m^2 for non-fired load bearing masonry walls (35,350 g/m^2 for non-load bearing plastered walls) and 97,118 g/m^2 for walls with fired masonry units (49,191 g/m^2 for non-load bearing plastered walls).

There are significant variations however, within both these groups as seen in the Figures presented. Fuel based emission factors were used to estimate emissions for non-fired materials whereas monitored results from the second component of this project were used for the fired bricks. This could account for the variations observed.

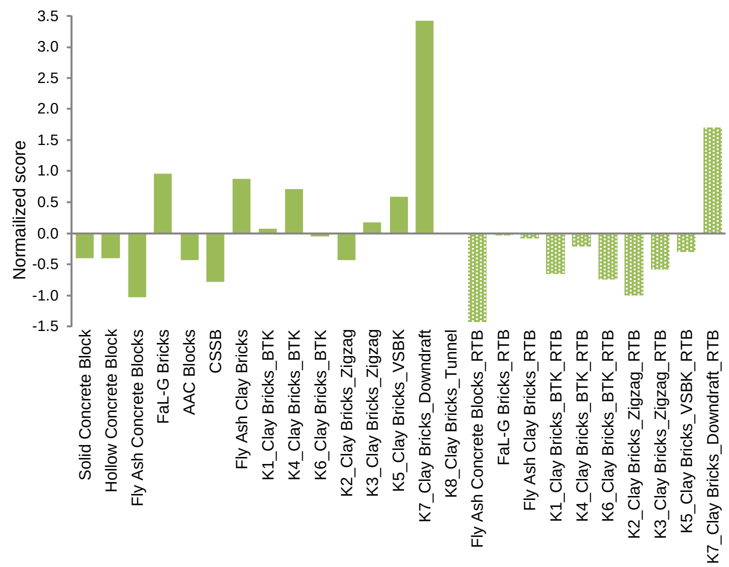

Figure 17: Normalized CO_2 emissions score for load bearing wall assemblies

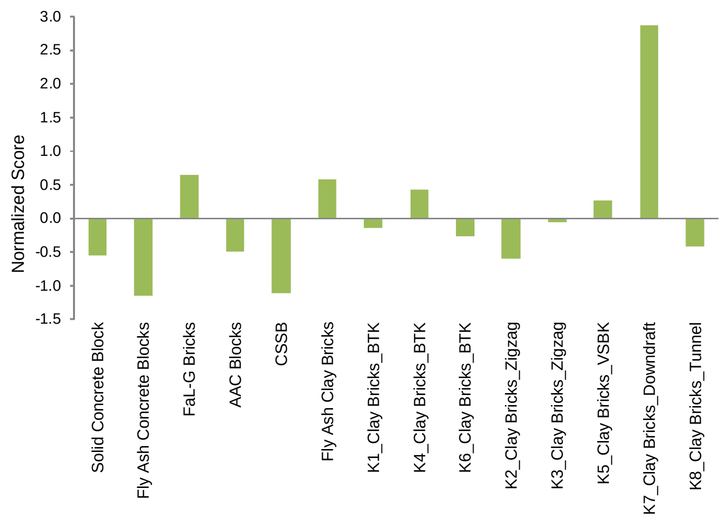

Figure 18: Normalized CO_2 emissions score for non-load bearing wall assemblies

9.4 Productivity and cost

Productivity, measured as the number of person-hours required to produce masonry material required to construct one square meter of wall as well as the number of person-hours required to construct the wall have been estimated and presented in **Annexure 7**. The quality of the masonry units produced has been assessed qualitatively as discussed in Section 2.5. These have been used to weight the production productivity parameter. With greater level of mechanization and larger scale of production, the quality is seen to improve, especially with regard to variation in physical characteristics. The normalized weighted productivity measure is presented for load bearing and non-load bearing walls in **Figures 19 and 20**.

Where mechanization is used, the productivity score is predictably better for these wall assemblies. Larger block sizes also contribute to higher productivity scores.

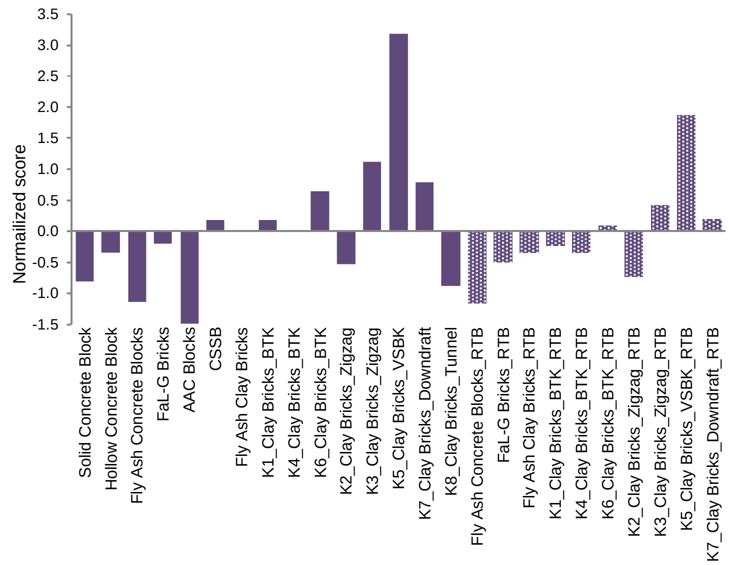

Figure 19: Normalized Productivity score for load bearing wall assemblies

Figure 20: Normalized Productivity score for non-load bearing wall assemblies

The total cost of construction for plastered walls, including the cost of material and labor, is also provided in **Annexure 7** along with the normalized cost score. The normalized cost is presented for load bearing and non-load bearing walls in **Figures 21 and 22**. With respect to cost, CSSB wall assemblies have the lowest cost, the negligible transportation costs for raw material and the low cement content being the main reasons. The larger size of blocks compared to standard fired clay bricks also reduces the mortar quantity and brings down the price of the wall assembly. AAC wall assemblies are the most expensive of all wall assemblies. The large size of AAC blocks reduces the quantity of mortar but the cost of the blocks is very high. One of the reasons for the high cost of AAC blocks is the large distances over which raw material is transported.

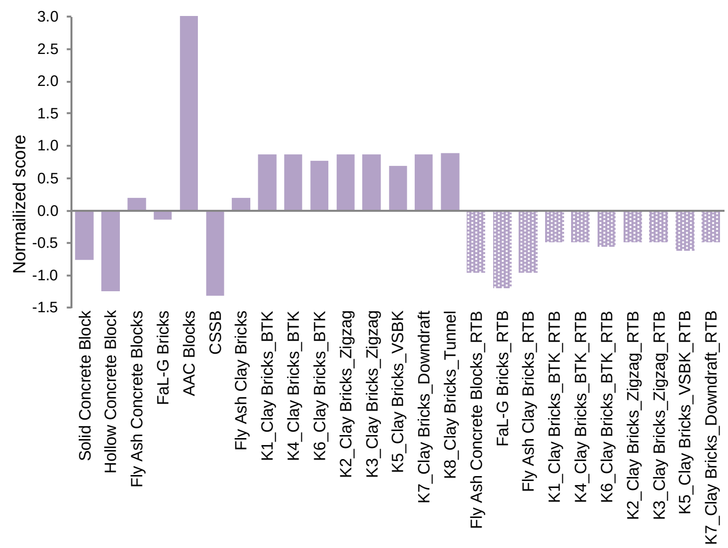

Figure 21: Normalized Cost score for load bearing wall assemblies

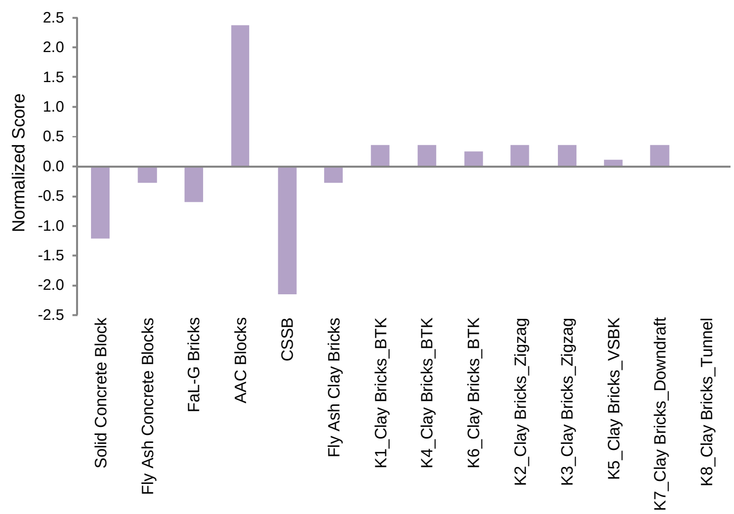

Figure 22: Normalized Cost score for non-load bearing wall assemblies

9.5 Occupational health and safety

The occupational risks and amenities available at production units of different walling material have been assessed using nine sub-parameters as discussed in Section 2.5. These nine parameters have been used to define an OHS Index presented in **Annexure 8**. The normalized OHS Index is presented in **Figure 23** for load bearing walls. Since the OHS Index applies to the production unit and not directly to the wall, the OHS index for non-load bearing walls would be identical for the same material. However, normalized scores would differ due to group size.

In units that operate throughout the year and where the scale of operation is significantly large, the OHS performance is better.

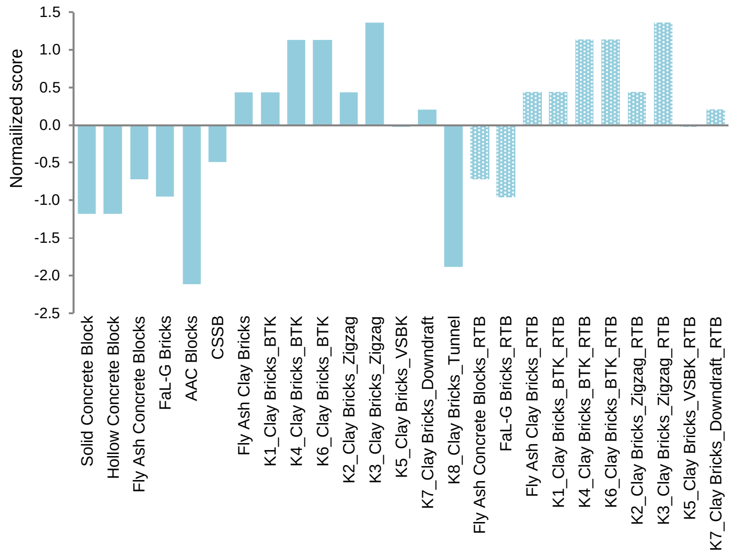

Figure 23: Normalized OHS Index for masonry materials

9.6 Ranking of wall assemblies

The normalized scores for each of the nine parameters discussed in the previous sections have been used to develop a composite Environmental Index for each wall assembly. The composite Environmental Index is the weighted sum of the normalized scores for each parameter as given in Equation 1 in Section 2.3. A weight of 1 has been assigned to all parameters. For environmental emissions, a weight of 0.5 has been assigned to regional (REI) emissions and CO_2 emissions to keep the overall weight for emissions the same as other parameters. Each wall assembly has then been ranked using the composite Environmental Index with the lowest Environmental Index score ranked the highest. The Environmental Indices and ranking for load bearing and non-load bearing wall assemblies are provided in **Tables 13 and 14**.

Wall assemblies that use non-fired products as masonry units are ranked higher compared to fired masonry unit wall assemblies. This is evident from the ranking of non-load bearing wall assemblies presented in **Table 14**. The clay fired masonry wall assemblies, regardless of kiln technology and fuel type, all exhibit poorer environmental performance compared to non-fired masonry wall assemblies. The only exception to this is seen in masonry walls that use clay fired bricks from the tunnel kiln. This wall assembly performs better with respect to most environmental parameters and is comparable to the other non-fired material based wall assemblies.

