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DEVELOPMENT OF AN ECO-FRIENDLY AND LOW-COST HOLLOW CONCRETE BLOCK FROM NEW BLENDED CEMENT AND BINARY AGGREGATE: THE CASE OF ADAMA TOWN ETHIOPIA

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ABSTRACT

This article presented the development of an eco-friendly and low-cost hollow concrete block (HCB) from a new blended cement with minimum clinker content combined with a binary aggregate. The new blended cement was a mix of Ordinary Portland cement (OPC), powder of volcanic clinker (VCP), pumice powder (PP), and limestone powder (LSP); while the binary aggregate was a blend of pumice and scoria aggregates. Six groups of HCBs samples were manufactured from four trial blended cement including two control samples; a constant cement to an aggregate ratio of 1:8 and water to cement ratio of 1:6 was applied. The physio-mechanical properties of HCB samples such as deviation from nominal dimension, density, water absorption, and compressive strength were tested at the age of 28-days. Based on the test results, a blended cement with minimum clinker content containing 50% OPC, 20% VCP, 20% PP, and 10% LSP combined with P60-S40 gave a non-structural HCB with an improved compressive strength complying with IS and ES strength requirements. Further comparative analysis on embodied energy, greenhouse gas (GHG), and life cycle cost (LCC) was carried out between the conventional and the new HCBs. And according to the overall results of the experimental and analytical studies, the combined use of the new blended cement and binary aggregate improved the compressive strength, embodied energy, GHG emission, and life cycle cost of conventional HCB by 31.4%, 41.4%, 47.4%, and 36.8%, respectively.

Index Terms - Blended cement, Binary aggregate, Compressive strength, Embodied energy, Greenhouse gas emission, Life cycle cost, Non-structural hollow concrete block.

1. Introduction

The construction industry exploits a vast quantity of natural resources and energy emitting large volumes of toxic and greenhouse gas (GHG). Cement and cement products are known for larger volumes of production and consumption in the building construction sector. As per the global cement report, 4.1 Gigatons of cement were produced in the year 2019. The production of cement consumes a larger amount of energy accompanied by ample greenhouse gas emissions [1]. Those energy and CO2 emissions are considered to be embodied within the materials thus known as embodied energy and CO2. Different global studies analysed the embodied energy and CO2 emissions of building materials; according to the result of a study on conventional building materials cement stands fifth next to aluminium, steel, glass, and lime both in embodied energy and CO2 [2]. This enables a good understanding of sustainable materials with lower embodied energy and CO2 emission. Analysing the embodied energy and CO2 emissions of the material enable devising solutions for environmental performances improvements of the material. As per the United Nations Environment Programme (UNEP), report buildings and construction sectors consumed more than 36% of global energy, and are responsible for 40% of energy-related CO2 emissions [3]. This points out that more research is needed for improvement on the sustainability of building materials. One of the fastest remedies for improving the sustainability of cement and cement products is the replacement of cement clinker with natural or artificial pozzolana. Many studies demonstrated the feasibility of replacing cement-clinker with varying amounts of volcanic minerals or limestone for the production of concrete. A fine slag powder that passed through sieve number 200 was used to replace cement in the making of concrete. The addition of the fine slag powder was found to improve the strength of concrete as compared to the control sample [4].

