COMPARATIVE ENVIRONMENTAL ASSESSMENT OF MASONRY WALL UNITS REGARDING MANUFACTURING PROCESS

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Summary

Sustainable building and construction with respect to environmental and economic considerations are becoming more and more important because of high energy and resource consumption in the building and construction sector. In Turkey, residential buildings are mostly built with in-situ reinforced concrete structural frame and infill external walls made of lightweight masonry such as autoclaved aerated concrete (AAC), pumice aggregate concrete hollow blocks and fired clay hollow bricks. In the paper, information gathered through field investigations on extraction of natural resources, processing of raw materials and manufacturing processes are given for AAC, pumice concrete blocks and fired clay hollow bricks and the obtained data is evaluated comparatively in terms of environmental sustainability issues such as resource depletion, greenhouse gas emissions, water use and waste generation etc.

1. Introduction

Environmental sustainability of buildings is an important matter of concern towards sustainable development, since construction and operation of buildings consume high amounts of energy and natural resources, and also are responsible for large quantities of CO_2 emissions (UNEP 2007). Environmental performance of buildings during operation period are widely studied and known whereas knowledge about the environmental performance of building products are relatively limited and also information found is differing/conflicting. This is mostly due to the fact that conditions of use, technology of manufacture, preferences, etc. are specific to country or region and these affect the assessment results. Information on energy necessary to extract raw materials, manufacture and distribution of products, which is referred as embodied energy, needs to be carefully used and national life cycle assessment (LCA) studies need to be conducted to construct a building product database in terms of embodied energy (UNEP 2007; ARUP 2006).

LCA is a general environmental assessment technique that has been widely accepted and used as a base to compare alternative materials, components and services. In building research community, as well as the studies focusing on improving and adapting the LCA methodology, research studies using LCA as a tool to assess buildings, building services or building products are found. Recent studies indicate that, product manufacturing and construction phases have also important effects on the total environmental impact as well as the use phase of buildings (Nässén *et.al.* 2007, Gerilla *et.al.* 2007, Kibert 2005). A brief survey on LCA applications at building product level and on embodied energy of building products as well is presented as follows. Koroneos and Dompros (2007) present a cradle-to-gate LCA field survey conducted to assess the brick production in Greece, and discuss the emissions to environment and their impacts. Ardente *et. al.* (2006) present a cradle-to-gate LCA field survey on kenaf-fibres insulation board, and compares its environmental performance with other insulation products in terms of energy consumption and environmental impacts when used in residential buildings. Schmidt *et. al.* (2004a, 2004b) present a comparative LCA study on roof insulation products made of stone wool, paper wool and flux, based on the inventory data collected from literature, LCA databases and suppliers. The comparison presented considers emissions to environment, energy and resource depletion, solid wastes, and their impacts. Health aspects are taken into account in the comparison as well. Reddy and Jagadish (2003) discuss the embodied energy of different types of basic building materials, masonry wall units and mortar types. Results derived from the practices in India indicate that total embodied energy of load bearing masonry buildings can be reduced by 50% when energy efficient/alternative building materials are used. Alcorn and Wood (1998) outline the embodied energy research at University of Victoria and describe the embodied energy coefficients, their background and derivation. They discuss the process-based hybrid analysis including input-output analysis. Basic approach given in the existing manual system of analysis for collecting data includes steps as: definition of product/material; major and minor players in the field; constituent ingredients and composition of product; detailed manufacturing process; energy inputs; output of a particular processing plant; prices; source, age and confidentiality of data; and other comparative data. Alcorn (2001) applies CO_2 emission factors and derives embodied CO_2 coefficients for New Zealand building materials, based on the previous embodied energy work. An example of recycled steel is also presented.

Essential requirements for sustainable building products include more efficient use of inputs such as: reduction in consumptions of non-renewable raw materials; adoption of energy efficient and clean production methods and technologies; optimum use of water; increased recycling/reuse of waste in the production; shortened distances for transportation; and the outputs such as minimized associated environmental impacts. Hence, depending on the energy efficiency during building use phase, relatively higher environmental impact of embodied energies of the building products can be anticipated.

In Turkey, in-situ reinforced concrete structural frame with masonry infill walls is the most preferred construction system in buildings. External thermal insulation systems are also used lately. Widely used infill masonry products are fired clay hollow bricks and autoclaved aerated concrete (AAC) blocks, and use of pumice aggregate concrete hollow blocks has increased recently. Studies on LCA of fired clay bricks and AAC blocks can be found in literature, since these are global products. However, research on pumice aggregate concrete blocks is limited due to its relatively local character. Additionally, as aforementioned, in each country, specific investigations are required to be done for every product in order to obtain correct information about embodied energy, gas and particulate matter emissions.

In this paper, within this context, environmental assessment of the aforementioned masonry wall products regarding the manufacturing processes is considered. The aim is to gather inventory information about these products and to develop a local comparative model that is highlighting differing characteristics of each product in terms of environmental issues such as energy and resource use, CO_2 emissions etc.

2. Methodology

LCA is a tool designed to aid in environmental evaluation and decision making at various hierarchical levels and consists of; (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation phases. Inventory analysis, includes the identification and quantification of all inputs and outputs of the studied system. The inputs and outputs cover items such as natural resources; energy; releases to air, water and land; co-products, etc. (ASTM 1991).

The inventory investigation of building products usually covers five main life-cycle stages, i.e. material acquisition, manufacturing, construction, use and disposal/recycling. The scope of this study on masonry wall units is, however, limited with material acquisition and manufacturing stages. Data is collected through field investigations of plants manufacturing fired clay hollow bricks, AAC, and pumice aggregate concrete hollow blocks. Following topics are studied in details:

- Raw materials acquisition
  - extracting mineral resources from quarry
  - supplying materials in processed form
  - transportation.
- Product manufacturing
  - constituent ingredients and composition of products
  - manufacturing processes – technology
  - packaging, storage and delivery.