When Rat-trap bond wall construction is considered, the environmental performance of clay fired brick walls is significantly improved as is seen in **Table 13**.

AAC, CSSB followed by cement concrete blocks are among the masonry materials with the best overall ranking for non-load bearing wall assemblies. For load bearing wall assemblies, this ranking would also hold for the same type of construction (English bond). When Rat-trap bond construction is considered, FaL-G bricks and fly ash concrete blocks outperform AAC block wall assemblies.

Table 13: Composite Environmental Index and Ranking of load bearing plastered wall assemblies

	Normalized Scores									Composite Environmental Index	RANKING
	RMI	Water	Embodied Energy	Operational Energy	REI	CO_2 Emissions	OHS Index	Productivity Index	Cost		
Solid Concrete Block	-1.29	0.24	-0.88	1.02	0.69	-0.40	-1.19	-0.82	-0.76	-3.53	6
Hollow Concrete Block	-1.40	0.24	-0.90	0.29	0.70	-0.40	-1.19	-0.35	-1.25	-4.40	4
Fly Ash Concrete Blocks	-1.55	2.60	-1.04	0.55	-0.33	-1.03	-0.72	-1.14	0.20	-1.78	9
Fal G Bricks	-0.78	2.64	0.09	-1.67	-0.04	0.96	-0.96	-0.20	-0.14	-0.56	12
AAC Blocks	-1.67	-0.46	-0.38	-3.13	0.89	-0.42	-2.11	-1.49	3.04	-5.97	1
CSSB	0.57	0.02	-1.03	0.46	-0.11	-0.78	-0.49	0.19	-1.31	-2.05	8
Fly Ash Clay Bricks	0.02	-0.43	0.61	-0.16	-0.13	0.88	0.44	0.02	0.20	1.06	17
K1_Clay Bricks_BTK	0.89	-0.50	0.75	0.72	2.46	0.08	0.44	0.19	0.87	4.63	21
K4_Clay Bricks_BTK	1.00	-0.52	0.40	0.72	-0.53	0.71	1.13	0.02	0.87	3.71	20
K6_Clay Bricks_BTK	1.28	-0.53	0.60	0.72	1.24	-0.05	1.13	0.64	0.77	5.21	23
K2_Clay Bricks_Zigzag	0.84	-0.50	0.39	0.72	-0.99	-0.43	0.44	-0.53	0.87	1.51	18
K3_Clay Bricks_Zigzag	0.91	-0.50	0.20	0.72	0.27	0.18	1.36	1.11	0.87	4.90	22
K5_Clay Bricks_VSBK	1.46	-0.49	0.53	0.72	-0.07	0.59	-0.03	3.18	0.70	6.34	24
K7_Clay Bricks_Downdraft	1.27	-0.52	3.34	0.72	1.84	3.43	0.20	0.79	0.87	9.31	25
K8_Clay Bricks_Tunnel	0.83	-0.44	0.77	0.72	0.54	-0.02	-1.88	-0.88	0.89	0.26	16
Fly Ash Concrete Blocks_RTB	-1.69	1.65	-1.48	-0.16	-1.13	-1.42	-0.72	-1.16	-0.96	-5.80	2
Fal G Bricks_RTB	-1.16	1.68	-0.69	-2.20	-0.93	-0.03	-0.96	-0.50	-1.19	-5.50	3
Fly Ash Clay Bricks_RTB	-0.60	-0.47	-0.33	-0.83	-0.99	-0.08	0.44	-0.35	-0.96	-3.63	5
K1_Clay Bricks_BTK_RTB	0.01	-0.52	-0.23	0.01	0.82	-0.65	0.44	-0.23	-0.48	-0.92	11
K4_Clay Bricks_BTK_RTB	0.09	-0.54	-0.48	0.01	-1.27	-0.20	1.13	-0.34	-0.48	-1.36	10
K6_Clay Bricks_BTK_RTB	0.28	-0.54	-0.33	0.01	-0.04	-0.73	1.13	0.09	-0.56	-0.31	14
K2_Clay Bricks_Zigzag_RTB	-0.02	-0.52	-0.49	0.01	-1.60	-1.00	0.44	-0.73	-0.48	-3.10	7
K3_Clay Bricks_Zigzag_RTB	0.03	-0.52	-0.61	0.01	-0.71	-0.57	1.36	0.42	-0.48	-0.45	13
K5_Clay Bricks_VSBK_RTB	0.41	-0.51	-0.39	0.01	-0.95	-0.29	-0.03	1.87	-0.61	0.13	15
K7_Clay Bricks_Downdraft_RTB	0.28	-0.54	1.58	0.01	0.38	1.70	0.20	0.20	-0.48	2.29	19

Table 14: Composite Environmental Index and Ranking of non-load bearing plastered wall assemblies

	Normalized Scores									Composite Environmental Index	RANKING
	RMI	Water	Embodied Energy	Operational Energy	REI	CO_2 Emissions	OHS Index	Productivity Index	Cost		
Solid Concrete Block	-1.39	0.55	-1.03	0.61	0.39	-0.55	-0.93	-0.32	-1.21	-3.80	3
Fly Ash Concrete Blocks	-1.63	2.24	-1.20	0.28	-0.71	-1.15	-0.51	-1.05	-0.28	-3.08	4
FaL-G Bricks	-0.93	2.28	-0.17	-1.50	-0.42	0.65	-0.72	-0.24	-0.60	-1.77	6
AAC Blocks	-1.68	-0.47	-0.47	-2.93	0.74	-0.50	-1.77	-1.54	2.38	-6.38	1
CSSB	0.00	-0.10	-1.42	0.55	-0.89	-1.11	-0.30	-0.10	-2.15	-4.51	2
Fly Ash Clay Bricks	-0.19	-0.44	0.30	-0.25	-0.51	0.58	0.54	-0.05	-0.28	-0.33	7
K1_Clay Bricks_BTK	0.61	-0.50	0.43	0.40	2.12	-0.15	0.54	0.10	0.36	2.93	10
K4_Clay Bricks_BTK	0.71	-0.52	0.10	0.40	-0.92	0.42	1.17	-0.05	0.36	1.93	9
K6_Clay Bricks_BTK	0.97	-0.53	0.29	0.40	0.87	-0.26	1.17	0.49	0.26	3.36	12
K2_Clay Bricks_Zigzag	0.57	-0.51	0.10	0.40	-1.39	-0.60	0.54	-0.53	0.36	-0.06	8
K3_Clay Bricks_Zigzag	0.63	-0.51	-0.07	0.40	-0.10	-0.05	1.38	0.90	0.36	3.02	11
K5_Clay Bricks_VSBK	1.07	-0.50	0.17	0.40	-0.51	0.26	0.12	2.62	0.11	3.89	13
K7_Clay Bricks_Downdraft	0.96	-0.52	2.79	0.40	1.49	2.88	0.33	0.62	0.36	7.12	14
K8_Clay Bricks_Tunnel	0.31	-0.46	0.17	0.40	-0.15	-0.42	-1.56	-0.86	-0.02	-2.32	5

Chapter 10: Conclusions and Strategies for Cleaner Walling Material in India

10.1 Summary of findings

The previous chapter has provided the relative impacts of the various wall assemblies on several environmental parameters. The study is based on case studies of production units manufacturing different types of masonry units. These production units are not necessarily representative of all units in the country producing a similar product, which is due to variations in scales of operation, level and type of mechanization adopted, regional variations in availability of raw material, etc. The rankings developed for each type of wall assembly therefore are to be seen within a broader context and are only indicative.

Further, the MCDA framework used in the analysis has an inherent subjectivity built into it and the results of such analysis could vary by changing assigned weights for any parameter. The rankings of wall systems are not very sensitive to the weights due to the fairly large number of parameters in this analysis (**Annexure 10** provides rankings when weights for clay have been reduced to 1 instead of 2, which shows that the overall conclusions do not change). Nonetheless, the findings have been presented for groups of wall systems - clay based wall systems, cement based systems, rat-trap bond systems, etc. – and the rankings of individual wall systems are not emphasized. This overcomes the weakness of MCDA in that the rankings of individual wall systems could change depending on the weights assigned, but when seen as a group, the conclusions remain the same.

Important conclusions drawn from the analysis are summarized below:

Raw materials:

- It is apparent that masonry units with the least clay content have the least raw material impact. Where waste material such as fly ash is used in large quantities, such as in AAC blocks, fly ash concrete blocks and FaL-G blocks, the impact is low. Materials that use stone dust from stone crushing units also have a lower raw material impact.

- Rat-trap bond construction in load bearing walls can reduce the raw material impact significantly. For fired clay bricks and similar sized masonry units such as FaL-G, and even fly ash concrete blocks included in this study, the placement of masonry units in the Rat-trap bond construction creates voids in the wall that result in fewer bricks and mortar being used for the same wall volume. This reduces the total quantity of raw materials needed to produce the wall.

- Density is also an important parameter that influences raw material impact. With lower densities, the quantity of raw materials required reduces as is evident in the very low density of AAC blocks resulting from the aerated nature of the material. The use of mechanized processes to mould bricks can result in higher densities due to higher compaction, which can in turn increase the use of raw materials. However, this can be offset by punching voids in the brick (resource efficient bricks) to reduce the overall block density.

- Size of the masonry unit is also negatively correlated with the RMI, or with increase in block size, the raw material impact is reduced. In this study, a high correlation between RMI and volume of blocks is observed for plastered non-load bearing walls (R = -0.80).

Water:

- Cement based walling materials such as concrete blocks and FaL-G blocks require more water than other materials due to the curing process involved in their production. Clay based walling materials require the least water. Larger block size reduces the quantity of mortar and therefore water in the construction of the wall. This is however, a negligible quantity and is overshadowed by the quantity of water that is used for curing the constructed wall.

- AAC blocks also use cement in the production process and require curing. However, steam curing under high pressure (autoclaving) results in significantly lower water consumption and this reduces the impact on water consumption.

Energy:

- Clay fired bricks have the highest embodied energy (average of 702 MJ/m^2 for plastered load bearing walls) compared to non-fired materials (464 MJ/m^2 for the same category of wall) irrespective of kiln efficiency. The transportation component of embodied energy is significant (22-57%) for all wall assemblies. Among non-fired based wall assemblies, Fal-G walls have the highest embodied energy.

- The thermal performance of non-fired based wall assemblies is also generally superior to those constructed with fired bricks as reflected in the U-values. AAC blocks wall assemblies have the lowest U-value among all wall assemblies due to the porous nature of the material.

Emissions:

- Regional pollutant emissions – PM, NOx and SO_2 - are lower for non-fired materials (average of 687 g/m^2 for plastered load bearing walls) compared to fired clay brick walls (average of 725 g/m^2 for same category of wall). Similar trends are observed for CO_2 emissions (average of 68,582 g/m^2 for non-fired materials and 97,118 g/m^2 for fired materials). The large variations in emissions within each of these groups should however be noted.

Productivity, OHS and cost:

- Fired clay brick production is traditionally a labor intensive process. The use of manual labor for moulding therefore results in significantly lower productivity compared to mechanized processes (e.g., AAC and fly ash concrete block production using mechanized processes have block productivities of 0.18 and 0.17 person-hrs/m^2 respectively for non-load bearing walls compared to about 2.5 person-hrs/m^2 for clay brick production). The highly mechanized tunnel kiln also has a higher productivity (0.84 person-hrs/m^2) but is unable to match the non-fired material productivities.

