Chapter

Production of Sustainable Concrete by Using Challenging Environmentally Friendly Materials Instead of Cement

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Abstract

The environmental problems accompanying concrete come from cement. This means that the final product i.e., concrete is an environmentally sociable material by itself. This guides us to play on the concrete constituents which cause the largest environmental impact, which is cement. Therefore, if we can abate cement amount and increase cementing materials which can substitute cement for concrete, we will be able to minimize the concrete impact on the environment. The saving of cement quantity in concrete can be realized by substituting it with diverse extra cementitious materials which are a by-product of another industry and waste of agriculture.

Keywords: Cement, Concrete, Cementous Materials, Sustainable

1. Introduction

The industry of construction is one of the booming economic sectors on the planet now a day. The sector comprehends constructions of horizontal and vertical structural elements. In Ethiopia, it was happened the same, since the governmental policy support infrastructure development projects to realize the transformation to the industry from agricultures. Due to this an exploitation of naturally deposited resources for concrete imputes becomes the main agenda for the government advanced than the other. Beyond this, concrete is concrete a blend of aggregates that is either crushed stone or gravel or sand or blending of them and cement paste which mixture of cement, water, chemical admixture, and cementitious materials. The paste contains cement and water and sometimes other cementitious and chemical admixtures, whereas the aggregates contain sand and gravel or crushed stone. The cement paste in the concrete helps to make strong bonds between aggregate particles. Aggregates, major ingredients of concrete by volume, are comparatively inactive fillers material that has a share of about 68–85% of concrete and can therefore be expected to influence its properties. The cement which is among the main concrete ingredient plays an excellent role but is that the costliest and environmentally inimical material.

Since that cement production requires high consumption energy and leads to discharges of greenhouse gas, there continues to be a global search for new binders and admixtures that could partially replace traditional ordinary hydraulic cement
and improve the environmental sustainability and sturdiness of concrete structures. The application of left-over by-products in construction materials as replacement of concrete constitutes become an attractive alternative to disposal and an eco-friendly solution to the challenges concerning the exploitation and shortage of non-renewable natural resources in the globe.

Sustainability is demarcated as a combination of environment, economy, and society, and among this parameter for development with sustainability, the environment is the dominant one due to deterioration of our environment is driving the current worldwide focus on sustainable development. Generally, almost all scholars agreed definitions of sustainability are “Meeting the desires of the present generation without compromising the ability of future generations to meet their needs.” As shown in Figure 1, to have sustainable construction outputs, there should be a balance among environmental (ecological), social and economic aspects of building (construction) activities.

2. Construction industry

The term construction is mostly accustomed designate the physical (tangible) infrastructure and related facilities, every type of activity associated with the erection and repair of immobile structures & facilities. Construction is creating or assembling of something from something and it produces a one-of-a-kind product, it's complex and undertaken through cooperation by a short-lived organization, and it's essential to the growth of a given country and a crucial sector within the nation's economy (in Ethiopia, about 60% of the federal capital budget is channeled to this sector for Physical infrastructures, 70% of the capital budget is allotted for Transport & Communication and Buildings cover only 13% of the capital budget). The sector has a significant and dynamic part in transforming the aspirations and desires of individuals into reality by physically implementing various construction development projects. The products of construction contribute extensively towards the creation of wealth and consequently the quality of the lifetime of the population.

The construction business furnishes capital improvements to countries, which is incredibly much allied with the event of investments to supply future benefits to nations. Since the industry primarily represents an investment, construction activities drop quite other industries during recessions. The construction industry often makes skills more immediately rewarding which is why most workers during
this industry became more prosperous professionals than in other industries. The industry is pigeonholed by converging (many components and lots of flows going together into one object), temporary (project being funded only for one object), highly fragmented with significant negative impacts, more complex & often associated with changes & uncertainties, amplified reaction in financial conditions, labor-intensive and land dependence. Outside this, it’s challenged by low productivity, cost and time target failure, quality failures (increase construction costs in rework alone), conflicts and disputes, leading to claims and time-consuming litigation, waste during construction (Unnecessary material handling & material waste, rework, poor material allocation, lack of constructability, etc.), image (it is a sector having the worst public image among industrial sectors, Dirty, dull, & environmentally insensitive), have the very best incident rate of fatal accidents and somber injuries of all industries and also the furthermost environmentally unfriendly industries.