Plant facility characteristics unique for each investigated specific building product also have some effects on environment and therefore included in the study. Plant location, plant capacity, number of workers and their transportation, electricity and water use for domestic purposes, heating of office buildings and plants, etc are relevant information considered in the case studies.

Impact assessment phase of LCA aims to evaluate the significance of potential impacts of the investigated system using the inventory data. The level of detail, choice of impacts evaluated and methodologies used depends on the scope of the study (ISO, 1997). Within the scope of this study, the following criteria are adopted for the input-output analysis in order to assess the embodied energy and the environmental impact of the investigated masonry wall units:

- Resource consumption
  - mineral use
  - water use
- Land disturbance
- Energy consumption
  - mining
  - production processes
  - transportation

- Environmental impact
  - gas emissions
  - particulate matter
- Waste management.

The interpretation of inventory analysis and impact assessment results are made on a general basis due to the fact that the field investigations were executed in limited number of manufacturing plants and therefore will not be representative of the whole masonry wall product manufacturing industry.

3. Inventory Investigations of Masonry Wall Units

Inventory investigations of pumice concrete block and AAC block were presented in detail in Kus *et. al.* (2007). In this report, only the brief information for these products are given for comparison purposes, while fired clay brick production is thoroughly explained.

3.1 Plant Facility Characteristics

The investigated plants are all located nearby the raw material sources in order to shorten the transportation distance to manufacturing units. This preference helps to save energy and in turn reduces transportation costs and environmental impacts. Final distribution distances for the delivery of manufactured products to construction sites have also an effect on the selection of plant location and the possible shortest distances to target market areas are preferred. Specific information about the investigated plants are given in Table 1.

Table 1 Some facts and figures about the investigated plants

	Pumice Concrete Block	AAC Block	Fired Clay Brick
Plant Location	Nevsehir (mid-Anatolia)	Hereke-Kocaeli (Marmara)	Isiklar-Istanbul (Marmara)
Plant Capacity / year	30,000,000 blocks	100,000 m^3	~175,500,000 bricks
Plant Operation Duration/day	24 hours – 3 Shift	24 hours – 3 Shift	24 hours – 3 Shift
Number of Production Lines	2	1	3 (extrusion and drying)
Electricity – supplied from / annual consumption (if available)	City supply network 1.8 million kWh	Private power plant using natural gas	Private power plant using natural gas
Water – supplied from	Wells in plant area	Wells in plant area + city supply network	Two artificial lake on former clay pits
Energy used in space heating / annual consumption (if available)	Coal 250-300 tons	Natural gas	Natural gas
Number of Workers (Total)	148	31	270
Office / Other	15 / 49	11 / -	41 / -
Production / Loading	60 / 12	20	89 / 140
Raw Material Acquisition	12	Outsourced (from sister company)	Outsourced
Transportation of workers			
Shuttles (number and type / travel distance per day)	1 minibus / ~240 km 1 bus / ~80 km	1 minibus / ~270 km	1 minibus / ~180 km 1 bus / ~100 km
Number of Private Cars	8 (for office workers)	-	8-10 (for office workers)

3.2 Materials Acquisition

Material acquisition phase includes all activities and processes required for obtaining all raw materials, energies and other material requirements for the product system (ASTM 1991). In the investigated plants raw materials are supplied either by extracting from the quarry or by purchasing in the processed form.

3.2.1 Raw Materials Acquisition of Pumice Concrete Blocks

Pumice aggregate, cement, water and iron oxide are constituent materials of pumice concrete block production. Auxiliary materials required in association with block production are timber pallet, steel and plastic strip, and kraft paper protection corner pieces for packaging. Information relevant to inventory analysis is summarised in Table 2.

Pumice aggregate preparation for block production is consisted of (i) excavation and loading of pumice, (ii) transportation to cleaning/sorting bunker, (iii) cleaning and sorting of pumice, and (iv) transportation to production bunker processes. Pumice is excavated from three different areas, one located at the factory site and the others located 4 and 10 km far from the factory. Pumice is usually found close to the surface and as 4-5 metres thick bands (Figure 1). Cleaned and washed pumice aggregate is screened into 0-3 mm, 3-8 mm, 8-16 mm and over 16 mm. Aggregates in 3-8 mm and 8-16 mm sizes, used in the block manufacturing, are filled into bunkers through band conveyors and are ready to be used in the production mix. Water, in addition to block production, is used for cleaning and sorting of pumice aggregate (Figure 2), and after re-used.

Table 2 Figures for Material Acquisition in Pumice Concrete Block Production (after Kus *et. al.* 2007)

Purchased basic materials	Annual consumption*	Supplied from (distance)	Transportation method/capacity	Transportation energy
Cement	30,000 t	65 km	Truck / 40 t	Diesel fuel
Iron oxide	84 t	797 km	Truck / Vary	Diesel fuel
		~8000 km	Ship / Vary	Diesel fuel
Timber pallet	150,000 pieces	70 km	Truck/ 40 t	Diesel fuel
Steel strip	150 t	797 km	Truck / 40 t	Diesel fuel
Plastic strip	70 t	797 km	Truck / 40 t	Diesel fuel
Kraft protection	35 t	Vary	Vary	Vary

Extracted material	Annual consumption*	Extraction processes	Machine used in processes	Energy input
Pumice	300,000 t	Excavation	Wheel loader	Diesel fuel
		Transportation (~4.5 km)	Truck / 32 m^3	Diesel fuel
		Cleaning / Sorting	Sieve	Electricity
		Loading	Wheel loader	Diesel fuel
		Transportation (~0.5 km)	Truck	Diesel fuel
Water for block production	95,000 t	Pumping	Water pump	Diesel fuel

* Consumption amounts are based on annual production of 30 million blocks having dimensions 19 x 33 x 24 cm and weight 7346 g/block.