- Block production productivity (0.17-4.26 person hrs/m^2) is a small component compared to the wall construction productivity (6.53-8.20 person hrs/m^2). Block size also influences construction productivity and a larger block size requires less time and effort for construction.

- Cost of walls with non-fired materials are generally lower than fired products (except for AAC block walls). Brick kiln owners have indicated that rising input costs over the past few years - raw material, labor and fuel – have necessitated an increase in the selling price of bricks and this has resulted in non-fired products becoming more competitively priced. The larger block size of non-fired masonry material also reduces the mortar quantity contributing to lower cost for the wall assembly.

- Poor conditions for labor at brick kiln sites are reflected in a lower OHS index compared to other materials. Units producing non-fired materials are generally located close to large urban areas and do not require labor to live on site during the production period as in the case of fired clay materials.

10.2 Strategies for cleaner walling material in India

The findings of the study presented in the previous section provide some direction for policy makers in India to promote masonry materials that have the least impact on natural resources, energy and water. Strategies that promote more efficient production and improve the conditions of the labor employed are also imperative given the scaling up of production needed to meet the growing demands for building material in the country. The broad strategies towards meeting this end are outlined below:

a) Promoting the use of non-fired masonry materials over fired material

Masonry walls constructed with fired masonry units have a higher embodied energy content compared to walls with non-fired masonry units. Emissions of regional as well as global pollutants are also higher for wall assemblies constructed with fired masonry units. The energy and emissions performance of the wall assembly with non-fired masonry units is thus better than wall assemblies with fired clay masonry units. The impact on natural resources is also high for clay fired bricks compared to non-fired masonry material, even when fly ash is used as a raw material. Typical brick production in India is seasonal with a significant proportion of migrant labor being employed. Housing and sanitation facilities are usually temporary in nature, except for large scale production units, due to the seasonal operations. Although providing employment to a large number of laborers, brick production is typically an informal industry with poor working conditions and inadequate amenities for laborers. Thus, when energy, raw materials, emissions and working conditions are considered, encouraging alternative non-fired masonry materials over fired masonry materials is a strategy that could be adopted. The rankings of wall assemblies presented in the previous chapter support this.

Non-fired masonry materials could be promoted in several ways. Demand for these materials could be created by specifying their use in large-scale government projects as well as by providing incentives for private projects to use these materials. Awareness could be created among various stakeholders on the benefits of using such material as discussed in this report. Finally, institutional support for land and finance could be provided and incentives that encourage entrepreneurship for the production of non-fired masonry material devised at various levels.

If the share of fired clay bricks were to reduce to 70% from a projected business-as-usual scenario of 85.9% in 2030, this could result in 1110 sq km less land from which clay would otherwise be mined[21]. The reductions in CO_2 emissions could be about 16.0 million tonnes over the period upto 2030.

b) Promoting mechanization in production units

In the brick sector, the use of mechanical equipment for moulding has not found much favor among brick manufacturers. Other than in Kerala and in a few instances in North India, moulding machines have not been commercially successful. Several manufacturers that have implemented mechanization as a pilot initiative have discontinued their use for several reasons. In the context of unreliable and intermittent electricity supply in most suburban and rural areas where production units have been established, the operation of diesel based back up power for long durations drives up production costs significantly. One brick manufacturer in Malur, Karnataka, has indicated that though these extruded bricks are of superior quality, their demand has been poor due to their higher cost. Moreover, the preference for plastered wall surfaces, even if not needed when good quality bricks are used, have caused the end user to opt for lower quality bricks at lower cost and then plaster the wall. The lower quality wall serves the purpose of providing adequate compressive strength. Extruded bricks cater to a niche market and are not widely used.

Semi-mechanization is more common in concrete block, CSSB and FaL-G production as also observed in the case studies presented in this report. These units are typically located closer to urban areas where the power situation is relatively better.

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[21] An accurate inventory of production is required for a more reliable estimate of savings presented here.

Brick makers, and indeed all other masonry material production units, today face a severe labor shortage. A certain degree of mechanization results in more efficient production and can overcome labor shortages. The quality of finished products can also be significantly improved through mechanization. However, the issue of power shortages needs to be considered and addressed through possible alternative decentralized renewable sources such as biomass gasification based on-site power generation. In mapping resources and demand as suggested earlier, the renewable energy potential could also be included to address the issue of power availability. Mechanization can result in higher block density due to mechanical compaction, particularly in clay or fly ash based fired bricks. This can be offset through cavities or perforations that can be built into the mechanization process.

The selection of appropriate technology and machinery is also key for the success of mechanizing production processes. The investment capacity and background of the manufacturer, the nature of raw materials, the availability of power and the market potential, should together be considered in selecting appropriate equipment. Thus, awareness and training to masonry unit manufacturers on choosing the best and most appropriate machinery for a particular situation, which is currently lacking, is necessary for mechanization to gain popularity.

The benefits of using better quality masonry units that obviate the need for plastering surfaces needs to be disseminated and awareness created among designers and end users to encourage the use of superior quality extruded bricks. Here too, demand for such material could be increased by specifying their use in large scale government housing projects.

c) Encouraging year round production of masonry units

The brick industry is a seasonal one and results in poor utilization of fixed assets and low profitability. Encouraging a shift to year-round production requires covered drying and firing operations. Chamber dryers that utilize hot flue from the down-stream kiln are a cost-effective option. If required, the kiln flue may be supplemented with hot gases generated by burning agricultural / industrial wastes. Continuous dryers and kilns have very short processing times, which results in more efficient production and greater utilization of assets. Continuous production would also encourage local employment generation and serve as a precursor to improving the working conditions. Lending agencies could consider financing projects on attractive terms to encourage manufacturers to move towards continuous production.

d) Promoting the production and use of larger sized low-density masonry units

Larger sized masonry units clearly reduce the quantity of mortar required to construct walls (Refer to mortar quantities for different wall assemblies provided in **Annexure 3**). However, this increases the block weight making it difficult to handle while laying them. Low-density blocks can overcome this issue and several technologies are available that reduce block density while increasing the volume of the block. The AAC blocks discussed in this report have low densities and are larger in size, therefore requiring the least quantity of raw materials for production as well as mortar for wall construction compared to smaller blocks. Cellular Light weight Concrete (CLC) blocks are similar to AAC blocks and have been produced by using a foaming agent in a mix of fly ash, cement and sand. These blocks are air cured and require less production energy compared to AAC blocks. Promoting the production and use of such larger masonry units of lower density is a potential strategy that could indirectly reduce resource use with corresponding energy and emission benefits.

Research and development on the use of expanded clay, recycled glass, blast furnace slag, and other waste materials in non-fired masonry blocks, could also be promoted with the objectives of developing larger sized low-density blocks for commercial production. Demand for such products could be created by raising awareness among end users, designers and engineers on the benefits of using such material. Alternative materials can also be popularized by specifying their use in large government housing projects. Small units producing such alternative material could also be provided with marketing support.

e) Promoting further use of fly ash in masonry material production

As discussed earlier in Chapter 4, the MoEF has issued notifications for greater fly ash utilization by mandating the use of fly ash in bricks, blocks and tiles by manufacturers located within a 100 km distance of a thermal power plant. Under this notification, construction of buildings within a radius of 100 km of a thermal power plant is required to use fly ash based products in the construction. In addition to these, the Bureau of Indian Standards (BIS), the country's standardization body, has updated Indian Standards on fly ash based Pozzolona Cement specification to use fly ash between 15 and 35% (IS 1489-Part 1: 1991), and also revised the basic design code for plain and reinforced concrete (IS 456: 2000) emphasizing the use of fly ash in concrete. Indian Standards for masonry materials using fly ash have also been developed and published (for e.g., IS 13757: 1993 for burnt clay fly ash building bricks, IS 12894: 1990 for fly ash-lime bricks, IS 4139: 1989 for calcium silicate bricks, IS 3115: 1992 for lime based blocks).

Despite such initiatives, the utilization of fly ash for bricks is only 2% and presents an opportunity for increasing its use and reducing the environmental footprint of masonry materials in India. Increasing fly ash utilization in masonry material production would encourage the development of masonry materials such as fly ash concrete, AAC and FaL-G, which would have similar benefits indicated in 10.2 (a) above. At present, very few thermal power plants have any facility to grade fly ash. Making available fly ash of different grades would encourage the production of fly ash based masonry products by smaller manufacturers since the grading process would ensure consistent quality of fly ash.

A mapping of thermal power plants, availability of other raw material, climatic conditions and demand centers could identify potential areas for establishing fly ash based production units in the country. Other incentives could also be devised and provided for entrepreneurs to establish units near thermal power plants (the Housing and Urban Development Corporation (HUDCO) for instance, has been providing support to building material industries that use fly ash in the form of term loan assistance).

f) Encouraging alternative construction practices

As seen in this study, the use of Rat-trap bond construction can significantly reduce the environmental impact of walling materials through reduced natural resource consumption, lower energy use and emissions, lower water consumption, higher productivity and lower cost. This form of construction improves the ranking of wall assemblies constructed with fired clay bricks surpassing even the rankings of some non-fired based wall assemblies.

The use of this technique is limited in the country for two main reasons - the lack of skills and trained manpower to implement this technique and the lack of awareness among the general public and also among designers and engineers about the benefits of this technique. Extensive awareness campaigns and demonstrations among the public, engineers and designers as well as local government agencies involved in providing approvals for construction are necessary to popularize this construction practice. Government agencies involved in large scale construction are also an important target sector. These techniques should also be included in the curriculum of engineering and architecture schools at the undergraduate and diploma level. Skill upgradation programmes for masons should be conducted across the country to provide a base of skilled manpower that can easily implement such techniques. Research efforts to develop alternative construction practices that reduce the environmental impact of construction are also needed.

If the Rat-trap bond were to be used for even 5% of all brick walls, the fewer bricks required would reduce the land required for clay mining by about 66 sq km and also reduce CO_2 emissions by about 13.5 million tonnes over the period upto 2030.

g) Establishing a quality control mechanism for masonry unit manufacturers

The carefully controlled production process of AAC blocks provides less dimensional variations and greater consistency in physical characteristics that could be lacking in CLC blocks that are produced at site with less control. This raises issues of safety, particularly when such blocks with unreliable or inconsistent compressive strengths are used for load bearing structures. Ensuring consistent dimensional and physical characteristics is therefore crucial when low density blocks are promoted as a strategy. In addition, inconsistent quality can also reduce market demand.

Indian Standards (IS) have been formulated for various working specifications on building materials and techniques and these have been included in the Schedule of Specifications of Central and State government agencies associated with housing and construction. The Building Materials and Technology Promotion Council, under the Ministry of Urban Poverty Alleviation, Government of India, also operates a Performance Appraisal Certification Scheme (PACS). This is a third party operated voluntary scheme for issuing a Performance Appraisal Certificate (PAC) to a manufacturer, supplier or installer of a product to promote the use of new materials, construction systems, machines for production of building elements that are not covered by IS. However, the IS nor the PACS do not ensure that quality standards and specifications are met in the actual production of materials, the lack of regulation in the building materials production sector being the primary cause. A system to certify that building materials produced at a particular unit are of a certain standard is therefore needed. In addition, testing support for small and medium scale production units is necessary. This is especially relevant to small units that produce alternative masonry material such as concrete blocks, FaL-G bricks and other fly ash based products.