Beyond its role in the nation’s development, the sector incorporates a negative bearing on the built-up and its surrounding milieu or sustainable development. The industry affects sustainability in its major five phases: (1) pre-design phase (material selection, building program, project budget, team selection, partnering, project schedule, codes, standards, laws, research, and site selection); (2) on-site phase (site analysis & assessment, site layout and development, watershed conservation and management, equipment and materials on-site); (3) design phase (passive solar design, materials & specification, indoor air quality): (4) construction phase (environmentally conscious construction, preservation of features & vegetation waste management and source control practices): (5) operation and maintenances phase (maintenance plans, indoor quality, energy efficiency, resource efficiency, renovation, housekeeping & custodial practices).

3. Concrete productions

Concrete construction demands land and hence the sourcing of materials for construction activities (aggregates, cement, waters, admixtures, etc.) from quarry sites and borrow pits can potentially end in the whole removal of vegetation and virgin materials. Additionally, the displacement of individual, concrete ingredients production resulted for losing of important ecological resources for local people, vegetation that gives watershed protection, and as a result the diminution of biodiversity of national or regional or global importance.

The aggregate manufacturing steps have many considerable environmental impacts. The foremost obvious environmental effect resulted from stone, aggregates, and mineral mines for industries is the degraded quality of air, and related health effects, sourcing from airborne emission from both stack and also disturbed areas at these mines. Natural deposits sources of aggregates are being depleted and causing a heavy threat to the environment and likewise to society. Because of a high rate of natural aggregates depletion from its source beds causing lots of problems such as loss of strata of water-retaining, bank slides, exposing water supply scheme intake wells, dropping underground water table levels which become a cause for agricultural effect and aquatic life disturbances.

In emerging nations like Ethiopia, due to rapid urbanization and infrastructure projects, there is a wide expansion of cement industries that releasing this pollutant to the surrounding. Apart from these environmental concerns regarding CO₂ emission during cement manufacturing, natural resource-demanding also makes cement expensive when compared with aggregates and water for concrete productions. Consequently, to overcome these problems, searching for more
environmentally friendly and economical materials that have cement properties has prolonged attention in other such types of materials that can be used fully or partially substitute normal Portland cement.

4. Cementious materials

Cement is a material with cohesive and adhesive characteristics that make it capable of bonding mineral fragments into a compact whole and having major roles in concrete for the construction industry. But in the reverse, it is not environmentally-friendly and the most expensive concreting materials.

Usage of concrete mix design with optimum cement content, enhancement of concrete durability, and use of supplementary cementing materials are the focus areas for sustainability in concrete industries.

Therefore, requirements for durable, economical, and more environmentally-friendly ingredients for concrete, particularly for cement, have stretched curiosity to other cementing construction materials which can be used as partially or fully replaced the normal Portland cement for the sustainable construction industry.

The cement which is one of the basic ingredients of concrete is the fine gray powder and when it reacted with water it forms to harden, rigid and stable structures which bonded aggregates together acting like glue and gives the desired strength of concrete. The first invention of cement started when Romans, mixed lime (CaCO$_3$) with volcanic ash, producing cement mortar which was used during the construction of monumental structures as coliseum [1]. In accumulation to this, cement is defined as a mineral chemical produced by mixing a well-defined ratio of raw materials at highly elevated temperatures. Cement is a universally known and applicable construction material throughout the world. Besides, the depletion of inputs raw material for manufacturing of cement is one of the environmental effects, there is plenty of emissions of CO$_2$ to the atmosphere. It is believed that one tone of cement clinker production creates almost an equivalent ton of CO$_2$ and other greenhouse gases [2]. This implies that the quantity of cement produced is directly proportional to gas emission to the environment. And also, it shows that the cement factories tremendously contribute to today’s worldwide apprehension, which is global warming. Furthermore, to its releases of different gases, extraction of raw materials is environmentally unfriendly due to degradation and disturbance of the existing natural environment. This shows that the cement industry contributes to today’s worldwide concern, which is global warming. This endangers the sustainability of the cement factory and that of concrete. Beyond this cement industry needs high capital investment, energy-intensive, and highly dependent on power and transport and it leads cement as the greatest environmentally unfriendly and costliest imputes of concrete for the following three reasons.