A non-load-bearing lightweight geopolymer block was produced from activated natural pozzolana and jute fibers; this block was found to have a compressive strength of 8.1 MPa at 28 days with a low bulk density [5]. Concrete blocks with an improved mechanical and durability performance were produced by replacing 100% of cement with carbon-activated steel slag [6]. Cement was replaced by coal bottom ash, waste marble powder, foundry sand, and tile dust in the production of concrete blocks; researchers in Pakistan reported that non-load-bearing concrete blocks could be produced by a partial replacement of cement with marble and glass powders. The test results on the properties of the concrete block confirmed that a 10% replacement of cement with marble and glass powders gave a block of acceptable mechanical strength [7]. A study in Saudi Arabia mentioned that concrete with good performances could be produced by replacing ordinary Portland cement with 30% of basaltic ash powder plus 15% limestone powder both based on mass; besides, self-compacting concrete with good workability was also produced by replacing cement with 50% of basaltic fine powders [8]. Pumice is a lightweight volcanic material formed from magma of volcanic eruptions; this volcanic material has been used as supplementary cementing material or aggregate for the production of lightweight concrete or concrete blocks. Besides, pumice was mentioned to be used as an input for making blended cement or geopolymer [9]. Pumice has uniform un-connected pores that make it light-weighted, less porous with soundproof and heatproof properties. Those all properties made pumice to be widely used as an aggregate for making lightweight concrete and masonry blocks [10]. A study used pumice powder (PP) for the production of self-compacting concrete which had shown a faster and more economical concrete construction process. Replacing cement with PP up to 20% can produce SCC without with no segregation, bleeding, loss of uniformity, and stability problems; however, increasing the replacement level induced an increment of fluidity with no segregation and loss of uniformity [11]. Volcanic ashes, such as pumice and scoria were pointed out to be used as a supplementary cementing material for low-grade concrete, and their reactivity was mentioned with an increase of increases [12]. In addition to replacing cement volcanic ashes such as pumice and scoria have been used as an aggregate for hollow concrete block production; for instance, a study in Ethiopia manufactured a binary aggregate from pumice and scoria complying with ASTM requirements. The study mentioned that, for a constant cement to aggregate and water to cement ratios, hollow concrete block produced from this binary aggregate improved the compressive strength of conventional block (control sample) by 125% [13].

In addition to the engineering merits, the incorporation of pozzolana in concrete production has environmental and economic advantages. A study on the use of sustainable materials for concrete production pointed out that concrete made from pozzolana Portland cement and ground granulated blast furnace slag showed better environmental performance than the control sample made from Ordinary Portland cement [14]. A comparative study on the environmental performances of cement production from conventional and alternative resources confirmed that a 12% improvement in the ecological impacts was achieved while using alternative resources [15]. In addition, a study compared the emission and embodied energy of cement stabilized soil block and cement-free alkali-activated block; as per the result, the first block had 46% lower emissions relative to the second while the second block had 41.5% lower embodied carbon as compared to the standard block [18]. Moreover, another study on the production of earthen and concrete masonry blocks revealed that the embodied energy of earthen masonry blocks was reduced by half with a dramatic reduction of CO2 emissions as compared to that of concrete blocks [19]. Different studies also compared the economic advantage of replacing cement with pozzolana in building materials with the same function; those comparative studies applied life cycle costing (LCC); life cycle cost is defined as the cost of an item over an estimated period. The whole-life costing covers an item's costs from the time of production to the time of disposal or recycling. According to ISO 15686-5 [20], LCC is the sum of all costs incurred over the study period discounted to present value. Different methods are available for LCC analysis; as per the review of the LCC studies, the most preferred LCC method for construction materials is the net present value (NPV) method [21]. NPV is defined as the sum of money that needs to be invested today to meet future financial requirements as they arise throughout the life of an investment. Most of the comparative LCC studies used the net present value (NPV) method for 20 - 60 years of service life, and a 3.5% - 6% discount rate. For instance, Younis [22] compared the life cycle costs of conventional concrete with concrete produced from different by-products using seawater; Ahmed [23] used LCC for the comparative economic assessment of three flooring systems, and Yuan [24] also compared the economic performances of concrete brick and permeable brick within the cradle to gate boundary using LCC approach. In all the above comparative LCC studies, environmental costs were not included; however, a study by Jeong, K., et al. [25] accounted for the costs of the environmental burden by incorporating the external costs in the life cycle cost equation.

A study in Ethiopia pointed out that cement and hollow concrete blocks were included in the list of the top commonly used materials in building construction. This study mentioned that cement, hollow concrete blocks (HCB), and reinforcement bars have the largest embodied energy and CO2 emission which accounts for 94% and 98%, respectively [26]. Ethiopian cement industries, particularly the Mugher cement factory (MCF), produce only two types of cement unless ordered by a client for a special purpose. Ordinary Portland cement (OPC) and Pozzolana Portland cement are the two types of cement produced by MCF. OPC is made from 95% clinker plus 5% gypsum, while PPC is produced from 67% clinker, 28% pumice, and 5% gypsum. Ethiopian cement industries use imported coal and petroleum products from South Africa and the United Arab Emirates; the use of imported fossil fuel in the Ethiopian cement industry adds more environmental and economic burdens on the industry [27].