Figure 1 Pumice excavation in the main quarry

Figure 2 Cleaning / sorting machine

3.2.2 Raw Materials Acquisition of AAC Blocks

Sand (quartz), cement, lime, gypsum, water and aluminium powder are constituents of AAC block production. Timber pallets and polyethylene wraps for packaging are the other materials used in the investigated plant in association with the block production. All materials required for production are purchased from outside sources. However lime and cement are supplied from sister companies located at the same site, therefore classified as in-house supplied material. Lime plant employs two 250 tonnes/day Maerz type parallel flow regenerative (PFR) shaft lime kilns. Information relevant to inventory analysis is summarised in Table 3.

Table 3 Figures for Material Acquisition in AAC Block Production (after Kus *et. al.* 2007)

Purchased Material	Annual Consumption	Supplied from (distance)	Transportation Method /Capacity	Transportation Energy
Sand	35,000 t **	~100 km	Truck / 16 t	Diesel fuel
Gypsum	1,500 t **	453 km	Truck / 16 t	Diesel fuel
		250 km	Truck / 16 t	Diesel fuel
Aluminium powder	400 t **	~2,000 km	Long vehicle / 20 t	Diesel fuel
			Ship / vary	Diesel fuel
Water*	25,000 m^3 **	-	-	-
Timber pallet	92,600 pieces	~30 km	Truck / 16 t	Diesel fuel
Polyethylene wrap	92,600 pieces	~80	Truck / 16 t	Diesel fuel

In-house Supplied Material	Annual Consumption	Supplied from (distance)	Machine used in processes	Energy input
Lime	7,000 t **	0 km	Air compressor	Electricity
Cement	7,000 t **	3 km	Truck / 16 t	Diesel fuel

* includes water supplied from wells at the factory site.
** Calculated consumptions based on annual production of the factory (100,000 m^3) and AAC recipe obtained from product literature (Masa-Henke, 2003). Aerated concrete paste recipe is for a density of 500 kg/m^3.

3.2.3 Raw Materials Acquisition of Fired Clay Bricks

Inner materials used in fired clay brick production are clay and water. In the investigated factory three different types of clay are used in the brick recipe. Clay pits of type 1 and 2 are about 1.5 km, and type 3 is about 2 km far from manufacturing facilities, and all pits are factory's own property.

In clay extraction excavators, front-end or backhoe wheel loaders, and in transporting clay to brick manufacturing storage area trucks are used. Trucks operating between pits and manufacturing plant are returning back to pit empty, and this situation doubles the energy consumption per a truck of clay.

Water required for brick production is supplied from in-house sources, i.e. two artificial lakes. One lake is about 0.5 km and the other is about 1 km far from the brick production facilities and water is transported to production area through pipelines.

Information relevant for inventory analysis of the investigated factory's material acquisition phase is summarised in Table 4.

Table 4 Figures for Material Acquisition in Fired Clay Brick Production

Extracted / In-house Material	Annual consumption	Extraction / Supply processes	Machine used in Processes / Capacity	Energy input
Clay	~381,489 t*	Excavation / Loading	Excavator	Diesel fuel
		Front-end of backhoe loader		Diesel fuel
		Transportation (~1.5 km)	Truck / 25 t	Diesel fuel
Water for block production	~15,895 t	Piping (~0.5-1 km)	Water pump	Electricity

* Calculated consumption figures based on annual production of 175,348,800 bricks (19 x 19 x 8.5 cm and weight 1850 g/brick) and assuming that moisture content of extracted clay is 20 % during whole year.

3.3 Manufacturing of Masonry Wall Units

Product fabrication, intermediate manufacture, raw material conversions excluded in material acquisition stage, packaging, storing and internal transportations either outdoors or indoors are processes included in the inventory investigations of the plants.

3.3.1 Pumice Concrete Block Manufacture

Pumice concrete block manufacturing processes in the investigated factory are mainly (i) mixing, (ii) moulding, (iii) drying, (iv) packaging, and (v) storing. Sometimes an additional crushing process prior to mixing process is included when pumice aggregates are stored in production bunker without a sorting process. Blocks are formed by injection and pressing through steel mould and subsequent vibration processes. Wet blocks are air-dried in a chamber for 72 hours. During production process, handling, placing and transport of pumice concrete blocks are made by the help of a robot arm and automatic controlled transport tower while the removal of faulty blocks and packaging are made only manually. In this respect, it can be said that highly mechanised technology is adopted by the plant. Information about sub processes of main phases, and machines and equipments used in these processes are summarised in Figure 3.

