Chapter

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

Abebe Demissew Gashahun

Abstract

The construction industry is a major contributor to environmental pollution. Cement is a costly material that is one of the largest industrial sources of greenhouse gases. As such, there is increased focus on developing sustainable and ecofriendly materials that can be used to replace cement. In this chapter, we discuss the construction industry, the harmful consequences of cement sourcing and production, and identify potential replacement materials for cement that have minimal negative effects on the environment.

Keywords: cement, concrete, cementitious materials, sustainable

1. Introduction

The construction industry is booming worldwide. In Ethiopia, governmental policy supports infrastructure development projects to help transform the country from an agricultural economy to an industrial one. As such, there has been increased exploitation of naturally deposited resources for concrete. Concrete is a blend of aggregates of either crushed stone, gravel, or sand blended with a paste of cement, water, chemical admixture, and cementitious materials. The cement paste in the concrete helps to make strong bonds between aggregate particles. Aggregates, major ingredients of concrete by volume, are comparatively inactive filler materials that make up approximately 68–85% of concrete and can therefore be expected to influence concrete's properties. Cement, which is among the main concrete ingredients, is the costliest and most environmentally inimical material.

Since cement production requires high energy consumption and leads to discharges of greenhouse gas, there continues to be a global search for new binders and admixtures to partially replace traditional ordinary hydraulic cement and improve the environmental sustainability and sturdiness of concrete structures. The application of leftover byproducts in construction materials as replacements for concrete is an attractive alternative to disposal and an eco-friendly solution to the challenges of exploitation and shortage of nonrenewable natural resources worldwide.

Sustainability is a combination of environmental, economic, and societal factors, with environment being the dominant parameter. The deterioration of our environment is driving the current worldwide focus on sustainable development. Generally, almost all scholars agree that definitions of sustainability include "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

Construction typically refers to every type of activity associated with the erection and repair of immobile structures and facilities. It is essential to the growth of nations and their economies. In Ethiopia, approximately 60% of the federal capital budget is allocated to the construction industry. Of this allotment, 70% goes to physical infrastructures, 13% to transport and communication, and 17% to buildings and other sectors. The products of construction contribute extensively to the creation of wealth and quality of life.

The construction industry furnishes capital improvements to countries. Since the industry is primarily based on investments, construction activities are the first to suffer during economic recessions. However, in good economic times, construction workers can become quite prosperous. The construction business faces many challenges, such as low productivity, high costs, missed deadlines, quality failures, high rates of fatal accidents and injuries, conflicts and disputes that lead to claims and time-consuming litigation, and poor image due to its harmful effects on the environment. It is viewed as dirty, dull, and environmentally unfriendly.

Construction affects sustainability in its five major phases: (1) predesign 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 and assessment, site layout and development, watershed conservation and management, equipment and materials); (3) design phase (passive solar design, materials and specification, indoor air quality); (4) construction phase (environmentally conscious construction, preservation of features and vegetation, waste management and source control practices); and (5) operation and maintenance phase (maintenance plans, indoor quality, energy efficiency, resource efficiency, renovation, housekeeping and custodial practices).

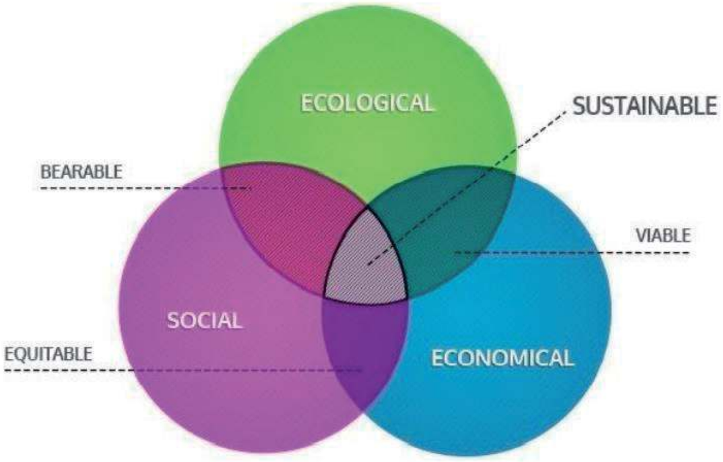

Figure 1.
Interrelations among the ecological, economic, and social impacts of construction.