In Ethiopia, particularly in Adama town, hollow concrete block (HCB) is a popular walling material used for shelter construction, HCB is produced from OPC or PPC and pumice aggregate. The embodied energy and CO2 of HCB can be reduced by using blended cement with lower clinker content. Blended cement can be made by replacing part of the clinker in OPC with pozzolanic materials. Accordingly, the study in this article aimed to develop an eco-friendly and low-cost hollow concrete block from a new blended cement and binary aggregate. The new blended cement was a mix of OPC, powder of volcanic clinker (VCP), pumice powder (PP), and limestone powder (LSP); while the binary aggregate was a blend of 60% pumice and 40% scoria aggregates as suggested by a study report of Lemma, B. et al. [13]. The nobility of this research work was the formulation of new blended cement with minimum clinker content that can be used for the development of an eco-friendly and low-cost HCB complying with Ethiopian standard requirements.

2. METHODS AND MATERIALS.

2.1 Methods

Experimental and analytical research methods were applied in the development of eco-friendly and low-cost hollow concrete blocks (HCB); this HCB was made from a new blended cement and binary aggregate. The new blended cement was a mix of OPC, powders of volcanic clinker (VCP), pumice powder (PP), and limestone powder (LSP); while the binary aggregate was a blend of pumice and scoria as suggested by a study report of Lemma, Beressa et al. [13]. The study in this article identified the proportion of inputs for the new blended that can be used for the production of new HCB. In addition, a comparative study between conventional and new HCBs on the embodied energy and GHG, and costs was carried out. The embodied energy, GHG emission, and cost analysis were carried out using cumulative energy demand (CED), Interconnectional panel for climate change (IPCC), and life cycle costing (LCC) methods, respectively.

2.2 Material preparation and assessment.

The study used Ordinary Portland cement (OPC) produced by Mugher cement factory (MCF) in Ethiopia; MCF produces OPC from 95% clinker and 5% gypsum. The remaining inputs for the new blended cement such as volcanic clinker, pumice, and limestone were collected from nearby sources around Adama town. Volcanic clinker was obtained from a quarry located at a distance of 62km from Adama town while pumice was collected from a quarry owned by Mugher cement factory situated at 20km distance from Adama town. However, the source of limestone was located at a distance of 255 km from Adama town in the West Shoa zone (between Shikute and Gindeberet districts). Raw materials were processed in a laboratory to obtain fine powders of VCP, PP, and LSP. Those fine powders were sieved through 45µm sieve sizes, and 70% passing through 45µm sieves were used for the blend. These particle sizes comply with the ASTM C618 specification for the particle sizes of pozzolanic materials which specified the maximum percent retained on 45µm sieve size is 34% [28].

In addition, the loose bulk densities of all inputs for blended cement were measured in a laboratory; as per the result bulk densities of OPC, VCP, PP, and LSP were 1293, 1373, 770, and 1136 kg/m^3, respectively. Moreover, the chemical properties of OPC, VCP, PP, and LSP were adopted from secondary sources [29,30] which were later assessed with ASTM C618 requirements. As per the assessment, both VCP and PP fulfilled ASTM requirements of chemical properties for pozzolanic materials. The summary of comparisons was presented in table 1 below.

Table 1. Assessment of pozzolanic properties of VCP and PP with ASTM C618 specifications

Chemical requirements	ASTM C 618 requirements for pozzolana (%)	Volcanic ash (%)	Pumice (%)
$SiO_2 + Fe_2O_3 + Al_2O_3$	Min, 70.0	77.68	72.6
Sulfur trioxide (SO_3)	Max, 4.0	0.215	4.0
Moisture content	Max, 3.0	1.0	2.2
Loss on ignition	Max, 10.0	7.89	5.9

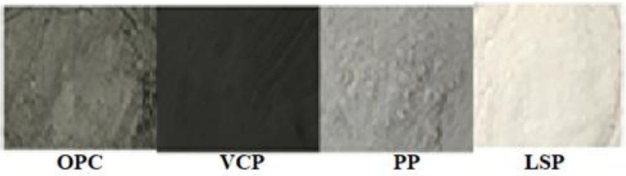

Fig 1. Input powders of blended cement

2.3 Blending scenarios

Based on earlier study reports, the study in this article used 15% as a minimum percentage replacement of OPC with varying percent of VCP, PP, and LSP; in addition, the replacement was planned up to a maximum of 65% on a volumetric basis. Accordingly, four-trial blending scenarios were suggested for making the new blended cement that can be used for HCB production using the binary aggregate; the trial blending scenarios were presented in table 2 below.