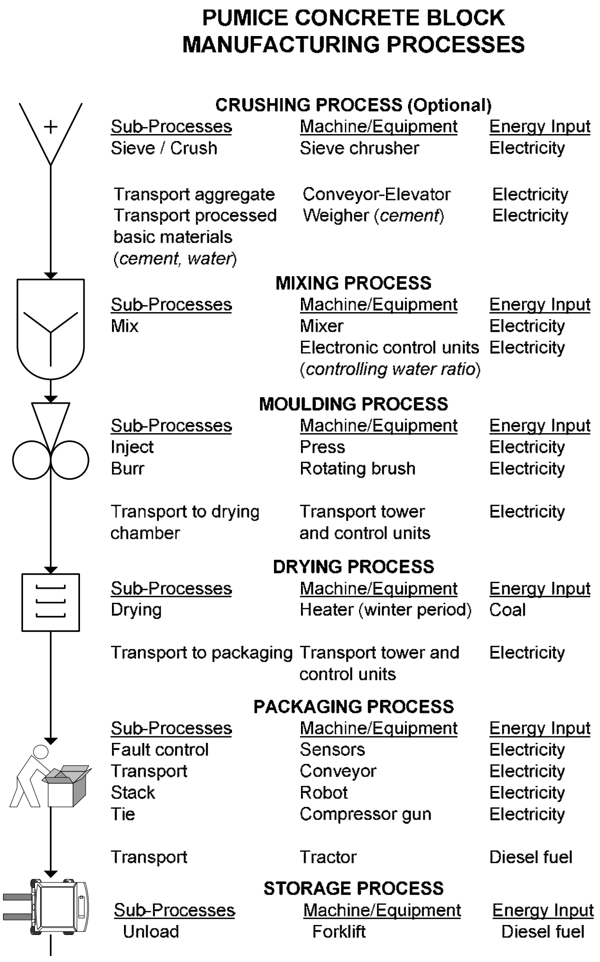
3.3.2 AAC Block Manufacture

AAC block manufacturing processes in the investigated factory are mainly (i) crushing, (ii) mixing, (iii) moulding, (iv) cutting, (v) steam curing, (vi) packaging and (vii) storing.

After crushing of silica sand with gypsum and then mixing all materials, aluminium powder is added and the paste is poured into the moulds. The expanded and hardened green cake is then wire-cut to desired size and steam-cured at 200 °C and 12 bar for about 10 hours for gaining its final strength and stiffness. The finished product is packaged and is usually delivered directly to the construction site.

The chemical reaction caused by addition of aluminium makes the mixture expand to about twice its volume, resulting in a highly porous structure. Approximately 80% of the volume of the hardened material is made up of pores, 50% being air pores and 30% being micropores. The microstructure of the solid matrix is mainly made up of microcrystalline platelets of tobermorite, calcium silicate hydrate, forming the pore walls (Aroni et.al. 1993). The quality of end product is highly influenced by the quality and mix design of raw materials, and the design of production technique among the other factors.

Information about sub processes of main phases, and machines and equipments used in these processes are summarised in Figure 4.



PUMICE CONCRETE BLOCK MANUFACTURING PROCESSES

CRUSHING PROCESS (Optional)

Sub-Processes	Machine/Equipment	Energy Input
Sieve / Crush	Sieve chrusher	Electricity
Transport aggregate	Conveyor-Elevator	Electricity
Transport processed basic materials (*cement, water*)	Weigher (*cement*)	Electricity

MIXING PROCESS

Sub-Processes	Machine/Equipment	Energy Input
Mix	Mixer	Electricity
	Electronic control units (*controlling water ratio*)	Electricity

MOULDING PROCESS

Sub-Processes	Machine/Equipment	Energy Input
Inject	Press	Electricity
Burr	Rotating brush	Electricity
Transport to drying chamber	Transport tower and control units	Electricity

DRYING PROCESS

Sub-Processes	Machine/Equipment	Energy Input
Drying	Heater (winter period)	Coal
Transport to packaging	Transport tower and control units	Electricity

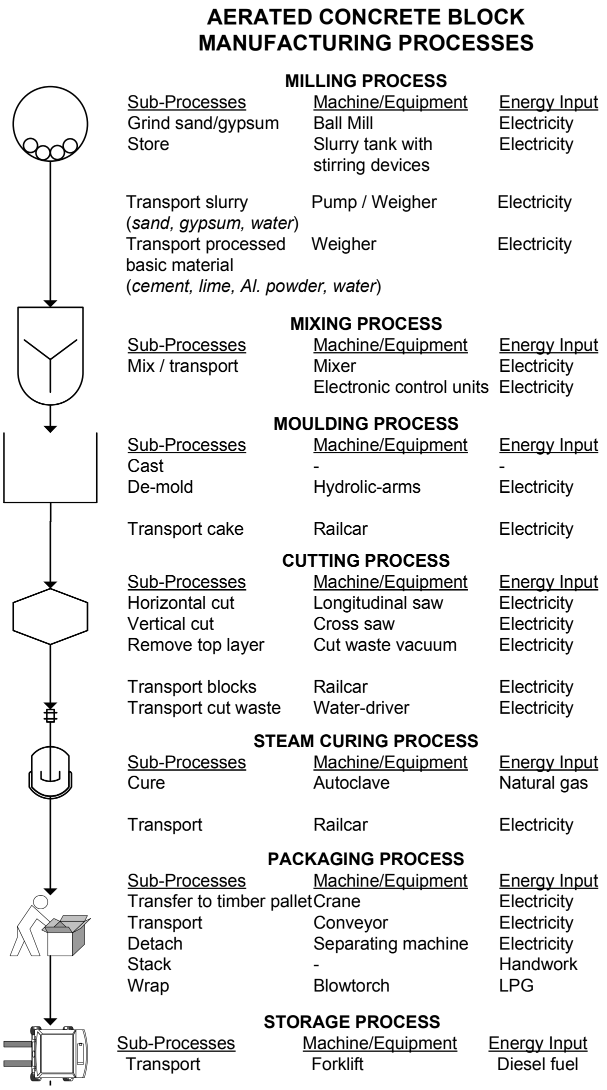
PACKAGING PROCESS

Sub-Processes	Machine/Equipment	Energy Input
Fault control	Sensors	Electricity
Transport	Conveyor	Electricity
Stack	Robot	Electricity
Tie	Compressor gun	Electricity
Transport	Tractor	Diesel fuel