10.3 Recommended Action Plan

An Action Plan at the National, State and local levels to facilitate development and production of non-fired masonry materials is delineated below:

National level:

Drafting a building materials policy for India

- The Ministry of Urban Development and Poverty Alleviation could draft a building materials policy that sets targets to increase the production and use of non-fired masonry materials (e.g., from current levels of 8% to 30% by 2030)[22].
- Targets could also be set in the policy to increase fly ash utilization in bricks and block production. Guidelines could be issued by the MoEF/MoP to thermal power plants mandating a fly ash processing facility at thermal power plants near major demand centers to make graded fly ash available to end users. This would provide an impetus for AAC block manufacturers as well as for CLC block making, which require fly ash of a certain grade.
- The policy needs to promote mechanization by providing incentives to manufacturers (e.g., tax benefits for equipment and machinery, financing options, etc.; financing units with proposals for year-round production) and to also encourage further use of fly ash (and other 'waste' material) in masonry materials production.
- Alternate construction techniques such as the Rat-trap bond also need to be promoted under the policy.
- The policy also needs to encourage the development and production of low-density, larger sized masonry units. BMTPC in collaboration with research and academic institutes could play an important role in the development of such masonry units as well as the development of other 'waste' material based masonry blocks of low density and larger size.

Skill upgradation and technical support

- Organizations such as Housing and Urban Development Corporation (HUDCO) could take the lead role in setting up entrepreneurship training and technical support centers for establishment of non-fired masonry industries (and fly ash based masonry block industries) in major demand centers; providing guidance on choosing appropriate machinery and equipment for mechanization; skill upgradation for masons on alternative construction techniques (Rat-trap bond construction).

[22] The actual targets could be set once a reliable inventory of materials production is developed.

Quality control of masonry products

- The Bureau of Indian Standards could be entrusted with the task of establishing a quality control mechanism for masonry unit manufacturers to ensure products adhere to IS.

Creating demand for alternative materials and practices

- Specification of non-fired masonry material (and other proven alternative masonry blocks with low environmental impact) in large building construction projects by the Central Public Works Department (CPWD).
- Specification of unplastered walls for large building projects using better / appropriate quality masonry material.
- Specification of alternative construction techniques (Rat-trap bond) in large building projects.
- Modifying building rating systems such as GRIHA and LEED to provide additional incentives for the use of non-fired masonry material.

State and local level:

Policy

- Identification of regional level strategies and policies based on demand and resources available in that geographical context – (for instance, land budgets could be defined for brick production in each state in order to protect agricultural land using a GIS based decision support system. The same decision support system could be used to prioritize walling material use and production in a particular region; a higher clay mining royalty combined with fly ash transportation subsidies could be explored to encourage greater fly ash utilization in existing brick making units). The Urban Development departments of each state could initiate such action together with other relevant departments such as the Mining Department.
- Earmark land for building materials production near high demand centers. The decision support system could be used by the Department of Industries in each state to identify suitable land that has easy access to demand centers as well as raw material sources; Provide incentives to entrepreneurs for establishment of non-fired masonry materials, e.g., tax benefits for equipment and machinery, financing options, land approvals, etc.
- Ensuring continuous power supply for (semi) mechanized masonry industries.
- Providing incentives for biomass based power generation for (semi) mechanized masonry industries.

Creating demand for alternative materials and practices

- Modifying building byelaws by Urban Local Bodies and Urban Development Agencies to encourage non-fired masonry materials.
- Specification of non-fired masonry material (and other proven alternative masonry blocks with low environmental impact) in large building construction projects. State Public Works Departments could play an instrumental role in this.
- Specification of unplastered walls for large building projects using better / appropriate quality masonry material.
- Specification of alternative construction techniques (Rat-trap bond) in large building projects.

Skill upgradation and technical support

- Awareness creation on benefits of non-fired masonry use among developers and other individual building construction proposers; on exposed masonry using better quality masonry units; and on alternative construction techniques (Rat-trap bond construction). The state level Building Centers or 'Nirmithi Kendras' could also provide such support taking into account local considerations.

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Glossary

Aggregate: Pieces of crushed stone, gravel, etc., used in making concrete

Autoclave: Process involving high temperature and pressure

Block: A larger type of brick not necessarily made of fired clay, but stabilized in some way, sometimes with central cores removed to reduce the weight

Brick: An object (usually of fired clay) used in construction, usually of rectangular shape, whose largest dimension does not exceed 300mm

Bulk Density: Density calculated including any moisture present in the material

Calcination: Thermal treatment process applied to ores and other solid materials to bring about a thermal decomposition, phase transition, or removal of a volatile fraction

Cement: Ordinary Portland Cement (OPC)

Clay: The finest of the particles found in soil, usually of less than 0.002mm in size and which possess significant cohesive properties

Clinker: Lumps, usually 3-25 mm in diameter, produced by sintering limestone and alumino-silicate during the cement kiln stage

Concrete: The finished form of a mixture of cement, sand, aggregate and water

Fines: General category of silts and clays

Frog: A tapered addition to a block mould to create an indentation in the finished block

Gravel: A mixture of rock particles ranging from 2mm to 60 mm in diameter

Green brick: The state of material immediately after forming and before any drying or curing has taken place

Mortar: The sand-cement mix used to join block courses

Sand: A mixture of rock particles ranging from 0.06mm to 2 mm in diameter

Silt: Moderately fine particles of rock from 0.002mm to 0.06mm in size

Soil: Material found on the surface of the earth not bigger than 20mm in size, not including rocks and boulders and predominantly non-organic. If soil is to be used for building material it must not contain any organic material and it can be a natural selection of particles or a mixture of different soils to attain a more suitable particle distribution

Annexure 1: Rat-Trap bond construction

A 'Rat-Trap Bond' is a type of wall brick masonry bond in which bricks are laid on edge as shown in **Figure A** below. A typical English bond construction is also shown in **Figure B**. This provides the wall with an internal cavity.

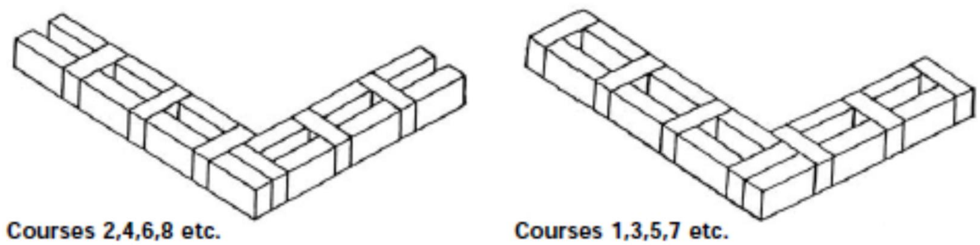

Figure A: One brick thick Rat-Trap bond construction

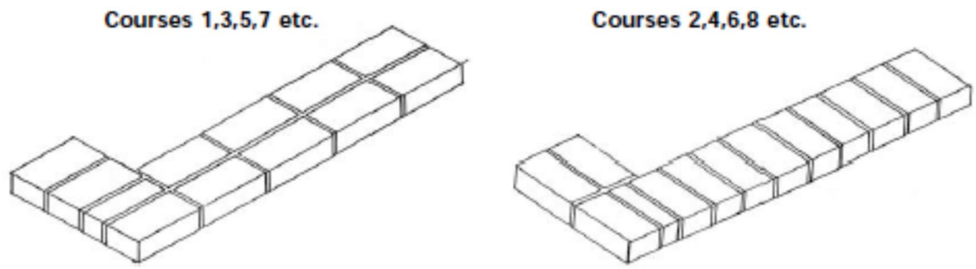

Figure B: One brick thick English bond construction

The Rat-Trap bond was commonly used in England for building houses of fewer than 3 stories up to the turn of the 20th century. However, the brick industry successfully opposed the Rat Trap Bond declaring it a non-load bearing wall bond) and promoted the traditional English and Flemish bond that uses approximately 20% more bricks. The Rat-Trap Bond then entirely disappeared from the construction sector for decades. Mr. Laurie Baker, a British architect, started the trend of cost efficient housing in India by re-introducing the Rat-Trap Bond. The Rat-Trap Bond is a proven and economical walling bond with good insulation properties due to the air cavities.

Source: Muller, Heini. 2004. Basic construction training manual for Trainers. Skat Foundation, St. Gallen, Switzerland. Available online at http://www.skat.ch/publications/prarticle.2005-09-29.1982292338/skatpublication.2005-11-04.1345119202/file

Annexure 2: Emission factors

	Emission Factors				Source
	PM	CO_2	SO_2	NOx	
Stationary combustion					
Diesel (g/l)	4.76	2519.80	4.46	67.76	US EPA: AP 42; Table 3.3-1
Furnace oil (g/l)	2.37	2519.80	4.07	6.60	US EPA: AP 42; Table 1.3-1
Grid Electricity (g/kWh)	21.70	810.00	8.80	3.07	PM, SO_2 and NOx emission factors derived from emissions data for a 500 MW thermal power plant in India[23] and 52.8% contribution of thermal power to grid[24]. CO_2 emission factors obtained from Central Electricity Authority, 2011[25].
Cement (g/kg)	1.20	1000.00	4.90	4.45	Infrastructure Leasing and Financial Services, 2009. Technical EIA Guidance Manual for Cement Industry. Technical report, ILFS, Hyderabad, India.
Lime (g/kg)	0.14	1600.00	2.70	1.60	US EPA: AP42; Table 11.17-1 for PM; US EPA: AP42; Table 11.17-5 for SO_2, NOx and CO_2
Mobile sources					
Diesel Trucks - HMV (g /km)	1.24	762.39	0.00	9.30	Automotive Research Association of India, 2007. Draft report on 'Emission Factor development for Indian Vehicles'. Automotive Research Association of India, Pune. India. Report available online at http://cpcb.nic.in/DRAFTREPORT-on-efdiv.pdf

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25 Ibid.

Annexure 3: Raw materials in block production and construction of wall assemblies (kg/m^2)