a. Cost of production

The cement factory is one of the most energy-consuming/intensive industry in the globe and consequently, 30–40% of the total production cost it goes to fuel and energy cost for production. The cost of raw materials represents the second-largest percentage of cement manufacturers’ cost structures. The abundance of this ingredient for cement production is reliable in most parts of the country and the availability of these raw materials is justified by the distribution of cement factories throughout the country with its raw materials for cement factories. However, variances across regions and companies depend on the operating efficiency of each producer comparative to others.
b. Ingredients for cement production

The major ingredients for the production of cement include clay, limestone, marl, chalk, and others, noteworthy quantities of which are endlessly quarried to service the demand for cement. Substitute materials have been sourced to substitute for traditional natural ingredients. The cement sector at present uses huge quantities of power station fly ash, blast furnace slag, natural pozzolana, limestone, and silica fume, mainly to substitute for natural raw materials in the production process of blended cement such as pozzolana fly ash and granular ground bluest farness. The use of these alternative materials has significant economic benefits and positive environmental advantages. The needs to quarry primary raw materials are reduced, energy consumption in cement production is cut, and overall reductions in emission of dust, CO$_2$ and acid gases are attained. In some applications, the performance of concrete can be enhanced when these alternative materials complement Portland cement clinker.

c. Energy/power

Cement production is one of the energy-intensive processes. The specific thermal energy-demanding of a cement kiln varies between 3,000 and 7,500 million joules for a ton of clinker, depending on the basic process design of the plant. The explicit electrical energy-demanding typically ranges between 90 and 130 kWh and 60–130 Kg of fuel oil per ton of cement." The industry of cement was expected to produce 4.7 million tons per year to meet the demand in 2015, 27 million tons per year. However, the industry achieved an output of only 11.17 million tons of it in the year 2009/2010. This result suggests the need to increase the production and supply capacity of cement to meet the need of the fast-growing construction industry.

4.1 Pozzolanic materials

The material of pozzolan is stated as an aluminosilicate/siliceous materials which are finely ground style and chemically react with calcium hydroxide within the presence of moisture it creates calcium silicate hydrate (CSH) and other cementitious materials. Clay and shale, opalinc chert, volcanic ash, and diatomaceous earth are an example of natural Pozzolanas while fly ash, rice husk ash, blast furnace slag, coffee husk ashy, silica fume, bagasse ash, and metakaolin are an example of artificial Pozzolanas. Most pozzolans used today are mainly widely available by-product materials. Since pozzolan has a variety of diversity, its chemical structure and contents also vary. Therefore, classifying Pozzolanas only depending on their chemical composition would be difficult. For this reason, ASTM C-618 classifies Pozzolanas depending on a performance basis as tabulated in Table 1 [3–6].

The reason behind using Pozzolanas is the improvement found on both the hardened and fresh state concrete. Lowering of the thermal shrinkage and heat of hydration, increase in water tightness, decrease in the alkali-aggregate reaction, resistance to sulfate attack, better workability, and price effectiveness are some of the improvements achieved by using Pozzolanas blended with cement [7–9].

Partially or cement replacing materials are special construction materials either naturally occurring materials or industrial wastes/byproducts or agricultural wastes which could be castoff for concrete production. And they rely on activation of by-products while incorporating minimal amounts of cement are promising low carbon candidates that can potentially complement the globe’s growing concrete industries by using the equivalent performance concept.
Due to the increase of awareness of environmental concerns and natural resource consumptions, the issue of energy saving has been gradually emphasizing by the public. Owning to the considerable use of concrete and cement material, the natural material resources associated with the construction sector have been continuously reducing in recent years. However, for each country particularly for developing countries like Ethiopia, concrete is the most significant material for fundamental and public constructions. Thus, an innovative and alternative concrete material, which possesses feasibility and practicality, is critical and significant for mitigating environmental impact and promoting energy-saving performance. For this purpose, the most common and practice in real concrete production for the cement replacement are natural pozzolana, Diatomaceous Earth, Glass Residue, Silpoz, fly ash, Corn Cob Ash, Ground granulated blast furnace slag, Silica Fume, Highly reactive metakaolin, rice husk ash (RHA), Bagasse ash, Coffee husk ash, calcined termite hell, water hyacinth ashy, etc.