STORAGE PROCESS

Sub-Processes	Machine/Equipment	Energy Input
Unload	Forklift	Diesel fuel

Figure 3 Pumice concrete block manufacturing processes



AERATED CONCRETE BLOCK MANUFACTURING PROCESSES

MILLING PROCESS

Sub-Processes	Machine/Equipment	Energy Input
Grind sand/gypsum	Ball Mill	Electricity
Store	Slurry tank with stirring devices	Electricity
Transport slurry (*sand, gypsum, water*)	Pump / Weigher	Electricity
Transport processed basic material (*cement, lime, Al. powder, water*)	Weigher	Electricity

MIXING PROCESS

Sub-Processes	Machine/Equipment	Energy Input
Mix / transport	Mixer	Electricity
	Electronic control units	Electricity

MOULDING PROCESS

Sub-Processes	Machine/Equipment	Energy Input
Cast	-	-
De-mold	Hydrolic-arms	Electricity
Transport cake	Railcar	Electricity

CUTTING PROCESS

Sub-Processes	Machine/Equipment	Energy Input
Horizontal cut	Longitudinal saw	Electricity
Vertical cut	Cross saw	Electricity
Remove top layer	Cut waste vacuum	Electricity
Transport blocks	Railcar	Electricity
Transport cut waste	Water-driver	Electricity

STEAM CURING PROCESS

Sub-Processes	Machine/Equipment	Energy Input
Cure	Autoclave	Natural gas
Transport	Railcar	Electricity

PACKAGING PROCESS

Sub-Processes	Machine/Equipment	Energy Input
Transfer to timber pallet	Crane	Electricity
Transport	Conveyor	Electricity
Detach	Separating machine	Electricity
Stack	-	Handwork
Wrap	Blowtorch	LPG

STORAGE PROCESS

Sub-Processes	Machine/Equipment	Energy Input
Transport	Forklift	Diesel fuel

Figure 4 AAC block manufacturing processes

3.3.3 Fired Clay Brick Manufacture

Fired clay brick manufacturing processes in the investigated factory are mainly (i) clay / mud preparation, (ii) forming, (iii) drying, (iv) firing and (v) storing.

In the clay / mud preparation process, clay mixture of three different clay types taken from storage area is crushed and watered in the edge mil. Clay mud then transported to Vals machine for being compacted to eliminate air pockets. Later, it is transported to double shafts mixer for proper mixing and watering if moisture content is not adequate. For a proper forming, moisture content of clay needs to be 23-25 % by weight. During winter time, moisture content of extracted clay is about 18 % and less watering is required. However in summer time additional watering to obtain adequate moisture content is always required. Finally clay mud is transported to interim silos for resting.

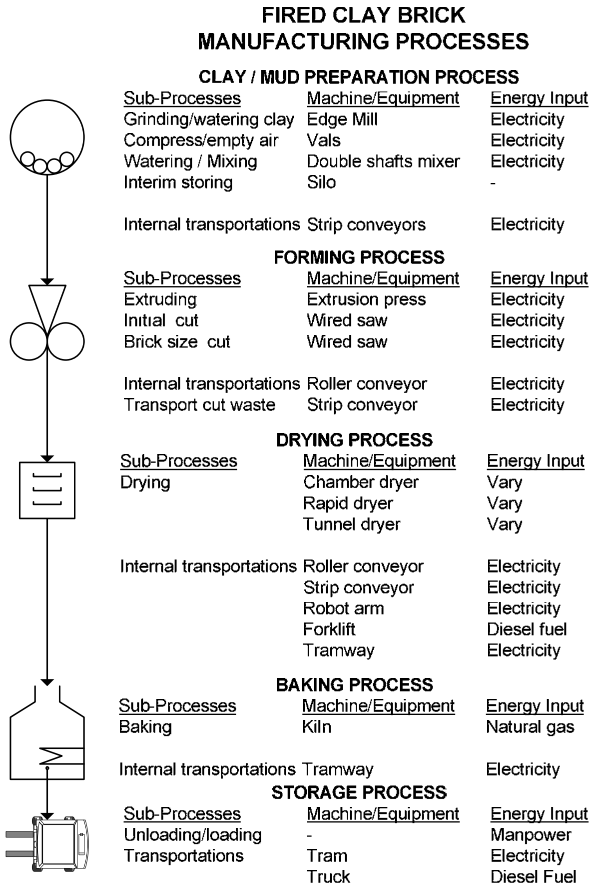
In the forming process, clay mud taken from silos are compacted in the Vals machine and then transported to extrusion press. A long piece of paste is extruded through the die and is cut into smaller pieces with an initial cut and then into individual brick size with a second cut by means of a wired saw. The cut waste of the second cut is transferred back to extruder. Formed bricks are either transferred to pallettes for being transported to tunnel or chamber drying units, or directly transported to rapid drying unit by roller conveyor.

In the drying process, three different types of drying techniques are used. The first one is “chamber drying technique” in which shelved pallettes are filled into the chamber and the temperature of the chamber is increased to about 200 ℃ and left for a certain time, then the temperature is slowly decreased and the shelved pallettes are taken out. The drying continues approximately for 17 hours. The second one is “tunnel drying technique”, in which shelved pallettes move in the tunnel where the temperature increases slowly and remains in about 200 ℃ for 8 hours then slowly decreases. It takes approximately 10 hours for drying. The last one is “rapid drying technique” in which bricks move on conveyors and the air temperature in rapid drying unit gradually increased up to 200 ℃ and remains for certain time then decreased along the unit. It takes ~4 hours to complete drying. Following the drying, dry bricks are transferred to and loaded on trams by the help of conveyors and robot arms. Moisture content of dried bricks is about 1-2 % in summer time and 3-5 % in winter time.

In the firing process, trams move in the kiln having a length of 187 metres and the air temperature is gradually increasing and then decreasing along the length of the kiln. The maximum air temperature in the kiln is about 900 ℃ and it takes about 20 hours to complete the firing of a brick loaded tram. The temperature in the kiln is continuously monitored at several places.