	Block production						Mortar and plaster				Raw Material Index[26] (Plastered wall)	Normalized Raw Material Index
							Plastered		Unplastered			
	Clay	Sand	Stone Dust	Lime	Cement	Fly ash	Cement	Sand	Cement	Sand		
Load bearing walls												
Solid Concrete Block	0.00	67.36	161.67	0.00	40.42	0.00	16.7	76.6	5.1	27.2	45.4	-1.29
Hollow Concrete Block	0.00	41.32	123.97	0.00	41.32	0.00	16.7	76.6	5.1	27.2	40.4	-1.40
Fly Ash Concrete Blocks	0.00	0.00	248.18	0.00	12.09	82.87	24.4	117.7	12.8	68.2	34.1	-1.55
FaL-G Bricks	0.00	137.25	0.00	45.75	0.00	91.50	24.4	117.7	12.8	68.2	67.2	-0.78
AAC Blocks	0.00	7.56	0.00	0.00	28.99	57.99	15.6	70.4	3.9	21.0	28.5	-1.67
CSSB	69.69	315.64	0.00	0.00	24.60	0.00	22.3	106.3	10.7	56.9	125.9	0.57
Fly Ash Clay Bricks	178.43	0.00	0.00	0.00	0.00	76.47	24.4	117.7	12.8	68.2	102.0	0.02
K1_Clay Bricks_BTK	272.16	1.37	0.00	0.00	0.00	0.00	24.4	117.7	12.8	68.2	139.8	0.89
K4_Clay Bricks_BTK	283.87	1.43	0.00	0.00	0.00	0.00	24.4	117.7	12.8	68.2	144.5	1.00
K6_Clay Bricks_BTK	312.78	1.57	0.00	0.00	0.00	0.00	24.9	120.0	13.3	70.5	156.6	1.28
K2_Clay Bricks_Zigzag	267.28	1.34	0.00	0.00	0.00	0.00	24.4	117.7	12.8	68.2	137.8	0.84
K3_Clay Bricks_Zigzag	274.11	1.38	0.00	0.00	0.00	0.00	24.4	117.7	12.8	68.2	140.5	0.91
K5_Clay Bricks_VSBK	330.72	1.66	0.00	0.00	0.00	0.00	25.5	123.4	13.9	74.0	164.7	1.46
K7_Clay Bricks_Downdraft	313.13	1.57	0.00	0.00	0.00	0.00	24.4	117.7	12.8	68.2	156.2	1.27
K8_Clay Bricks_Tunnel	259.31	1.30	0.00	0.00	0.00	0.00	26.4	127.9	14.8	78.5	137.2	0.83
Fly Ash Concrete Blocks_RTB	0.00	0.00	173.73	0.00	8.46	58.01	19.4	98.8	7.7	49.4	27.8	-1.69
FaL-G Bricks_RTB	0.00	96.08	0.00	32.03	0.00	64.05	19.4	98.8	7.7	49.4	51.0	-1.16
Fly Ash Clay Bricks_RTB	124.90	0.00	0.00	0.00	0.00	53.53	19.4	98.8	7.7	49.4	75.3	-0.60
K1_Clay Bricks_BTK_RTB	190.51	0.96	0.00	0.00	0.00	0.00	19.4	98.8	7.7	49.4	101.8	0.01
K4_Clay Bricks_BTK_RTB	198.71	1.00	0.00	0.00	0.00	0.00	19.4	98.8	7.7	49.4	105.1	0.09
K6_Clay Bricks_BTK_RTB	218.95	1.10	0.00	0.00	0.00	0.00	19.6	100.5	8.0	51.1	113.6	0.28
K2_Clay Bricks_Zigzag_RTB	187.10	0.94	0.00	0.00	0.00	0.00	19.4	98.8	7.7	49.4	100.4	-0.02
K3_Clay Bricks_Zigzag_RTB	191.88	0.96	0.00	0.00	0.00	0.00	19.4	98.8	7.7	49.4	102.3	0.03
K5_Clay Bricks_VSBK_RTB	231.50	1.16	0.00	0.00	0.00	0.00	20.0	103.0	8.4	53.6	119.2	0.41
K7_Clay Bricks_Downdraft_RTB	219.19	1.10	0.00	0.00	0.00	0.00	19.4	98.8	7.7	49.4	113.3	0.28

[26] Raw Material Index = (Clay quantity x 2 + Sand quantity x 1 + Stone dust quantity x 0 + Lime quantity x 1 + Cement quantity x 1 x 1.45 + Fly ash quantity x 0)/5

	Block production						Mortar and plaster				Raw Material Index[26] (Plastered wall)	Normalized Raw Material Index
							Plastered		Unplastered			
	Clay	Sand	Stone Dust	Lime	Cement	Fly ash	Cement	Sand	Cement	Sand		
Non-load bearing walls												
Solid Concrete Block	0.00	33.68	80.84	0.00	20.21	0.00	9.68	61.80	2.21	14.09	27.8	-1.39
Fly Ash Concrete Blocks	0.00	0.00	124.09	0.00	6.04	41.44	13.01	83.02	5.53	35.30	22.1	-1.63
FaL-G Bricks	0.00	68.63	0.00	22.88	0.00	45.75	13.01	83.02	5.53	35.30	38.7	-0.93
AAC Blocks	0.00	3.78	0.00	0.00	14.50	28.99	10.11	64.52	1.70	10.84	20.8	-1.68
CSSB	31.47	142.55	0.00	0.00	11.11	0.00	10.44	66.61	2.96	18.89	60.7	0.00
Fly Ash Clay Bricks	89.22	0.00	0.00	0.00	0.00	38.24	13.01	83.02	5.53	35.30	56.1	-0.19
K1_Clay Bricks_BTK	136.08	0.68	0.00	0.00	0.00	0.00	13.01	83.02	5.53	35.30	74.9	0.61
K4_Clay Bricks_BTK	141.93	0.71	0.00	0.00	0.00	0.00	13.01	83.02	5.53	35.30	77.3	0.71
K6_Clay Bricks_BTK	156.39	0.79	0.00	0.00	0.00	0.00	13.19	84.20	5.72	36.49	83.4	0.97
K2_Clay Bricks_Zigzag	133.64	0.67	0.00	0.00	0.00	0.00	13.01	83.02	5.53	35.30	74.0	0.57
K3_Clay Bricks_Zigzag	137.06	0.69	0.00	0.00	0.00	0.00	13.01	83.02	5.53	35.30	75.3	0.63
K5_Clay Bricks_VSBK	162.12	0.81	0.00	0.00	0.00	0.00	13.35	85.23	5.88	37.51	85.9	1.07
K7_Clay Bricks_Downdraft	156.57	0.79	0.00	0.00	0.00	0.00	13.01	83.02	5.53	35.30	83.2	0.96
K8_Clay Bricks_Tunnel	117.31	0.59	0.00	0.00	0.00	0.00	13.23	84.47	5.76	36.75	67.8	0.31

Annexure 4: Water consumption in block production and construction of wall assemblies (l/m^2)

	Block production	Construction		Total water consumption (Plastered wall)	Normalized water consumption score
		Unplastered	Plastered		
Load bearing walls					
Solid Concrete Block	383.3	201.7	405.6	788.8	0.24
Hollow Concrete Block	383.3	201.7	405.6	788.8	0.24
Fly Ash Concrete Blocks	1500.0	204.3	408.1	1908.1	2.60
FaL-G Bricks	1519.6	204.3	408.1	1927.7	2.64
AAC Blocks	48.2	201.3	405.2	453.4	-0.46
CSSB	275.1	203.6	407.4	682.5	0.02
Fly Ash Clay Bricks	63.7	204.3	408.1	471.8	-0.43
K1_Clay Bricks_BTK	29.6	204.3	408.1	437.7	-0.50
K4_Clay Bricks_BTK	17.9	204.3	408.1	426.1	-0.52
K6_Clay Bricks_BTK	13.3	204.4	408.3	421.5	-0.53
K2_Clay Bricks_Zigzag	26.7	204.3	408.1	434.8	-0.50
K3_Clay Bricks_Zigzag	27.5	204.3	408.1	435.6	-0.50
K5_Clay Bricks_VSBK	33.1	204.6	408.5	441.5	-0.49
K7_Clay Bricks_Downdraft	17.9	204.3	408.1	426.1	-0.52
K8_Clay Bricks_Tunnel	54.9	204.9	408.8	463.7	-0.44
Fly Ash Concrete Blocks_RTB	1050.0	202.6	406.4	1456.4	1.65
FaL-G Bricks_RTB	1063.7	202.6	406.4	1470.2	1.68
Fly Ash Clay Bricks_RTB	44.6	202.6	406.4	451.0	-0.47
K1_Clay Bricks_BTK_RTB	20.7	202.6	406.4	427.2	-0.52
K4_Clay Bricks_BTK_RTB	12.6	202.6	406.4	419.0	-0.54
K6_Clay Bricks_BTK_RTB	9.3	202.7	406.5	415.8	-0.54
K2_Clay Bricks_Zigzag_RTB	18.7	202.6	406.4	425.1	-0.52
K3_Clay Bricks_Zigzag_RTB	19.2	202.6	406.4	425.6	-0.52
K5_Clay Bricks_VSBK_RTB	23.1	202.8	406.6	429.8	-0.51
K7_Clay Bricks_Downdraft_RTB	12.6	202.6	406.4	419.0	-0.54
Non-load bearing walls					
Solid Concrete Block	297.3	200.7	403.2	700.5	0.55
Fly Ash Concrete Blocks	750.0	201.8	404.3	1154.3	2.24
FaL-G Bricks	759.8	201.8	404.3	1164.1	2.28
AAC Blocks	24.1	201.8	403.4	427.5	-0.47
CSSB	124.3	200.6	403.5	527.7	-0.10
Fly Ash Clay Bricks	31.9	201.0	404.3	436.2	-0.44
K1_Clay Bricks_BTK	14.8	201.8	404.3	419.1	-0.50
K4_Clay Bricks_BTK	9.0	201.8	404.3	413.3	-0.52
K6_Clay Bricks_BTK	6.6	201.9	404.4	411.0	-0.53
K2_Clay Bricks_Zigzag	13.3	201.8	404.3	417.7	-0.51
K3_Clay Bricks_Zigzag	13.7	201.8	404.3	418.0	-0.51
K5_Clay Bricks_VSBK	16.2	202.0	404.4	420.6	-0.50
K7_Clay Bricks_Downdraft	9.0	201.8	404.3	413.3	-0.52
K8_Clay Bricks_Tunnel	24.9	201.9	404.4	429.3	-0.46

Annexure 5: Embodied energy (MJ/m^2) and operational energy (W/m^2.K) in wall assemblies

	Block production	Transportation (raw materials & finished product)	Mortar & plaster production		Transportation of mortar & plaster		Total embodied energy (plastered wall)	Normalized Embodied Energy	Operational Energy (plastered wall)	
			Unplastered	Plastered	Unplastered	Plastered			U-value (W/m^2.K)	Normalized U-value
Load bearing walls										
Solid Concrete Block	179.2	81.1	21.5	70.3	30.9	95.4	426.0	-0.88	2.14	1.02
Hollow Concrete Block	184.9	70.2	21.5	70.3	30.9	95.4	420.7	-0.90	1.89	0.29
Fly Ash Concrete Blocks	64.7	83.7	53.9	102.7	77.6	142.0	393.1	-1.04	1.98	0.55
FaL-G Bricks	308.4	75.6	53.9	102.7	77.6	142.0	628.8	0.09	1.20	-1.67
AAC Blocks	228.0	149.5	16.6	65.3	23.8	88.3	531.1	-0.38	0.70	-3.13
CSSB	103.3	67.9	45.0	93.7	64.7	129.2	394.1	-1.03	1.94	0.46
Fly Ash Clay Bricks	303.3	187.9	53.9	102.7	77.6	142.0	736.0	0.61	1.73	-0.16
K1_Clay Bricks_BTK	399.4	122.2	53.9	102.7	77.6	142.0	766.3	0.75	2.04	0.72
K4_Clay Bricks_BTK	319.5	127.5	53.9	102.7	77.6	142.0	691.7	0.40	2.04	0.72
K6_Clay Bricks_BTK	159.8	63.7	55.7	54.6	80.2	85.1	363.2	0.60	2.04	0.72
K2_Clay Bricks_Zigzag	325.0	120.0	53.9	102.7	77.6	142.0	689.8	0.39	2.04	0.72
K3_Clay Bricks_Zigzag	283.8	123.1	53.9	102.7	77.6	142.0	651.6	0.20	2.04	0.72
K5_Clay Bricks_VSBK	141.9	61.6	58.4	54.6	84.1	85.1	343.1	0.53	2.04	0.72
K7_Clay Bricks_Downdraft	915.8	145.3	53.9	102.7	77.6	142.0	1305.8	3.34	2.04	0.72
K8_Clay Bricks_Tunnel	387.8	116.5	62.0	110.8	89.3	153.7	768.78	0.77	2.04	0.72
Fly Ash Concrete Blocks_RTB	45.3	58.6	32.5	81.3	50.6	115.1	300.3	-1.48	1.73	-0.16
FaL-G Bricks_RTB	215.9	52.9	32.5	81.3	50.6	115.1	465.2	-0.69	1.02	-2.20
Fly Ash Clay Bricks_RTB	212.3	131.6	32.5	81.3	50.6	115.1	540.3	-0.33	1.50	-0.83
K1_Clay Bricks_BTK_RTB	279.5	85.6	32.5	81.3	50.6	115.1	561.5	-0.23	1.79	0.01
K4_Clay Bricks_BTK_RTB	223.7	89.2	32.5	81.3	50.6	115.1	509.3	-0.48	1.79	0.01
K6_Clay Bricks_BTK_RTB	242.1	98.3	33.6	82.4	52.3	116.8	539.6	-0.33	1.79	0.01
K2_Clay Bricks_Zigzag_RTB	227.5	84.0	32.5	81.3	50.6	115.1	508.0	-0.49	1.79	0.01
K3_Clay Bricks_Zigzag_RTB	198.6	86.2	32.5	81.3	50.6	115.1	481.2	-0.61	1.79	0.01
K5_Clay Bricks_VSBK_RTB	221.0	104.0	35.2	84.0	54.9	119.3	528.4	-0.39	1.79	0.01
K7_Clay Bricks_Downdraft_RTB	641.1	101.7	32.5	81.3	50.6	115.1	939.2	1.58	1.79	0.01