3. Concrete production

Concrete construction demands land. The sourcing of materials for construction activities (aggregates, cement, waters, admixtures, etc.) from quarry sites and borrow pits can potentially result in the wholesale removal of vegetation and virgin materials. It can also lead to displacement of individuals and loss of important ecological resources and biodiversity of national, regional, or global importance.

The steps of aggregate manufacturing have many considerable environmental impacts. The foremost environmental effect resulting from stone, aggregate, and mineral mining is air pollution from airborne emissions from both stack and disturbed areas at these mines. Natural deposit sources of aggregates are being depleted, threatening the environment and society. The high rate of natural aggregate depletion from source beds causes many problems, such as loss of water-retaining strata, bank slides, exposure of water supply scheme intake wells, and decreasing underground water table levels, which are causes of negative agricultural effects and aquatic life disturbances.

In emerging nations such as Ethiopia, due to rapid urbanization and infrastructure projects, there has been a wide expansion of cement industries that release pollutants. Apart from these environmental concerns regarding CO_2 emissions during cement manufacturing, natural resource demands also make cement expensive when compared with aggregates and water for concrete production. Consequently, to overcome these problems, scientists are searching for more environmentally friendly and economical materials that have cement-like properties and can be used as full or partial substitutes for normal Portland cement.

4. Cementitious materials

Cement is a material with cohesive and adhesive characteristics that make it capable of bonding mineral fragments into a compact whole. Although it plays a major role in concrete for the construction industry, it is not environmentally friendly and is the most expensive concrete material.

Using concrete mix with optimum cement content, enhancing cement's durability, and developing 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 that can be used as partial or full replacements for normal Portland cement.

Cement is a fine gray powder, and when it reacts with water, it forms hardened, rigid, and stable structures that bond aggregates together, acting as glue and giving the desired strength of concrete. In ancient times, Romans mixed lime ($CaCO_3$) with volcanic ash, producing cement mortar, which was used during the construction of monumental structures such as the Colosseum [1]. Cement is defined as a mineral chemical produced by mixing a well-defined ratio of raw materials at highly elevated temperatures. Producing cement depletes natural resources and emits greenhouse gases into the atmosphere. It is believed that producing one ton of cement clinker 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 the amount of greenhouse gases emitted during the production process. Additionally, cement factories contribute tremendously to global warming as well as degrade and disturb the natural existing environment. Beyond this, the cement industry requires high capital investment, energy intensiveness, and high dependence on power and transport.

4.1 Cost of production

Cement factories are some of the most energy-consuming/intensive industries worldwide, with 30–40% of their total production costs going to fuel and energy for production. The cost of raw materials represents the second-largest percentage of cement manufacturers' cost structures.

4.2 Ingredients for cement production

The major ingredients of cement include clay, limestone, marl, chalk, and others, noteworthy quantities of which are endlessly quarried to meet the demand for cement. The cement sector currently uses large quantities of power station fly ash, blast furnace slag, natural pozzolana, limestone, and silica fumes to substitute for natural raw materials in the production process of blended cements. The use of these alternative materials has significant economic benefits and positive environmental advantages, such as reduced energy consumption and emissions of dust, CO_2, and acid gases. In some applications, the performance of concrete can be enhanced when these alternative materials complement Portland cement clinker.

4.3 Energy/power

Cement production is an energy-intensive process. The specific thermal energy demand of a cement kiln varies between 3000 and 7500 million joules for a ton of clinker, depending on the basic process design of the plant. The explicit electrical energy demand typically ranges between 90 and 130 kWh and 60 and 130 kg of fuel oil per ton of cement. The cement industry 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 in 2009/2010. This result suggests the need to increase the production and supply capacity of cement to meet the needs of the fast-growing construction industry.

4.4 Pozzolanic materials

Pozzolan is an aluminosilicate/siliceous material that is finely ground and chemically reacts with calcium hydroxide in the presence of moisture to create calcium silicate hydrate (CSH) and other cementitious materials. Clay and shale, volcanic ash, and diatomaceous earth are examples of natural pozzolanas, while fly ash, rice husk ash, blast furnace slag, coffee husk ash, silica fume, bagasse ash, and metakaolin are examples of artificial pozzolanas. Most pozzolanas used today are widely available byproduct materials. Since there are many types of pozzolana, its chemical structure and contents also vary. Therefore, classifying pozzolanas depending only on their chemical composition is difficult. For this reason, ASTM C-618 classifies pozzolanas based on performance, as shown in **Table 1** [3–6].