Finally, the trams are transported to the outside of the manufacturing building for either being transported to storage area or for being directly distributed to construction sites.

The machines and equipments, and energy used in the manufacturing of fired clay bricks are summarised in *Figures* 5-7.



FIRED CLAY BRICK
MANUFACTURING PROCESSES

CLAY / MUD PREPARATION PROCESS

Sub-Processes	Machine/Equipment	Energy Input
Grinding/watering clay	Edge Mill	Electricity
Compress/empty air	Vals	Electricity
Watering / Mixing	Double shafts mixer	Electricity
Interim storing	Silo	-
Internal transportations	Strip conveyors	Electricity

FORMING PROCESS

Sub-Processes	Machine/Equipment	Energy Input
Extruding	Extrusion press	Electricity
Initial cut	Wired saw	Electricity
Brick size cut	Wired saw	Electricity
Internal transportations	Roller conveyor	Electricity
Transport cut waste	Strip conveyor	Electricity

DRYING PROCESS

Sub-Processes	Machine/Equipment	Energy Input
Drying	Chamber dryer	Vary
	Rapid dryer	Vary
	Tunnel dryer	Vary
Internal transportations	Roller conveyor	Electricity
	Strip conveyor	Electricity
	Robot arm	Electricity
	Forklift	Diesel fuel
	Tramway	Electricity

BAKING PROCESS

Sub-Processes	Machine/Equipment	Energy Input
Baking	Kiln	Natural gas
Internal transportations	Tramway	Electricity

STORAGE PROCESS

Sub-Processes	Machine/Equipment	Energy Input
Unloading/loading	-	Manpower
Transportations	Tram	Electricity
	Truck	Diesel Fuel

Figures 5 - 7 Fired clay brick manufacturing processes (left); cutting and transportation of cut waste (right-top) and brick extruded from die and shelved bricks for being transported to drying unit (right-bottom)

4. Environmental Assessment

Resource and energy consumption, green house gas emissions and land use issues are thoroughly discussed for environmental assessment of masonry wall units regarding manufacturing phase.

4.1 Resource Consumption

Depletable resources consumed as raw materials in the manufacturing processes of clay bricks and concrete blocks can be classified as minerals and water. Considering sustainability, the amount of available reserves and the materials extracted in a year come into question. Low density of building products means lower consumption of raw materials contributing to their conservation. This is also beneficial during the use phase of the building, either by reducing the total loads of the building or providing better thermal insulating properties achieving greater energy efficiency. Despite their contribution to energy efficiency (with their low thermal conductivity) during the operation (use) phase of buildings, extended durability and service life of these products gain importance in reducing the depletion of natural resources by decreasing the need for new building construction.

Non-renewable energy resources like natural gas, fuel oil and coal are considered under the energy consumption sub-heading. Less-used raw materials and auxiliary materials used for packaging are left out of the scope of the present study.

4.1.1 Mineral Use

Pumice, quartz sand and clay are the main minerals needed to produce concrete blocks and clay bricks. In addition, limestone is used for cement and lime production. All these minerals are often obtained by surface quarrying. Use of recycled materials in the production is regarded as very important for decreasing the amount of extracted materials and thus protecting the finite mineral resources. In Table 5, annual mineral consumption amounts are given for all three plants. In cement manufacture, in average, 1.27 tonnes of limestone and 0.05 tonne gypsum are consumed per 1 tonne of cement (IPPC 2001). Regarding lime production, 1.78 tonnes of limestone is consumed to produce 1 tonne of quicklime (Hill and Mason 1997).

Table 5 Annual Mineral Consumption of the Visited Plants Manufacturing AAC, Pumice Concrete and Brick

	Density (kg/m^3)	Annual consumption	Pumice (tonne)	Clay (tonne)	Sand (tonne)	Gypsum (tonne)	Limestone (tonne)
AAC Block	500 (bulk)	100,000 m^3	-	-	35,000	1,850	21,350
Pumice Concrete Block (Hollow) 7.346 kg/block	488 (bulk)	30,000,000 block 451,598 m^3	300,000	-	-	1,500	38,100
Fired Clay Brick (Hollow) 1.85 kg/brick	602 (bulk)	175,500,000 brick 539,327 m^3	-	381,489	-	-	-

4.1.2 Water Use

Water needed for the production of block and brick is obtained in three ways: (i) by pumping underground water from the wells opened in the plant area; (ii) utilizing rainwater collected in the artificial lakes; and (iii) city water supply network. Total amount of water required for the processes and used for domestic purposes gains importance. Climate change is the biggest threat for the sustainability of water resources thus minimizing water use and recycling of waste water is important for efficient use and conservation of water.

4.2 Land Disturbance

From a sustainability point of view, the world reserves including non-renewable mineral resources are increasingly consumed in construction sector and the natural state of the landscape is destroyed leaving back a permanent change. After surface mining of minerals like pumice, clay, sand and limestone, disturbed land, i.e. the quarry and the surrounding land, needs rehabilitation. Land reclamation can be determined according to the specific characteristics of the open pits and the site. Agriculture and forestry are generally preferred land cover types.

In our case, depleted pumice pits are used as cultivation substrate to potato field. Clay extraction pits are rehabilitated as artificial lakes from which the water needed for the production is transported by pipes to the plant.

4.3 Energy Consumption

Natural gas, fuel oil and coal are the main energy resources for space heating in Turkey. These are depletable energy resources therefore need to be conserved and replaced by recycled or renewable ones as much as possible. On the other hand, energy for drilling of oil, gas and coal is indirectly covered by the embodied energy of the masonry wall units as for all other construction products. Electricity needed for space lighting and operating the machines is provided from city supply network and is mainly generated either from hydro-electric power stations or thermal power stations using natural gas. Besides, industry can also generate its own electricity using natural gas, as in our case, brick and AAC plants do. Vehicles used for transportation of either goods or people of industry mostly have diesel engine with manual gear type.