	Block production	Transportation (raw materials & finished product)	Mortar & plaster production		Transportation of mortar & plaster		Total embodied energy (plastered wall)	Normalized Embodied Energy	Operational Energy (plastered wall)	
			Unplastered	Plastered	Unplastered	Plastered			U-value ($W/m^2.K$)	Normalized U-value
Non-load bearing walls										
Solid Concrete Block	89.61	40.54	9.27	40.67	14.43	63.32	234.13	-1.03	3.00	0.61
Fly Ash Concrete Blocks	32.35	41.87	23.23	54.63	36.17	85.06	213.90	-1.20	2.84	0.28
FaL-G Bricks	154.21	37.82	23.23	54.63	36.17	85.06	331.72	-0.17	1.94	-1.50
AAC Blocks	114.00	74.73	23.23	42.46	36.17	66.11	297.30	-0.47	1.23	-2.93
CSSB	46.65	30.66	7.14	43.83	11.11	68.25	189.39	-1.42	2.97	0.55
Fly Ash Clay Bricks	151.66	93.97	12.43	54.63	19.36	85.06	385.31	0.30	2.57	-0.25
K1_Clay Bricks_BTK	199.68	61.11	23.23	54.63	36.17	85.06	400.48	0.43	2.90	0.40
K4_Clay Bricks_BTK	159.76	63.74	23.23	54.63	36.17	85.06	363.19	0.10	2.90	0.40
K6_Clay Bricks_BTK	172.89	70.23	24.01	55.41	37.38	86.27	384.81	0.29	2.90	0.40
K2_Clay Bricks_Zigzag	162.52	60.02	23.23	54.63	36.17	85.06	362.23	0.10	2.90	0.40
K3_Clay Bricks_Zigzag	141.88	61.55	23.23	54.63	36.17	85.06	343.12	-0.07	2.90	0.40
K5_Clay Bricks_VSBK	154.78	72.80	24.68	56.08	38.43	87.32	370.99	0.17	2.90	0.40
K7_Clay Bricks_Downdraft	457.90	72.66	23.23	54.63	36.17	85.06	670.24	2.79	2.90	0.40
K8_Clay Bricks_Tunnel	175.44	52.68	24.19	55.58	37.66	86.55	370.25	0.17	2.90	0.40

Annexure 6: Emissions related to wall assemblies (g/m^2)

	Production emissions								Transportation emissions[27]						Regional Emissions Index[28] (Plastered wall)	Normalized REI	CO_2 Emissions (Plastered wall)	Normalized CO_2 emissions
	Plastered wall				Unplastered wall				Plastered wall			Unplastered wall						
	PM	CO_2	SO_2	NOx	PM	CO_2	SO_2	NOx	PM	CO_2	NOx	PM	CO_2	NOx				
Load bearing walls																		
Solid Concrete Block	83.5	57921.3	286.3	262.5	69.6	46308.4	229.4	210.9	14.6	8951.4	109.2	12.3	7576.3	92.4	756.1	0.69	66,872.7	-0.40
Hollow Concrete Block	87.5	58977.7	292.0	268.2	73.6	47364.8	235.1	216.5	13.0	8021.2	97.8	10.8	6646.2	81.1	758.6	0.70	66,999.0	-0.40
Fly Ash Concrete Blocks	73.8	37726.3	191.2	169.0	59.8	26113.4	134.3	117.4	16.5	10172.7	124.1	14.3	8797.6	107.3	574.7	-0.33	47,899.0	-1.03
FaL-G Bricks	51.3	98532.7	249.9	192.9	37.3	86919.8	193.0	141.3	15.4	9482.7	115.7	13.2	8107.6	98.9	625.2	-0.04	108,015.4	0.96
AAC Blocks	119.5	51610.6	250.9	219.4	105.6	39997.7	194.0	167.8	23.8	14633.6	178.5	21.6	13258.5	161.7	792.2	0.89	66,244.2	-0.42
CSSB	56.3	46911.1	229.9	208.8	42.4	35298.2	173.0	157.1	13.9	8547.3	104.3	11.7	7172.3	87.5	613.1	-0.11	55,458.5	-0.78
Fly Ash Clay Bricks	103.5	86638.9	134.0	108.8	89.6	75026.1	77.1	57.1	31.0	19062.4	232.5	28.8	17687.3	215.8	609.9	-0.13	105,701.4	0.88
K1_Clay Bricks_BTK	483.4	67936.0	294.8	108.8	469.5	56323.1	237.9	57.1	21.9	13456.6	164.2	19.7	12081.5	147.4	1073.0	2.46	81,392.6	0.08
K4_Clay Bricks_BTK	103.5	86638.9	134.0	108.8	89.6	75026.1	77.1	57.1	22.6	13905.1	169.6	20.4	12530.0	152.8	538.6	-0.53	100,544.0	0.71
K6_Clay Bricks_BTK	234.2	62597.6	301.1	110.7	220.2	50984.7	244.2	59.0	24.5	15068.3	183.8	22.3	13693.2	167.0	854.3	1.24	77,665.9	-0.05
K2_Clay Bricks_Zigzag	40.1	52919.3	122.5	108.8	26.1	41306.5	65.6	57.1	21.6	13269.8	161.9	19.3	11894.7	145.1	454.8	-0.99	66,189.1	-0.43
K3_Clay Bricks_Zigzag	158.8	71002.7	227.2	108.8	144.9	59389.8	170.3	57.1	22.0	13531.4	165.1	19.8	12156.3	148.3	681.9	0.27	84,534.0	0.18
K5_Clay Bricks_VSBK	93.8	81027.1	194.8	113.6	79.8	69414.2	137.9	61.9	25.8	15838.5	193.2	23.5	14463.4	176.4	621.2	-0.07	96,865.6	0.59
K7_Clay Bricks_Downdraft	520.3	167321.3	119.8	108.8	506.3	155708.4	62.9	57.1	25.1	15426.1	188.2	22.9	14051.0	171.4	962.1	1.84	182,747.4	3.43
K8_Clay Bricks_Tunnel	112.4	65210.3	316.9	117.4	98.5	53597.4	260.0	65.7	21.5	13213.7	161.2	19.3	11838.6	144.4	729.4	0.54	78,424.0	-0.02
Fly Ash Concrete Blocks_RTB	54.3	28653.7	144.9	128.3	40.4	17040.8	88.0	76.6	12.1	7455.3	90.9	9.9	6080.2	74.2	430.6	-1.13	36,109.0	-1.42
FaL-G Bricks_RTB	38.6	71218.2	186.0	145.1	24.6	59605.3	129.1	93.4	11.3	6972.4	85.1	9.1	5597.3	68.3	466.0	-0.93	78,190.5	-0.03
Fly Ash Clay Bricks_RTB	75.2	62892.6	104.8	86.1	61.2	51279.7	47.9	34.5	22.2	13678.1	166.9	20.0	12303.1	150.1	455.2	-0.99	76,570.7	-0.08
K1_Clay Bricks_BTK_RTB	341.1	49800.5	217.4	86.1	327.1	38187.6	160.5	34.5	15.9	9754.1	119.0	13.6	8379.0	102.2	779.4	0.82	59,554.6	-0.65
K4_Clay Bricks_BTK_RTB	75.2	62892.6	104.8	86.1	61.2	51279.7	47.9	34.5	16.4	10068.0	122.8	14.1	8692.9	106.0	405.3	-1.27	72,960.6	-0.20
K6_Clay Bricks_BTK_RTB	166.6	46022.0	221.5	87.3	152.6	34409.2	164.6	35.6	17.7	10879.6	132.7	15.5	9504.5	115.9	625.8	-0.04	56,901.7	-0.73
K2_Clay Bricks_Zigzag_RTB	30.7	39288.8	96.7	86.1	16.8	27675.9	39.8	34.5	15.7	9623.3	117.4	13.4	8248.2	100.6	346.7	-1.60	48,912.1	-1.00
K3_Clay Bricks_Zigzag_RTB	113.9	51947.2	170.1	86.1	99.9	40334.3	113.2	34.5	15.9	9806.4	119.6	13.7	8431.3	102.8	505.6	-0.71	61,753.6	-0.57
K5_Clay Bricks_VSBK_RTB	68.2	58860.5	146.9	89.0	54.3	47247.6	90.0	37.3	18.6	11414.9	139.2	16.3	10039.8	122.5	461.9	-0.95	70,275.3	-0.29
K7_Clay Bricks_Downdraft_RTB	366.9	119370.2	94.8	86.1	353.0	107757.3	37.9	34.5	18.1	11132.7	135.8	15.9	9757.6	119.0	701.8	0.38	130,502.9	1.70
Non-load bearing walls																		

[27] SO_2 emission factors are negligible

[28] REI = PM emissions + SO_2 emissions + NOx emissions

	Production emissions								Transportation emissions[27]						Regional Emissions Index[28] (Plastered wall)	Normalized REI	CO_2 Emissions (Plastered wall)	Normalized CO_2 emissions
	Plastered wall				Unplastered wall				Plastered wall			Unplastered wall						
	PM	CO_2	SO_2	NOx	PM	CO_2	SO_2	NOx	PM	CO_2	NOx	PM	CO_2	NOx				
Solid Concrete Block	43.3	30277.0	149.6	137.1	34.4	22801.2	113.0	103.9	7.8	4808.8	58.7	6.1	3765.9	45.9	396.6	0.39	35,085.8	-0.55
Fly Ash Concrete Blocks	37.8	19647.8	99.5	88.0	28.9	12172.0	62.8	54.7	8.8	5385.9	65.7	7.1	4343.0	53.0	299.8	-0.71	25,033.7	-1.15
FaL-G Bricks	26.6	50051.0	128.8	100.0	17.6	42575.2	92.2	66.7	8.2	5040.9	61.5	6.5	3998.0	48.8	325.0	-0.42	55,091.9	0.65
AAC Blocks	62.5	28137.4	136.9	120.1	43.7	36628.3	34.2	24.6	12.7	7785.3	95.0	14.3	8787.9	107.2	427.2	0.74	35,922.7	-0.50
CSSB	25.9	21544.1	105.6	95.9	52.5	19727.1	95.7	82.7	6.6	4071.7	49.7	10.8	6612.1	80.7	283.6	-0.89	25,615.8	-1.11
Fly Ash Clay Bricks	52.7	44104.2	70.9	57.9	16.9	14068.3	68.9	62.6	16.0	9830.7	119.9	4.9	3028.8	36.9	317.4	-0.51	53,934.9	0.58
K1_Clay Bricks_BTK	242.6	34752.7	151.3	57.9	233.7	27276.9	114.6	24.6	11.4	7027.8	85.7	9.7	5985.0	73.0	548.9	2.12	41,780.5	-0.15
K4_Clay Bricks_BTK	52.7	44104.2	70.9	57.9	43.7	36628.3	34.2	24.6	11.8	7252.1	88.5	10.1	6209.2	75.7	281.7	-0.92	51,356.2	0.42
K6_Clay Bricks_BTK	118.0	32053.8	154.2	58.7	109.0	24578.0	117.6	25.4	12.7	7831.8	95.5	11.0	6789.0	82.8	439.2	0.87	39,885.6	-0.26
K2_Clay Bricks_Zigzag	21.0	27244.4	65.1	57.9	12.0	19768.5	28.4	24.6	11.3	6934.4	84.6	9.6	5891.6	71.9	239.8	-1.39	34,178.8	-0.60
K3_Clay Bricks_Zigzag	80.3	36286.0	117.5	57.9	71.4	28810.2	80.8	24.6	11.5	7065.2	86.2	9.8	6022.4	73.5	353.4	-0.10	43,351.2	-0.05
K5_Clay Bricks_VSBK	47.0	40562.4	99.6	59.4	38.0	33086.5	63.0	26.2	13.1	8073.5	98.5	11.4	7030.7	85.8	317.7	-0.51	48,635.9	0.26
K7_Clay Bricks_Downdraft	261.1	84445.3	63.7	57.9	252.1	76969.5	27.1	24.6	13.0	8012.6	97.7	11.3	6969.7	85.0	493.5	1.49	92,457.9	2.88
K8_Clay Bricks_Tunnel	52.4	30801.2	149.7	58.9	43.5	23325.4	113.1	25.6	10.3	6340.4	77.3	8.6	5297.5	64.6	348.7	-0.15	37,141.6	-0.42