i. Natural pozzolans

Natural pozzolans originated from volcanic activities are worldwide available materials, with varied compositions and subsequently a varied performance. However, for the reason that huge content in amorphous silica, it is usually an excellent material to be used as cement replacement. Curiously, before the invention of ordinary Portland cement, volcanic ash and air lime mixtures were commonly used, with a good performance and proven durability. Difficulties in the usages of these products are lack of characterization and the varied composition of raw-material layers, sometimes within the same area. However, naturally occurring pozzolanas are used successfully in cement composition and may be looked at with cement replacement potential with the replacing percentage of cement up to 20% by mass. The use of ash of volcano for concrete production helps to reduce chloride ion diffusivity of concrete, inhibiting the localized corrosion of steel and further concrete degradation. This addition also promotes lesser heat of hydration and higher setting time. The improved performance has been qualified to the refinement of the stomate structure and the pozzolanic action of volcanic ash. One of the probable weaknesses using of these natural pozzolana materials is their diversity. To minimize this problem, usually natural pozzolanic materials from different extraction heights are mixed before use [1–3, 6, 10].

ii. Diatomaceous earth

Diatomaceous earth, which is also acknowledged as diatomite/fossil flour, is a sedimentary material mainly constituted by diatom outer shells. This very
fine powder formed by the external skeletons of these unicellular beings is extremely rich in silica, has high porosity and surface areas. It is usually commercialized after it has been subjected to the previous calcination to remove organic matter and its characteristics make it liable to be replacement materials of cement. Its application in concrete production is usually in a weight percentage of 10–20% over the cement binder weight.

iii. Glass residue

Traditional soda-lime glass, predominantly composed of silica, but with a high percentage of sodium and calcium is a common residue that is finely ground for posterior use and 20–30% of cement replacement without harmful effects, performed satisfactorily concerning alkali reactivity and drying shrinkage. In addition to this, glass powder can significantly reduce the chloride ion penetrability of the concrete.

iv. Silpozz

Silpozz is extracted from rice husk ash and finer than cement with a particle size of 25 micrometers which helps it to fill the gaps between the aggregate and cement i.e., the determinants of density and strength of concrete. Because of this, it reduces the cement amount in the given concrete proportioning, and consecutively it elevates the compressive strength of concrete by 10–20% and high resistance towards the chemical attack, abrasion, and reinforcement corrosion.

v. Corn cob ash

Demanding for corn cob ash as cement replacing alternative materials is increased due to less amount of organic content, which proved the binding properties of cement. When we use it as alternative cement replacing materials, it will serve up to 20% by mass, and having advantages increasing the water amount which help as to obtain the desired plasticity as well as the initial and final setting time. Probably it is due to the reduced cement surface area and hence the delayed hydration process. Corn cob ash may therefore be most applicable when a low rate of heat development is necessary.

vi. Fly ash

Fly ash is a cementitious supplementary material for concrete production concrete and a byproduct of the pulverized coal in electric power generating plants. And also, a material of fine-grained having alumina, silica, iron, and calcium as a major content and sulfur, sodium, magnesium, carbon, and potassium as a minor percentage and it will serve as a cement replacement by weight up to 15%.

vii. Ground granulated blast furnace slag

Blast-furnace slag is the iron manufacturing industry’s byproduct having the necessary minerals calling as cementitious materials like aluminosilicates and silicates and calcium.
viii. Silica fume

Silica fume is a waste from the production of silicon/ferrosilicon alloy in an electric furnace from high-purity quartz with coal. It is used as cement replacing concreting materials in between 5–10% by mass and it is recommended to be used in high strength and impermeable concrete.

i. Highly Reactive Metakaolin

Highly reactive metakaolin has nowadays available as a highly active pozzolana concrete material. Contrasting slag, fly ash, or silica fume, it is not the byproduct rather manufactured from high-purity kaolin clay by calcination at temperatures in the region of 700 to 800°C. Unlike silica fume, which has above 85% SiO$_2$, and it contains equal proportions of SiO$_2$ and Al$_2$O$_3$ by mass.

ii. Bagasse ash

Bagasse is fiber from cellulose from the extraction sugar-bearing juice of sugarcane and has silica and alumina which are the most vital component of cement replacing materials. It is also finding in large amounts as a byproduct from factories of sugar.