In addition, there is indirect embodied energy required for the investments like the machines, tools and all equipments used for extraction, production and transportation of construction products as well as infrastructure needed for generating electricity. Indirect energy for the production and maintenance of vehicles used in transportation can also be mentioned.

4.3.1 Energy Consumption in Mining

Equipment required for performing this process comprises front-end or backhoe wheel loaders. To power these work machines, diesel engine is used. Energy consumption greatly depends on the properties and efficiency of machines used as well as the amount (in weight and volume) of raw materials extracted and the depth of the excavation. Density of the material extracted thus play important role.

4.3.2 Energy Consumption in Production Processes

In the production process of masonry wall products, in general, (grinding, mixing and forming) machines work with electricity.

Heating and firing processes account for the highest energy use than any other processes; therefore temperature/time relationship is significant in determining energy consumption. For autoclaving and brick firing processes in the investigated plants, the required energy is supplied by natural gas. The autoclaving temperature of AAC is about 200 °C at 12 bar for about 10 hours. Waste steam generated at the power plant owned by the manufacturer is used in this process, thus no extra energy is required. Electricity is also supplied by this gas turbine and combined-cycle power plant. For brick, drying temperature is about 200 °C for about 4-17 hours depending on the type of the technique used, and the firing temperature is about 900°C for 20 hours. In the visited plant, the waste heat from the cooling zone of brick kiln is utilized in the drying process. In pumice concrete block manufacturing; on the other hand, there is no need for high temperatures in the process. The only heating needed is, in winter, for keeping the drying chamber air temperature around 15 °C. However, the production process of raw materials like cement and lime is highly energy intensive. High temperatures (about 1500 °C) are required in the cement clinker production phase. For the production of cement and lime, shaft kilns are generally used. Cement content in pumice concrete mix design, and cement and lime contents in AAC mix design constitute the total energy intensity together with the energy required for the other manufacturing processes. Indeed, embodied energies based on volumetric bulk densities of the wall units yield more practical values. Shape and hollow design of pumice concrete blocks and bricks are thus taken into account in terms of their contribution to energy efficiency and/or saving.

In Table 6, embodied energies, as found in literature are given (Elliott 2007, Hendriks *et.al.* 2004, NRC-OEE).

Table 6 Embodied Energy of Masonry Wall Products Manufacturing (excluding transportation)

	Mining & Hauling (MJ/m^3)	Screening & Sorting (MJ/m^3)	Cement production (MJ/kg)	Lime production (MJ/kg)	Embodied Energy (MJ/kg)	Embodied Energy (MJ/m^3)
AAC Block	Sand/limestone 78.79 / 78.79	Sand/limestone 78.79 / 78.79	3.5 – 5.5 (dry process)	5.0 – 7.0 (vertical kiln)	2.1 - 3.6	1050-1800*
Pumice Concrete Block	Pumice/limestone 48.14 / 78.79	Pumice/limestone 78.79 / 78.79	3.5 – 5.5 (dry process)	-	0.94 - 1.5	459-732*
Fired Clay Brick	Clay 78.79	Clay 78.79	-	-	1.2 - 2.5	722-1505*

* Calculated values in terms of bulk densities of the investigated plants' products.

4.3.3 Transportation

Internal (short distance) transportation within the plants, either indoors or outdoors, is generally provided by (horizontal, inclined or vertical) belt, roller conveyors and bucket elevators, 1-rail and/or 2-rail carriage systems, robot arm systems, crane, fluid transfer (slurry or watering) pumps and pipelines. All these transport equipments work with electricity. Furthermore, diesel tractor and forklifts are employed in moving and transporting final products within plant area. Between the quarry and the plant, diesel engine trucks are used. For the delivery of final products, dominating means of transport is road truck. Depending on the weight (and volume) of carried products (raw materials, auxiliary materials or masonry wall units) and the type/properties of vehicle, diesel consumption of rigid trucks varies between 30-45 litre/100 km. Shuttle bus or minibus, on the other hand, consumes diesel between 15-30 litre/100 km depending on the model (age) and type of engine.

In the investigated plants, annual total diesel consumption amounts needed for transportation of raw materials including transportation of plant workers and excluding final distribution of products are given in Table 7. Assumptions were made as all three plants work 330 days and offices 300 days a year. Trucks operating between pits and manufacturing plants are returning back to pit empty. This situation doubles the energy consumption per a truck of raw material transported but transportation of aluminium powder from abroad is exception. It is clearly seen that, transportation of AAC raw materials consumes significantly high energy and transportation of brick raw materials significantly less. This is probably not associated with the capacities of the plants. It is most likely related to the distances and the capacities of the vehicles employed.

Table 7 Annual Diesel/Gasoline Consumption from Transportation including Transportation of Plant Workers

	Raw Materials Truck (diesel)	Shuttle (diesel)	Car (gasoline)	Total Diesel consumption	Total Gasoline Consumption	CO_2* (Materials)	CO_2* (Workers)
AAC	174,640 l	17,820 l	-	192,460 l	-	501,216 kg	51,143 kg
Pumice concrete	71,200 l	21,120 l	6,000 l	92,320 l	6,000 l	204,344 kg	76,154 kg
Brick	14,650 l	18,480 l	7,200 l	33,130 l	7,200 l	42,045 kg	71,685 kg

*1 litre of diesel = 2.87 kg of CO_2 equivalence and 1 litre of gasoline = 2.59 kg of CO_2 equivalence (Jaques et.al. 1997).