Table 2. Trial blending scenarios for blended cement

Blend code	Percentage of inputs in the blended cement on a volumetric basis (%)			
	OPC	VCP	PP	LSP
S_1	85	6	6	3
S_2	70	12	12	6
S_3	50	20	20	10
S_4	35	25	25	15

3. PRODUCTION OF HCB FROM TRIAL BLENDED CEMENT AND BINARY AGGREGATE.

A total of six groups of HCB samples were produced where four groups (S_1, S_2, S_3, S_4) were made from the four-trial blended cement and binary aggregates, and the remaining two groups were control samples. The first control sample (S_{0*}) was conventional HCB made from 100% OPC and conventional pumice aggregate while the second control sample (S_0) was produced from 100% OPC and the binary aggregate. Both blended cement and binary aggregate were mixed separately on a volumetric basis as per the suggested ratios presented in table xxx above, and table 1.18 [13]. A constant cement to aggregates ratio of 1:8 and a water to cement ratio of 1:6 was used for the HCB production. The pre-blended cement and aggregates were mixed in a dry state using a mechanical mixer; water was added and the mixing process continued until a uniform mixture is obtained. The uniform mixture was placed in a 40cmx20cmx15cm molding machine and compacted mechanically. After adequate compaction, blocks were de-moulded and laid in an open-air with an average temperature and humidity of 20.7c^0 and 60%, respectively. Blocks were cured by spraying water twice a day for 28 days.

4. TESTS ON HOLLOW CONCRETE BLOCKS.

The physio-mechanical properties of HCB samples such as deviation from nominal dimensions, dry density, water absorption, and compressive strength were tested. ASTM [31,32,33], Ethiopian standard (ES) [34,35], and Construction Materials Laboratory Manual [36] sampling and testing procedures were. As per ASTM C140/C140M–20 and ES 2310:2005 specifications, three full-sized units with similar configuration and dimensions are tested for density and water absorption, and results were reported as an average of the three units. Besides, as per the Ethiopian standard (ES 2310:2005), six units were tested for compressive strength, and the result was reported as an average of the six units. Moreover, each block specimen is checked for deviation from the nominal dimension, and the results were reported as the average of all units.

5. EXPERIMENTAL FINDINGS.

The results of the experimental study were summarized and assessed with ASTM, Ethiopian standard (ES), and Indian standard (IS) specifications as presented in table 3 below.

Table 3. Summary of average test results and comparison with standard specifications.

Physio-mechanical properties	HCB designation	Average Test result	Standard specifications for non-structural HCB		
			ASTM	IS	ES
Compressive strength (N/ mm^2)	S_{0*}	1.56	3.5	1.5	2
	S_0	3.51			
	S_1	2.76			
	S_2	2.12			
	S_3	2.05			
	S_4	1.39			
Density for light weight HCB (Kg/m^3)	S_{0*}	1066.6	< 1682	1000-1500	600-900
	S_0	1181.85			
	S_1	1172.96			
	S_2	1152.94			
	S_3	1105.53			
	S_4	1048.61			
Water absorption (%)	S_{0*}	26.17	30-40	10	30
	S_0	20.57			
	S_1	21.57			
	S_2	24.75			
	S_3	25.62			
	S_4	28.6			

Based on the assessment of test results, all groups of HCB samples, except S_{0*} and S_4, comply with ES compressive strength requirements for non-structural Hollow concrete block (HCB). And the density test results of all HCB samples were found within the range of lightweight blocks as specified on ASTM and IS specifications; however, as per ES density specification, all HCB samples conformed to the density requirement for normal weight HCB. In addition, water absorption test results comply with ASTM and ES water absorption requirements for non-structural HCB. More importantly, HCB samples coded by S_3 were found to contain the minimum clinker content (OPC) producing non-structural HCB which comply with ES and IS requirements for compressive strength. This blended cement with minimum clinker content was a mix of 50%OPC (47.5% clinker), 20% VCP, 20% PP, 10% LSP. All the test results corresponding to S_3 comply with Ethiopian standard requirements for non-structural HCB. Hence, a new blended cement containing 50% OPC (47.5% clinker), 20% VCP, 20% PP, and 10% LSP combined with the binary aggregate can be used to produce a non-structural HCB. Even the combined use of the new blended cement and binary aggregate improved the strength of conventional hollow concrete block (manufactured from OPC and un-processed pumice aggregate) by 31.4%.