iii. Rice husk ash

Rice husk ash is a byproduct of agriculture and used up to 20% to replace cement in concrete and it has a good tendency to reduce temperature for the production of high strength mass concrete.

iv. Coffee husk ash

The use of different replacing of cement materials has become a popular practice in the industry of construction. The chemical composition of coffee husk ash has a significant value of Al$_2$O$_3$ and SiO$_2$, which are major components of cement. It can replace cement about 10% and concrete produced from CHA has high potential as a source of environmental-friendly cementitious material that reduces pollution and provides a sound coffee waste management option.

v. Termite hill clay

The chemical properties of calcined termite hill clay powder include the fact that the material is pozzolanic with the sum of SiO$_2$ (38.82%), Al$_2$O$_3$ (23.98%), and Fe$_2$O$_3$ (11.68%) constituting 74.48% of the material, leading to the conclusion that termite hill clay powder calcined at the temperature of 650°C satisfied the requirement of ASTM C618 of a minimum of 70%. Moreover, classified as natural Pozzolana class N. It means, the material can produce the cementitious compound that has binding property upon reaction with calcium hydroxide gained from the hydration of cement. Therefore, calcined termite hill clay powder was found suitable to partially replace cement in the production of concrete. up to 11.3% by weight and it implies it can reduce the CO$_2$ emission by 11.3% due to cement production and it will save the natural materials by the same percentages.
vi. Water hyacinth Biochar

Water hyacinth Biochar, a carbonaceous solid material obtained through a pyrolysis process from solid waste materials, and has properties like extremely low thermal conductivity, high chemical stability, low flammability, ability to absorb water, and highly capture and store CO₂. Recently, these properties of biochar favor its use as a partial cement replacing material in concrete construction up to 5% of cement by weight. In addition to this, every tone of biochar used in a building’s envelope means that the equivalent of more or less one tone of CO₂ is prevented from re-entering the atmosphere.

4.2 Advantages of cement replacing materials

4.2.1 Environmental advantages

The cement industry is an energy-intensive industry with energy typically accounting for about 40% of operational costs, i.e., excluding capital costs but including electricity costs. The production of cement involves the consumption of large quantities of raw materials, energy, and heat. Cement production also results in the release of a significant amount of solid waste materials and gaseous emissions. The cement manufacturing industry is under higher scrutiny these days because of the large volumes of CO₂ emitted. This industrial sector is thought to represent 5–7% of the total CO₂ anthropogenic emissions. Concern over the impact of anthropogenic carbon emissions on the global climate has increased in recent years due to growth in global warming awareness. In addition to the generation of CO₂, the cement manufacturing process produces millions of tons of the waste product cement kiln dust each year contributing to respiratory and pollution health risks. To produce 1 ton of clinker, the typical average consumption of raw materials is 1.52 tones.

The amount of clinker needed to produce a given amount of cement can be reduced by the use of supplementary cementitious materials such as coal fly ash, slag, and natural Pozzolanas (e.g., rice husk ash, coffee husk ash, and volcanic ashes). The addition of these materials into concrete not only reduces the amount of material landfilled (in the case of industrials byproducts) but also reduces the amount of clinker required per ton of cement produced. Therefore, replacing the portion of Portland cement with those cementitious materials can substantially reduce the environmental impact of concrete associated with cement production like consumption of raw materials and energy use as well as emissions to air and avoiding environmental pollution due to avoiding as a waste.

a. Energy saving

The cement industry plays a significant role in global energy consumptions. Worldwide the cement industry is one of the most energy-intensive sectors in which energy represents 40% of the total production cost. The energy consumption in cement manufacturing is mainly related to the production methods that are wet methods consume more energy than dry methods. For instance, in the dry method, 1450°C of temperature is needed for the production of clinker which accounts for 97.2% of the total and the remaining is for finishing and raw materials grinding with the share of 0.9% and 1.9% respectively.
b. Reduction of \( \text{CO}_2 \) emission