4.4 Environmental impact

In order to provide a basis for a comparative environmental assessment of masonry wall units, it is necessary to identify the processes which require higher energy, and consequently, to determine the approximate embodied energies. Environmental impact depends principally on the amount and type of energy used in:

- extraction and processing of raw or primary materials
- manufacturing of products
- operation and maintenance of plant facilities including offices
- transportation of raw and auxiliary materials, manufactured products (delivery), and industry workers involved in the manufacturing processes.

Gas emissions and particulate matters are considered as the environmental impacts associated with the embodied energies of masonry wall units.

4.4.1 Gas Emissions

The main source of CO_2 emissions is burning fossil fuels like coal, oil and natural gas, and can be attributed to the high temperatures required in cement, lime, brick and AAC block production. In cement and lime production, the calcination process also gives out CO_2, which makes up about 50 % of the total CO_2 emission. In Table 8, gas emission factors are given as found in literature (EPA, ETS, GBC).

Table 8 Emission Factors

	SO_X kg/Mg	CO_2 kg/Mg	C_2H_4 Kg/Mg
Brick	1.22	194 - 235.5	0.07
AAC block	2.23	265 – 448	0.175
Pumice concrete hollow block	0.172	106	0.0229
Cement	0.56	710 – 970	0.0231
Lime	0.55	859 - 1210	0.0252

4.4.2 Particulate Matter

Particulate matters (PM), as coarse and fine particles, are emitted from power plants, industries, vehicles and buildings. PM quantities widely vary according to the plant characteristics and use of measures such as dry filter systems or electrostatic precipitators. Amount of PM emissions generated from cement, lime and brick production, depends mainly on the type of fuel, pre-heater, kiln (rotary, vertical shaft) and cooler used.

4.5 Waste Management

Minimizing waste generation and effective reuse/recycle through manufacturing processes are very important regarding reduced raw materials consumption and energy needed for post-processing of waste.

Waste material left over from the AAC manufacturing processes, prior to steam-curing process while it is still wet and unhydrated, are water-driven to auxiliary return tank for being used in the mix preparation. Faulty AAC blocks detected after curing process is stored in a waste area and sometimes used as pavement filler. Recycling of these blocks by grinding and adding to the mix production is planned for the near future.

In the pumice concrete block manufacturing processes, since the mixture is injected and pressed through moulds as individual units, there is no wet waste. Faulty or broken pumice concrete blocks which are already hardened after drying, are used as pavement filler material in the factory area to cover the pumice dust lying over the ground. Pumice aggregates left over after sorting and which are not used in the block manufacturing, having sizes over 16 mm, are used in the textile industry and in agriculture whereas sizes of 0-3 mm are used to produce plaster mortar.

Regarding the waste material from the brick manufacturing processes, the cut waste material is transferred back to the extruder. Faulty or broken bricks which are detected after firing, are stored at plant site for more than 30 years, and sometimes used as landfill when requested by neighbour factories. A research project is to be set up by the plant owner for utilizing this collected waste in the best way.

In all three plants, measures are taken to reduce the amount of faulty/broken products and the ratio of these remains between 1-2% of total production.

No wastewater is generated in any of the three plants except for the domestic water waste in the offices.

5. Conclusions

In this report, an attempt is made for understanding and comparatively assessing the manufacturing phase of masonry wall units regarding energy consumptions and environmental impacts. Comprehensive information on extraction of natural resources, processing of raw materials, manufacturing and transportation were collected from masonry wall products' manufacturing plants and data obtained was systematically organized. One plant for each masonry wall product, namely pumice concrete block, AAC and brick, was visited and their productions were investigated in detail. Plant facility characteristics were also considered as a factor affecting the environmental performance of factory-made building products. It should be noted that each plant has its own unique manufacturing characteristics and therefore it should not perceived as representing the general situation in Turkey. Other factories manufacturing masonry wall units may differ on certain measures. When assessing embodied energies according to the volume of the end-product the following conclusions can be drawn;

- AAC block manufacturing requires very low raw materials consumption due to the high porosity of the end-product. However, cement, lime and aluminium powder content in the production mixture are energy intensive processed materials although used in low quantities compared to the amount of end-product, and therefore product's embodied energy increases. Besides, autoclaving also requires relatively high energy.
- Fired clay brick manufacturing can be considered, relatively, energy intensive due to the high energy required for high temperatures in the kiln. However, its low bulk density (because of hollow design of brick) significantly reduces the embodied energy.
- Pumice concrete block manufacturing, although energy intensive cement is used, seems to be the most energy efficient among all, since no heating required in the processes, and because of its low bulk density due to porous structure of pumice aggregate and also hollow design of block.

Maximum efficiency is obtained in terms of consuming less depletable resources by either hollow design of bricks and blocks or porous material structure of the latter. In general, less use of raw materials according to the volume of the end-product contributes energy efficiency both in production and transportation. In addition, adopted efficient operation strategies in the investigated plants, such as use of waste heat in other energy consuming processes or reprocessing of cut wastes contributes energy and resource saving. From this point of view, all investigated products can be regarded as sustainable. Fuel consumption during transportation of raw materials and plant workers, on the other hand, seems to have considerable effects. Thus, strategies like decreasing the number of employed workers by changing and/or improving production systems and employing technology leading higher levels of automation rather than manual operations as well as shortening distances between quarries and plants would help to save energy and, in turn, minimize environmental impacts.

Briefly, profiling the environmental performance of building products in terms of aforementioned key issues according to sustainability approach, and bringing the assessment results in discussion may help;

- to encourage the use of energy efficient technologies in production,
- to develop methods for minimally processed materials,
- to recommend measures for reducing the impacts and costs,
- to select alternative products/materials on environmental performance,
- to plan production waste management,
- to rehabilitate quarry and the surrounding land.

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