6. COMPARATIVE EMBODIED ENERGY, GHG, AND COSTS ANALYSIS

a. Comparative embodied energy and GHG emission.

For the sake of showing the improvement achieved on embodied energy and GHG emissions in the new improved HCB, a comparative assessment was carried out on the embodied energy and GHG between conventional and improved HCBs. The embodied energy of HCB was computed using the cumulative energy demand (CED) method. This method sums up all energy consumptions for activities contained within the HCB production processes. The major activities in HCB manufacturing included mining and loading of raw materials, transportation of raw materials to the HCB plant, and the production process in the plant (mixing and molding).

The energy consumptions in all these activities were summed up to obtain the total embodied energy of the final product (HCB) at the gate of the manufacturing plant. In addition, GHG emissions from the use of total renewable and non-renewable energy sources were computed using the Intercontinental panel for climate change (IPCC) method. For simplicity, the conventional and improved hollow concrete block production processes are mapped using flow charts. The simplified system boundary and activities contained in the conventional and improved HCB production processes were shown in figures 2 and 3 below. The embodied energy and GHG emissions from conventional and improved HCB production were computed within these system boundaries.

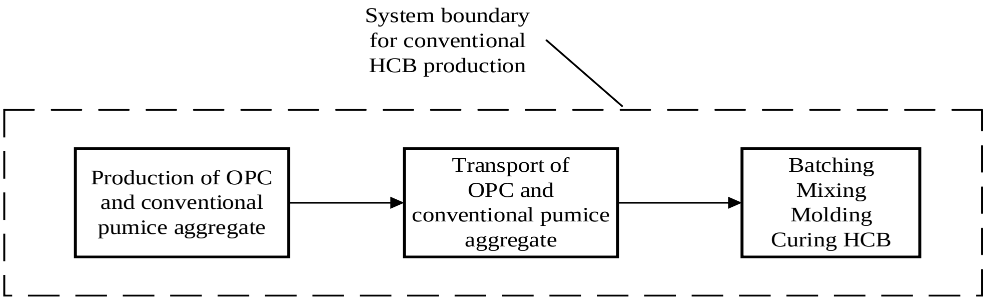

Fig 2. Simplified system boundary for conventional HCB production.

As it was mentioned in the experimental study, Ordinary Portland cement (OPC) manufactured by Mugher Cement factory (MCF) was used for HCB production. Hence, the input energy and output GHG emissions from productions of OPC in MCF were adopted from a study report by Lemma Beressa, et al. [27]. According to the study report, the embodied energy and GHG emission from the production of 1-ton of OPC were 3.67 GJ/ton-OPC and 0.84 kgCO2eq./ton-OPC, respectively. However, the remaining inputs for blended cement such as VCP, PP, and LSP are new materials that are not produced at the industry level. But these powders were produced from raw materials having particle sizes nearly similar to sizes of cement clinker; practically, the production of VCP, PP, and LSP involves only mining and grinding processes. The mining activities for volcanic clinker, pumice, and limestone are identical to the open quarry mining of raw materials in the Mugher cement factory. Hence, the input energy used for the mining of raw materials in the MCF was adopted for the input energy of volcanic clinker, pumice, and limestone mining. As per the specific energy consumption data for mining sites of Mugher cement quarry sites, the specific diesel fuel consumption for the mining/loading process was 0.62 L/ton [27]. In addition, the input energy used for the grinding of volcanic clinker, pumice, and limestone was assumed to be equivalent to the energy used for clinker grinding in MCF i.e., 32.8 kWh/ton-clinker [27]. Moreover, the specific diesel fuel consumption data for the transportation of raw materials in MCF was adopted for the transportation of OPC, VCP, PP, LSP, pumice, and scoria aggregates.