Annexure 7: Productivity and wall cost for masonry wall assemblies

	Block production (person-hrs/m²)	Quality parameter[29]	Construction (person-hrs/m²)		Total Productivity Index[30] (plastered)	Normalized Productivity Index	Cost				
			Unplastered	Plastered			Masonry unit cost (INR)	Blocks/m²	Cost of blocks (INR/m²)	Plastered Wall cost (INR/m²)	Normalized Wall cost
Load bearing walls											
Solid Concrete Block	1.75	M	5.4	8.6	12.112	-0.82	32.00	11.6	371.66	764.20	-0.76
Hollow Concrete Block	2.09	L	5.4	8.6	14.881	-0.35	26.00	11.6	301.97	694.51	-1.25
Fly Ash Concrete Blocks	0.33	G	6.7	9.9	10.205	-1.14	4.00	98.0	392.16	903.24	0.20
FaL-G Bricks	1.96	L	6.7	9.9	15.752	-0.20	3.50	98.0	343.14	854.22	-0.14
AAC Blocks	0.35	G	4.6	7.8	8.1331	-1.49	158.00	6.1	957.58	1315.78	3.04
CSSB	9.43	G	5.4	8.6	18.053	0.19	5.00	45.9	229.27	685.00	-1.31
Fly Ash Clay Bricks	3.59	M	6.7	9.9	17.056	0.02	4.00	98.0	392.16	903.24	0.20
K1_Clay Bricks_BTK	4.10	M	6.7	9.9	18.07	0.19	5.00	98.0	490.20	1001.28	0.87
K4_Clay Bricks_BTK	3.60	M	6.7	9.9	17.063	0.02	5.00	98.0	490.20	1001.28	0.87
K6_Clay Bricks_BTK	5.43	M	6.7	9.9	20.725	0.64	5.00	94.1	470.59	986.54	0.77
K2_Clay Bricks_Zigzag	3.93	G	6.7	9.9	13.804	-0.53	5.00	94.1	470.59	1001.28	0.87
K3_Clay Bricks_Zigzag	4.56	L	6.7	9.9	23.537	1.11	5.00	94.1	470.59	1001.28	0.87
K5_Clay Bricks_VSBK	8.65	L	6.7	9.9	35.817	3.18	5.00	90.6	452.83	976.08	0.70
K7_Clay Bricks_Downdraft	5.88	M	6.7	9.9	21.635	0.79	5.00	98.0	490.20	1001.28	0.87
K8_Clay Bricks_Tunnel	1.85	G	6.7	9.9	11.716	-0.88	3.00	157.0	470.99	1003.96	0.89
Fly Ash Concrete Blocks_RTB	0.23	G	6.7	9.9	10.104	-1.16	5.00	68.6	343.14	736.24	-0.96
FaL-G Bricks_RTB	1.37	L	6.7	9.9	13.988	-0.50	5.00	68.6	343.14	701.92	-1.19
Fly Ash Clay Bricks_RTB	2.52	M	6.7	9.9	14.9	-0.35	5.00	68.6	343.14	736.24	-0.96
K1_Clay Bricks_BTK_RTB	2.87	M	6.7	9.9	15.61	-0.23	5.00	68.6	343.14	804.86	-0.48
K4_Clay Bricks_BTK_RTB	2.52	M	6.7	9.9	14.905	-0.34	5.00	68.6	343.14	804.86	-0.48
K6_Clay Bricks_BTK_RTB	3.80	M	6.7	9.9	17.468	0.09	5.00	65.9	329.41	794.35	-0.56
K2_Clay Bricks_Zigzag_RTB	2.75	G	6.7	9.9	12.624	-0.73	5.00	68.6	343.14	804.86	-0.48
K3_Clay Bricks_Zigzag_RTB	3.19	L	6.7	9.9	19.437	0.42	5.00	68.6	343.14	804.86	-0.48
K5_Clay Bricks_VSBK_RTB	6.05	L	6.7	9.9	28.033	1.87	5.00	63.4	316.98	786.74	-0.61
K7_Clay Bricks_Downdraft_RTB	4.12	M	6.7	9.9	18.105	0.20	5.00	68.6	343.14	804.86	-0.48

[29] L = 3, M = 2 and G = 1

[30] Productivity Index = Block production productivity x Quality parameter + Construction productivity

	Block production (person-hrs/m²)	Quality parameter[29]	Construction (person-hrs/m²)		Total Productivity Index[30] (plastered)	Normalized Productivity Index	Cost				
			Unplastered	Plastered			Masonry unit cost (INR)	Blocks/m²	Cost of blocks (INR/m²)	Plastered Wall cost (INR/m²)	Normalized Wall cost
Non-load bearing walls											
Solid Concrete Block	1.75	M	4.17	7.37	10.86	-0.32	16.00	11.6	185.83	489.98	-1.21
Fly Ash Concrete Blocks	0.17	G	5.00	8.20	8.37	-1.05	4.00	49.0	196.08	562.14	-0.28
FaL-G Bricks	0.98	L	5.00	8.20	11.14	-0.24	3.50	49.0	171.57	537.63	-0.60
AAC Blocks	0.18	G	3.33	6.53	6.71	-1.54	79.00	6.1	478.79	767.22	2.38
CSSB	4.26	G	4.17	7.37	11.63	-0.10	5.00	20.7	103.75	417.22	-2.15
Fly Ash Clay Bricks	1.80	M	5.00	8.20	11.79	-0.05	4.00	49.0	196.08	562.14	-0.28
K1_Clay Bricks_BTK	2.05	M	5.00	8.20	12.30	0.10	5.00	49.0	245.10	611.16	0.36
K4_Clay Bricks_BTK	1.80	M	5.00	8.20	11.80	-0.05	5.00	49.0	245.10	611.16	0.36
K6_Clay Bricks_BTK	2.71	M	5.00	8.20	13.63	0.49	5.00	47.1	235.29	603.65	0.26
K2_Clay Bricks_Zigzag	1.97	G	5.00	8.20	10.17	-0.53	5.00	49.0	245.10	611.16	0.36
K3_Clay Bricks_Zigzag	2.28	L	5.00	8.20	15.03	0.90	5.00	49.0	245.10	611.16	0.36
K5_Clay Bricks_VSBK	4.24	L	5.00	8.20	20.92	2.62	5.00	44.4	221.98	592.32	0.11
K7_Clay Bricks_Downdraft	2.94	M	5.00	8.20	14.08	0.62	5.00	49.0	245.10	611.16	0.36
K8_Clay Bricks_Tunnel	0.84	G	5.00	8.20	9.04	-0.86	3.00	71.0	213.07	581.94	-0.02

Annexure 8: Occupational Health and Safety assessment for masonry wall assemblies

	Occupational Health And Safety[31]										
	Exposure to dust (1)	Exposure to heat (2)	Exposure to air pollutants (3)	Manual Handling Risk (4)	Personal protective equipment (a)	Risk of falling (5)	Sanitation facilities available at plant (b)	Safe drinking water available at plant (c)	Housing for temporary workers (d)	OHS Index[32]	Normalized OHS Index
Load bearing walls											
Solid Concrete Block	M	L	L	M	N	L	A	A	NA	1.3	-1.19
Hollow Concrete Block	M	L	L	M	N	L	A	A	NA	1.3	-1.19
Fly Ash Concrete Blocks	H	L	L	L	N	M	A	A	A	1.6	-0.72
FaL-G Bricks	M	L	L	M	N	L	A	A	A	1.4	-0.96
AAC Blocks	L	L	L	L	A	L	A	A	NA	0.9	-2.11
CSSB	L	L	L	M	N	L	N	A	I	1.7	-0.49
Fly Ash Clay Bricks	H	H	M	M	N	L	I	A	I	2.1	0.44
K1_Clay Bricks_BTK	H	M	M	M	N	M	I	A	I	2.1	0.44
K4_Clay Bricks_BTK	H	M	M	H	N	M	N	A	N	2.4	1.13
K6_Clay Bricks_BTK	H	M	M	H	N	M	N	A	N	2.4	1.13
K2_Clay Bricks_Zigzag	H	M	M	H	N	M	I	A	A	2.1	0.44
K3_Clay Bricks_Zigzag	H	M	M	H	N	M	N	I	N	2.6	1.36
K5_Clay Bricks_VSBK	L	L	M	M	N	L	N	I	I	1.9	-0.03
K7_Clay Bricks_Downdraft	M	M	M	H	N	L	N	A	A	2.0	0.20
K8_Clay Bricks_Tunnel	L	L	L	L	A	L	A	A	A	1.0	-1.88
Fly Ash Concrete Blocks_RTB	H	L	L	L	N	M	A	A	A	1.6	-0.72
FaL-G Bricks_RTB	M	L	L	M	N	L	A	A	A	1.4	-0.96
Fly Ash Clay Bricks_RTB	H	H	M	M	N	L	I	A	I	2.1	0.44
K1_Clay Bricks_BTK_RTB	H	M	M	M	N	M	I	A	I	2.1	0.44
K4_Clay Bricks_BTK_RTB	H	M	M	H	N	M	N	A	N	2.4	1.13
K6_Clay Bricks_BTK_RTB	H	M	M	H	N	M	N	A	N	2.4	1.13
K2_Clay Bricks_Zigzag_RTB	H	M	M	H	N	M	I	A	A	2.1	0.44
K3_Clay Bricks_Zigzag_RTB	H	M	M	H	N	M	N	I	N	2.6	1.36
K5_Clay Bricks_VSBK_RTB	L	L	M	M	N	L	N	I	I	1.9	-0.03
K7_Clay Bricks_Downdraft_RTB	M	M	M	H	N	L	N	A	A	2.0	0.20
Non-load bearing walls											

[31] Scores for each sub-parameter: L=1, M=2 and H=3 for (1), (2), (3), (4), (5); N=3, I=2, A=1 for (a), (b), (c) and (d); NA=0 for (d)