Sustainable development of the cement and construction industry about environmental impact is one of the biggest challenges. The production of one ton of Portland cement release approximately one ton of \( \text{CO}_2 \) into the atmosphere in the manufacturing process. The cement industry contributes about 5\% of the total atmospheric \( \text{CO}_2 \) emissions globally. As a matter of fact, we are now concerned by the environmental impact of civil engineering structures. Judicious use of those cementitious materials as a partial replacement of cement can result from a significant result reduction of the \( \text{CO}_2 \) footprint of concrete structures. Most of the \( \text{CO}_2 \) emissions and energy use in the cement industry are related to the production of the clinker; 63\% of the \( \text{CO}_2 \) emitted during cement production comes from the calcination process, while the rest (37\%) is produced during the combustion of fossil fuels to feed the calcination process.

c. Economic advantages

The production of cement is energy-intensive, depends on the availability of raw materials near the cement manufacturing area and natural disturbances due to the extraction of raw materials. The process is mainly classified into three, the raw material preparation process, the clinker burning process, and the finish grinding process. Of all these processes, clinker burning is the most energy-intensive process, accounting for about more than 97.3\% of the fuel consumed and about 30\% of the electric power consumption, and the rest about 40\% of the electric power is consumed by the finish grinding process and about 30\% by the raw material preparation. Fuel costs are a large part of the manufacturing cost of the cement industry, making cement plants have aggressive energy consumption. Moreover, the clinker burning process as shown above takes more than 97\% of the fuel consumption, implying that it is the most expensive part of cement production.

5. Concrete and sustainability

Currently, Sustainability is an important issue all over the globe and it is affected by cement and concrete technology. The construction industry particularly cement and concrete are responsible for the production of 7\% carbon dioxide of the total world \( \text{CO}_2 \) emission. Green concrete capable of sustainable construction is characterized by the application of industrial wastes to reduce consumption of natural resources and energy and pollution of the environment. Replacement of materials over nominal concrete is what makes green concrete more environmentally friendly concrete.

Cement is a pillar to develop infrastructures in the given nations. At the same time, cement production affects the local environment and nearby communities. The environmental issues of cement manufacturing are related to local, regional, and global problems in their mining and mineral processing. The local problems include dust, ground subsidence, noise, vibrations, chemical contamination, tailings spills, scenic and local ecological degradation, and health problems among miners. Regional problems are acid rain and contamination of surface and/or groundwater spills of processing chemicals and stream sediment loading. Global problems are the effects of mineral use and anthropogenic greenhouse gases contributing to global warming. On the one hand, dust emission sources are kiln, crusher, grinders, clinker coolers, and material handling equipment, which are in
crushing and pyro processing. Besides, clinker manufacturing of pyro-processing is a considerable source of emission such as Cement Kiln Dust (CKD), gases like CO$_2$, Sulfur oxide, nitrogen oxide, and dioxins [11–15].

Air emitted/vented from various stages of cement processing contains dust, SO$_2$, NOx, CO$_2$, and heavy metals which can negatively affect the air quality of the area. One of the most common methods for reducing the environmental effect of concrete is by adding recycled materials to the concrete. The increased environmental awareness and dwindling resources in conjunction with regulation-based impetus enforced by governments/regional councils of different countries have led to the research and development of products and processes that employ effective waste utilization.

6. Conclusion

The concrete industry is a major contributor to air pollution and the user of natural resources. As such it bears a special responsibility to make a contribution towards sustainable development that is commensurate with its size. It can do so by pursuing three goals: (1) Searching for cement production technologies that are less energy-intensive and cause less air pollution. Since such technologies will not be available in the foreseeable future, the more realistic approach is to reduce the need for Portland cement, primarily by increased use of supplementary cementitious materials, especially waste materials. (2) Replacing concrete ingredients with recycled materials, such as recycled concrete or waste glass. (3) Through careful concrete mix design and prudent choice of admixtures, improve the durability of structures such that they need to be replaced less frequently.

In addition to this, sustainable construction makes wise use of all the natural resources and a 50% reduction in energy use, improves occupant health, comfort, productivity, reduces pollution and landfill waste that is not easily quantified, a sustainable building may cost more upfront, but saves through lower operating costs over the life of the building, construction is designed as one system rather than a collection of stand-alone systems with the help of the integrated system approach. Saying all this, I recommend to researchers make material characterization on those potential cement replacing materials.

Conflict of interest

“The authors declare no conflict of interest.”
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