The total diesel fuel consumption for the transportation was computed by referencing quarry distances of each material. Besides, electricity was consumed for mixing and molding processes in the HCB plant. According to the electric meter reading for the one-month study period in the case study plant (the case study plant was a plant where the experimental study was conducted-Abel Sisay Concrete Blocks Production Plant), electricity consumption for the mixing and molding process was recorded as 61.2 kWh/1000HCB. Based on primary and secondary data presented in the above discussion, the specific energy consumption for the production of new materials used in the improved HCB productions was summarized in table 4 below.

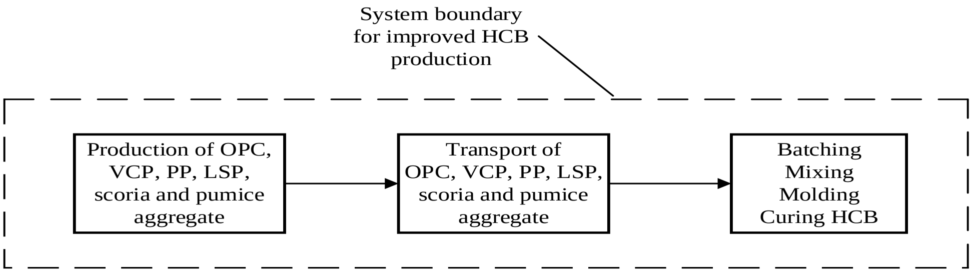

Fig 3. Simplified system boundary for improved HCB production.

Table 4. Specific energy consumption data for the new materials used in the improved HCB production.

Activity	Specific energy consumption	Remark on the source of specific energy values
Mining/loading	VCP = 0.62 L / ton	Specific diesel fuel consumption for mining of raw materials from open pit quarry of Mugher cement factory [27]
	PP = 0.62 L / ton	
	LSP= 0.62 L / ton	
	Pumice aggregate = 0.62 L / ton	
	Scoria aggregate = 0.62 L / ton	
Transportation	VCP =1.775 L / ton	Specific diesel fuel consumption for on-road transportation of raw materials to Mugher cement factory [27]
	PP = 0.5725 L / ton	
	LSP=7.2958 L / ton	
	Pumice aggregate = 0.62 L / ton	
	Scoria aggregate = 0.62 L / ton	
Grinding	VCP =32.8 kwh / ton	Specific electricity consumption for clinker grinding in Mugher cement factory [27]
	PP =32.8 kwh / ton	
	LSP =32.8 kwh / ton	
Molding HCB	61.2 kWh / 1000HCB	Primary data collected from HCB plant

The total energy consumption for the conventional and improved HCB productions varies with the quantities of input raw materials. Based on raw materials consumption data collected from the case study HCB plant, the quantities of input raw materials for the production of 1000-units of conventional and improved blocks were summarized in Table 5 below.

Table 5. Summary of quantity for raw materials consumed for HCB production

Type of input raw materials	Unit	Quantities of input raw materials for the production of 1000 HCB units	
		Conventional HCB	Improved HCB
OPC	ton	1.15	0.57474
VCP	m^3	-	0.1778
PP	m^3	-	0.1778
LSP	m^3	-	0.0889
Pumice aggregate	m^3	7.011	4.207
Scoria aggregate	m^3	-	2.804

The embodied energy of conventional and improved HCBs was computed using the cumulative energy demand (CED) method. This method quantified the primary energy used for both conventional and improved HCB production processes within the defined system boundary; no normalization or weighting data was included in the method. The total energy consumptions for each type of HCBs were computed by referencing the specific energy use data and quantities of raw materials. Accordingly, the total energy consumed for the production of 1000 units of a conventional and improved block is 5.19 GJ/1000-HCB and 3.04 GJ/1000-HCB. The results revealed that the combined use of the new blended cement and binary aggregate lowered the embodied energy of conventional block by 41.4%.