[32] OHS Index = (Sum of scores for each sub-parameter)/9

	Occupational Health And Safety[31]										
	Exposure to dust (1)	**Exposure to heat (2)**	**Exposure to air pollutants (3)**	**Manual Handling Risk (4)**	**Personal protective equipment (a)**	**Risk of falling (5)**	**Sanitation facilities available at plant (b)**	**Safe drinking water available at plant (c)**	**Housing for temporary workers (d)**	**OHS Index[32]**	**Normalized OHS Index**
Solid Concrete Block	M	L	L	M	N	L	A	A	NA	1.33	-0.93
Fly Ash Concrete Blocks	H	L	L	L	N	M	A	A	A	1.56	-0.51
FaL-G Bricks	M	L	L	M	N	L	A	A	A	1.44	-0.72
AAC Blocks	L	L	L	L	A	L	A	A	NA	0.89	-1.77
CSSB	L	L	L	M	N	L	N	A	I	1.67	-0.30
Fly Ash Clay Bricks	H	H	M	M	N	L	I	A	I	2.11	0.54
K1_Clay Bricks_BTK	H	M	M	M	N	M	I	A	I	2.11	0.54
K4_Clay Bricks_BTK	H	M	M	H	N	M	N	A	N	2.44	1.17
K6_Clay Bricks_BTK	H	M	M	H	N	M	N	A	N	2.44	1.17
K2_Clay Bricks_Zigzag	H	M	M	H	N	M	I	A	A	2.11	0.54
K3_Clay Bricks_Zigzag	H	M	M	H	N	M	N	I	N	2.56	1.38
K5_Clay Bricks_VSBK	L	L	M	M	N	L	N	I	I	1.89	0.12
K7_Clay Bricks_Downdraft	M	M	M	H	N	L	N	A	A	2.00	0.33
K8_Clay Bricks_Tunnel	L	L	L	L	A	L	A	A	A	1.00	-1.56

Annexure 9: Summary of regulations governing fly ash utilization in India

Year	Notification	Agency	Main Points
1999	Notification describing the utilization of ash by Thermal Power Plants	CPCB and concerned State Pollution Control Boards / Committees and concerned regional office of the MoEF	• Use of fly ash, bottom ash or pond ash in the manufacture of bricks and other construction activities: - No person shall within a radius of 50 km from coal or lignite based thermal power plants, manufacture clay bricks or tiles or blocks for use in construction activities without mixing at least 25% by weight of ash (fly ash, bottom ash or pond ash). - In case of non-compliance, consent order issued to establish the brick kiln and the mining lease after approval can be cancelled. • Every coal or lignite based thermal power plant shall make available ash, for at least ten years from the date of publication of this notification, without any payment or any other consideration, for the purpose of manufacturing ash-based products such as cement, concrete blocks, bricks, panels. • Action plan provides for 30% of fly ash utilization, within three years from the publication of this notification with further increase in utilization by at least 10% every year progressively for the next six years to enable utilization of the entire fly ash generated in the power plant at least by the end of ninth year. • Action plan to be submitted to concerned authorities within a period of six months from the date of publication of this notification. • Annual implementation report providing information about the compliance of provisions in this notification to be submitted by the 30th April every year to the concerned authorities.
1999	Notification describing the specifications for use of ash-based products	Bureau of Indian Standards, Central Building Research institute (CBRI), Building Materials and Technology Promotion Council (BMTPC)	• Manufacture of ash-based products such as cement, concrete blocks, bricks, panels or any other material shall be carried out in accordance with specifications and guidelines laid down by the Bureau of Indian Standards; CBRI, Roorkee; BMTPC, New Delhi. • The Central Public Works Department, Public Works Departments in the State/Union Territory Governments, Development Authorities, Housing Boards, National Highway Authority of India and other construction agencies including those in the private sector shall also prescribe the use of ash and ash-based products in their respective schedules of specifications and construction applications, including appropriate standards and codes of practice, within a period of four months from the publication of this notification. • All local authorities shall specify in their respective building bye-laws and regulations the use of ash and ash-based products and construction techniques in building materials within a period of four months from the date of publication of this notification.
2003	Notification amending the fly ash utilization	State Pollution Control Board or Pollution Control Committees	• No person shall within a radius of 100 km from coal or lignite based thermal power plants, manufacture clay bricks or tiles or blocks for use in construction activities without mixing at least 25% by weight of ash (fly ash, bottom ash or pond ash).
2008	Notification to amend the	State Pollution Control Board or	• Every construction agency engaged in the construction of buildings within a radius of 100 km (by road) from a coal or lignite based thermal power plant shall use only fly ash based products for construction.

	utilization of fly ash standards	Pollution Control Committees	• This is applicable to all construction agencies of Central or State or Local Government and private or public sector. • Annual returns need to be submitted to the concerned authorities.
2008	Notification amending Minimum fly ash content for building materials or products to qualify as "fly ash based products"		• Fly ash bricks, blocks, tiles, etc. made with fly ash, lime, gypsum, sand, stone dust, cement, etc. (without clay) should have a minimum of 50% fly ash content by weight of total raw material. • Clay based building materials such as bricks, blocks, tiles, etc., should have a minimum of 25% fly ash content by weight of total raw material.
2007	Green Rating for Integrated Habitat Assessment (GRIHA)	MNRE & The Energy and Resources Institute (TERI)	• Criteria 9: Reduce air pollution during construction • Criteria 15: Utilization of fly ash in building structure • Criteria 16: Adopt energy efficient technology in construction

Annexure 10: Rankings of wall assemblies with weightages for clay reduced to 1

Plastered load-bearing assemblies

	Normalized Scores									Composite Environmental Index	RANKING
	RMI	Water	Embodied Energy	Operational Energy	REI	CO_2 Emissions	OHS Index	Productivity Index	Cost		
Solid Concrete Block	-1.02	0.24	-0.88	1.02	0.69	-0.40	-1.19	-0.82	-0.76	-3.26	7
Hollow Concrete Block	-1.24	0.24	-0.90	0.29	0.70	-0.40	-1.19	-0.35	-1.25	-4.24	4
Fly Ash Concrete Blocks	-1.52	2.60	-1.04	0.55	-0.33	-1.03	-0.72	-1.14	0.20	-1.75	8
Fal G Bricks	-0.05	2.64	0.09	-1.67	-0.04	0.96	-0.96	-0.20	-0.14	0.18	15
AAC Blocks	-1.77	-0.46	-0.38	-3.13	0.89	-0.42	-2.11	-1.49	3.04	-6.06	1
CSSB	1.95	0.02	-1.03	0.46	-0.11	-0.78	-0.49	0.19	-1.31	-0.67	12
Fly Ash Clay Bricks	-0.09	-0.43	0.61	-0.16	-0.13	0.88	0.44	0.02	0.20	0.96	17
K1_Clay Bricks_BTK	0.76	-0.50	0.75	0.72	2.46	0.08	0.44	0.19	0.87	4.51	21
K4_Clay Bricks_BTK	0.87	-0.52	0.40	0.72	-0.53	0.71	1.13	0.02	0.87	3.58	20
K6_Clay Bricks_BTK	1.15	-0.53	0.60	0.72	1.24	-0.05	1.13	0.64	0.77	5.08	23
K2_Clay Bricks_Zigzag	0.72	-0.50	0.39	0.72	-0.99	-0.43	0.44	-0.53	0.87	1.39	18
K3_Clay Bricks_Zigzag	0.78	-0.50	0.20	0.72	0.27	0.18	1.36	1.11	0.87	4.78	22
K5_Clay Bricks_VSBK	1.35	-0.49	0.53	0.72	-0.07	0.59	-0.03	3.18	0.70	6.23	24
K7_Clay Bricks_Downdraft	1.13	-0.52	3.34	0.72	1.84	3.43	0.20	0.79	0.87	9.17	25
K8_Clay Bricks_Tunnel	0.76	-0.44	0.77	0.72	0.54	-0.02	-1.88	-0.88	0.89	0.19	16
Fly Ash Concrete Blocks_RTB	-1.80	1.65	-1.48	-0.16	-1.13	-1.42	-0.72	-1.16	-0.96	-5.91	2
Fal G Bricks_RTB	-0.77	1.68	-0.69	-2.20	-0.93	-0.03	-0.96	-0.50	-1.19	-5.11	3
Fly Ash Clay Bricks_RTB	-0.80	-0.47	-0.33	-0.83	-0.99	-0.08	0.44	-0.35	-0.96	-3.83	5
K1_Clay Bricks_BTK_RTB	-0.20	-0.52	-0.23	0.01	0.82	-0.65	0.44	-0.23	-0.48	-1.13	10
K4_Clay Bricks_BTK_RTB	-0.13	-0.54	-0.48	0.01	-1.27	-0.20	1.13	-0.34	-0.48	-1.58	9
K6_Clay Bricks_BTK_RTB	0.07	-0.54	-0.33	0.01	-0.04	-0.73	1.13	0.09	-0.56	-0.53	13
K2_Clay Bricks_Zigzag_RTB	-0.23	-0.52	-0.49	0.01	-1.60	-1.00	0.44	-0.73	-0.48	-3.31	6
K3_Clay Bricks_Zigzag_RTB	-0.19	-0.52	-0.61	0.01	-0.71	-0.57	1.36	0.42	-0.48	-0.67	11
K5_Clay Bricks_VSBK_RTB	0.21	-0.51	-0.39	0.01	-0.95	-0.29	-0.03	1.87	-0.61	-0.08	14
K7_Clay Bricks_Downdraft_RTB	0.05	-0.54	1.58	0.01	0.38	1.70	0.20	0.20	-0.48	2.06	19

Plastered non-load bearing assemblies

	Normalized Scores									Composite Environmental Index	RANKING
	RMI	Water	Embodied Energy	Operational Energy	REI	CO_2 Emissions	OHS Index	Productivity Index	Cost		
Solid Concrete Block	-1.29	0.55	-1.03	0.61	0.39	-0.55	-0.93	-0.32	-1.21	-3.70	2
Fly Ash Concrete Blocks	-1.78	2.24	-1.20	0.28	-0.71	-1.15	-0.51	-1.05	-0.28	-3.23	4
FaL-G Bricks	-0.34	2.28	-0.17	-1.50	-0.42	0.65	-0.72	-0.24	-0.60	-1.18	6
AAC Blocks	-1.90	-0.47	-0.47	-2.93	0.74	-0.50	-1.77	-1.54	2.38	-6.59	1
CSSB	1.03	-0.10	-1.42	0.55	-0.89	-1.11	-0.30	-0.10	-2.15	-3.48	3
Fly Ash Clay Bricks	-0.38	-0.44	0.30	-0.25	-0.51	0.58	0.54	-0.05	-0.28	-0.52	7
K1_Clay Bricks_BTK	0.45	-0.50	0.43	0.40	2.12	-0.15	0.54	0.10	0.36	2.77	10
K4_Clay Bricks_BTK	0.56	-0.52	0.10	0.40	-0.92	0.42	1.17	-0.05	0.36	1.78	9
K6_Clay Bricks_BTK	0.84	-0.53	0.29	0.40	0.87	-0.26	1.17	0.49	0.26	3.23	12
K2_Clay Bricks_Zigzag	0.41	-0.51	0.10	0.40	-1.39	-0.60	0.54	-0.53	0.36	-0.22	8
K3_Clay Bricks_Zigzag	0.47	-0.51	-0.07	0.40	-0.10	-0.05	1.38	0.90	0.36	2.86	11
K5_Clay Bricks_VSBK	0.96	-0.50	0.17	0.40	-0.51	0.26	0.12	2.62	0.11	3.78	13
K7_Clay Bricks_Downdraft	0.81	-0.52	2.79	0.40	1.49	2.88	0.33	0.62	0.36	6.98	14
K8_Clay Bricks_Tunnel	0.16	-0.46	0.17	0.40	-0.15	-0.42	-1.56	-0.86	-0.02	-2.47	5