Moreover, greenhouse gas emission (GHG) from the use of the total energy in the HCB productions were computed as per the Intergovernmental Panel for Climate Change (IPCC) method [39]. IPCC method is a global method that gives an option for emission calculation where country-specific emission factors are lacking; default emission factors were adopted from IPCC -GHG analysis. As per IPCC guidelines, primary GHG emissions include CO2, CH4, and N2O gases. Direct GHG emissions from diesel fuel consumption by quarry machinery were computed using IPCC-mobile combustion-off-road categories; While, the indirect GHG-emission from the transportation activities was computed using IPCC- mobile source category in road transportation using heavy-duty vehicles. Moreover, GHG-emission from the uses of electricity in the HCB plant were computed using the electricity consumption data and country-specific emission factors [40]. The IPPC 2007 method was used to obtain the 100-year global warming potentials (GWP100) of GHG using 100-year values from IPCC. The 100-year global warming potentials of CO2, CH4, and N2O were converted to the equivalent CO2 using the conversion factor of 1, 21, and 310 for CO2, CH4 N2O, respectively [39,41]. Hence, in line with the specific energy and raw materials consumption data, the total GHG emission from conventional and improved HCB productions was computed. Accordingly, the GHG emissions from conventional and improved HCBs were 1,024.71 kgCO2eq./1000HCB units and 539.03 kgCO2eq./1000HCB units, respectively. Hence, the combined use of the new blended cement and binary aggregate lowered GHG emissions from conventional blocks by 47.4%.

a. Comparative life cycle cost analysis.

Life cycle cost (LCC) sums all relevant costs associated with a product over the study period. The costs of alternative products for the same function can be compared using LCC. Many studies applied conventional LCC for comparing the life cycle costs of alternative materials, all aiming to select the best material based on its economic performance. Accordingly, this section presented a comparative economic assessment for conventional and improved HCBs. The scope of the LCC analysis was cradle to gate of the HCB plant within the system boundary shown in Figures 2 and 3. As per the defined scope of the LCC study, the LCC of conventional and the improved HCB production was computed using the net present value (NPV) method considering all internal costs and one external cost. The internal costs included the cost of raw material, transportation, energy, and labor, whereas the external cost contained carbon tax. Primary cost data were collected from actual market values during the study period (2020); all costs were expressed in terms of Ethiopian local currency (Birr) which was later converted to equivalent USD; during the study year, 1 USD was equivalent to 44.30 Birr.

6.2.1 Input cost data for LCC of HCB production.

Input data for the consumption of raw materials, energy, water, and labor were collected from the case study HCB plant. The costs of cement (OPC), pumice, and scoria aggregates were directly obtained from suppliers in Adama town. However, the powder of volcanic clinker (VCP), pumice powder (PP), and limestone powder (LSP) are new materials and their prices are not available in the market. Since there were no known costs for VCP, PP, and LSP their unit prices were computed from their production, transportation, and labor costs. The production of VCP, PP, and LSP involve mining and grinding processes. Therefore, their production costs are computed based on the costs of energy consumed for mining and grinding processes. Finally, the unit prices of VCP, PP, and LSP are taken as the totals of cost of energy used for mining, transportation, grinding process, and labor cost; labor cost for VCP, PP, and LSP are assumed as 40% of the production costs. The costs of energy (cost of diesel fuel and electricity) were directly obtained from the energy suppliers in Adama town. Electricity is supplied by Ethiopian Electric Power Corporation (EEPCO) and the tariff for electricity was obtained from the EEPCO Adama branch. Besides, the cost of diesel fuel was quoted from diesel fuel stations located near the sources of materials. Moreover, the labor costs for the production of HCB were obtained from the case study HCB plant during a one-month study period. In the HCB plant, labor cost was decided based on individuals' productivity. As per the primary data collected from the HCB plant, energy and water consumptions for the mixing, molding, and curing processes were recorded as 61.2 kWh/1000 HCB and 4.0 m^3/1000 HCB, respectively. Finally, the unit prices of all cost elements were summarized in Table 6 below; the unit price for CO2 emission was adopted from Ethiopian carbon tax value quoted in carbon pricing used for developing countries [41].

Table 6. Summary of unit prices used in life cycle cost analysis

Item	Unit	Unit price
Materials		
OPC	Birr / ton	4,500
VCP	Birr / m^3	146.10
PP	Birr / m^3	58.91
LSP	Birr / m^3	277.10
Pumice aggregate	Birr / m^3	130
Scoria aggregate	Birr / m^3	120
Energy		
Electricity	Birr / kwh	1.019
Diesel fuel	Birr / L	17.80
Water		
Potable water from a tap	Birr / m^3	11.96
Personnel		
Store keeper & production recorder (1)	Birr / 1000 HCB	40
Machine operator (1)	Birr / 1000 HCB	60
Daily laborers (10)	Birr / 1000 HCB	600
Mix design worker (1)	Birr / 1000 HCB	70
Guard (1)	Birr / 1000 HCB	20
External cost (Environmental cost for the case of Ethiopia)		
Carbon tax (taking the minimum value)	Birr / ton-CO2	200

Based on the quantities of inputs (summarized in table 5) and unit prices (presented in table 6), the total costs of conventional and improved hollow concrete blocks were estimated. Accordingly, the estimated costs for the productions of 1000-units of conventional and improved HCB were computed and presented in Table 7 below.

Table 7. Summary of the estimated costs for 1000 units of hollow concrete blocks.

Cost element		Conventional HCB		Improved HCB	
		Quantity	Total Cost (Birr)	Quantity	Total Cost (Birr)
Material cost	OPC	1.15 ton	5,175	0.57474 ton	2,586.33
	VCP	-	-	0.1778 m^3	25.98
	PP	-	-	0.1778 m^3	10.47
	LSP	-	-	0.0889 m^3	24.63
	Pumice aggregate	7.011 m^3	911.43	4.207 m^3	546.91
	Scoria aggregate	-	-	2.804 m^3	336.48
Energy cost	Electricity	61.2 kWh	62.36	61.2 kWh	62.36
Water cost	Tap water	4.0 m^3	47.84	4.0 m^3	47.84
Personnel cost	Employees	14 workers	790	14 workers	790
External cost	Carbon tax	1.02471 ton	204.94	0.53903 ton	107.81
Estimated production cost / 1000 HCB			7,191.57		4,538.84

6.2.2 LCC analysis using NPV method.

As per the result of cost analysis summarized in table 7 above, the estimated costs (Ct) of 1000-units of conventional and improved blocks were 7,191.57 Birr (162.34 USD) and 4,538.84 Birr (102.46 USD), respectively. The cradle to gate life cycle cost of HCB was computed using the NPV equation given below:

$$NPV = \sum_{t=0}^{T} \frac{Ct}{(1+r)^t} \tag{1}$$

where Ct is the estimated cost in year-t, r is the discount rate, and T is the period of analysis in years.

Applying NPV's equation (Equ.1) for a discount rate of 3.5% and 20 years of service life, the cradle to gate life cycle costs of conventional and improved HCB productions were 3.61 Birr/HCB and 2.28 Birr/HCB, respectively. Based on this result, the life cycle cost of an improved block was noted to be 36.8% lower than the conventional block.

7. RESULTS AND DISCUSSION.

The results of the experimental study (summarized in table 3) showed a blended cement with a mix of 50% OPC, 20% VCP, 20% PP, and 10% LSP was identified as a new blended cement with minimum clinker content. This new blended cement combined with the binary aggregate gave a non-structural hollow concrete block (S_3) with improved compressive strength as compared to the conventional HCB (S_{0*}). The improvement in the compressive strength of the new block (S_3) was noted as 31.4% higher as compared to the conventional block (S_{0*}). All the four standard properties of the new block were compared with ASTM, IS, and ES specifications. According to the comparison, the new block fulfilled IS and ES requirements for compressive strength of non-structural HCB. The density of the new block conforms to the density requirement of lightweight HCB as per ASTM and IS, but the density of the new block conforms to the normal weight blocks as specified on ES. In addition, the water absorption test results of the new block fulfilled ASTM and ES requirements for the water absorption requirement for non-structural HCB. Moreover, the experimental study revealed that a new blended cement can be made with minimum clinker content (47.5%) that can be used for the production of non-structural HCB conforming to Ethiopian standards. As per the results of a comparative embodied energy, GHG, and life cycle cost analysis, the study confirmed that the new block showed significant improvements in the environmental and cost performances over the conventional HCB. As per the results of the comparison, the use of the new blended cement and binary aggregate lowered the embodied energy, GHG emission, and life cycle cost of conventional non-structural HCB by 41.4%, 47.4%, and 36.8%, respectively.

8. CONCLUSION

Based on the result of the study, a new blended cement with a reduced cement clinker content can be produced by the Mugher cement factory that can be used for the production of non-structural HCB. This new blended cement combined with the binary aggregate made from pumice and scoria can improve the compressive strength, environmental and economic performances of non-structural HCB. This makes the new improved non-structural HCB eco-friendlier and cost-effective. In addition, the Mugher cement factory and the HCB producer in Adama town can produce one more variety of products for their market which can solve the urban housing problem.

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