Pozzolanas improve both hardened and fresh concrete. Decreasing thermal shrinkage and heat of hydration, increasing water tightness, decreasing the alkali-aggregate reaction, resisting sulfate attack, improving workability, and price effectiveness are some of the benefits of using pozzolanas blended with cement [7–9].

Materials used to either partially or fully replace cement are special construction materials, either naturally occurring or byproducts of industrial or agricultural waste. They rely on the activation of byproducts while incorporating minimal amounts of cement and are promising low-carbon candidates that can potentially complement the globe's growing concrete industries.

	F	C
$SiO_2 + Al_2O_3 + Fe_2O_3$ (min %)	70	50
MgO (max %)	…	5
SO_3 (max %)	5	5
Moisture content (max %)	3	3
Loss on Ignitions (max %)	12	10
Available alkalis as Na_2O (max %)	1.5	1.5

Table 1.
Chemical requirement for pozzolanic materials.

4.4.1 Chemicals pozzolan class

Due to the increase in awareness of environmental concerns and natural resource consumption, the issue of energy savings has been gradually emphasized by the public. Owing 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 such as Ethiopia, concrete is the most significant material for fundamental and public constructions. Thus, an innovative and alternative concrete material that is feasible and practical is critical and significant for mitigating environmental impacts and promoting energy-saving performance. Some of the most common cement replacements in concrete production are natural pozzolanas, diatomaceous earth, glass residue, Silpoz plaster, fly ash, corn cob ash, ground granulated blast furnace slag, silica fume, highly reactive metakaolin, rice husk ash, bagasse ash, coffee husk ash, calcined termite hell, water hyacinth ashy, and so on.

4.4.2 Natural pozzolanas

Natural pozzolanas originating from volcanic activities are available worldwide, with varied compositions and subsequently varied performance. Because of their large content of amorphous silica, pozzolanas are excellent replacement materials for cement. Curiously, before the invention of ordinary Portland cement, volcanic ash and air lime mixtures were commonly used, with good performance and proven durability. Difficulties in the usage of these products are a 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 used to replace up to 20% of cement's mass. The use of volcano ash for concrete production helps to reduce the chloride ion diffusivity of concrete, inhibiting the localized corrosion of steel and further concrete degradation. This addition also promotes less heat of hydration and a longer setting time. The improved performance was qualified for the refinement of the stomate structure and the pozzolanic action of volcanic ash. One of the challenges of using natural pozzolana materials is their diversity. To minimize this problem, natural pozzolanic materials from different extraction heights are usually mixed before use [1–3, 6, 10].

4.4.3 Diatomaceous earth

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

4.4.4 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. It can replace up to 20–30% of cement without harmful effects; it performs satisfactorily concerning alkali reactivity and drying shrinkage. In addition, glass powder can significantly reduce the chloride ion penetrability of concrete.

4.4.5 Silpoz

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

4.4.6 Corn cob ash

The demand for corn cob ash as an alternative cement material is increased due to its low organic content, which proves the binding properties of cement. It can be used to replace up to 20% of cement's mass and increases the water amount, which helps to obtain the desired plasticity as well as the initial and final setting time. This is probably 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.

4.4.7 Fly ash

Fly ash is a byproduct of pulverized coal in electric power plants. It is a fine-grained material containing alumina, silica, iron, and calcium, as well as sulfur, sodium, magnesium, carbon, and potassium. It can be used to replace up to 15% of cement's mass.

4.4.8 Ground granulated blast furnace slag

Blast furnace slag is a byproduct of the iron manufacturing industry that contains cementitious materials such as aluminosilicates, silicates, and calcium.

4.4.9 Silica fume

Silica fume is waste from the production of silicon/ferrosilicon alloy in an electric furnace from high-purity quartz with coal. It is used as cement to replace

5–10% of concrete's mass. It is recommended for use in high-strength and impermeable concrete.

4.4.10 Highly reactive metakaolin

Highly reactive metakaolin is a highly active pozzolana concrete material. In contrast to slag, fly ash, or silica fume, it is not a byproduct but rather is manufactured from high-purity kaolin clay by calcination at temperatures of 700–800°C. Unlike silica fume, which has more than 85% SiO_2, metakaolin contains equal proportions of SiO_2 and Al_2O_3 by mass.

4.4.11 Bagasse ash

Bagasse is fiber from cellulose obtained via the extraction of juice from sugarcane. Large amounts are obtained from sugar factories. It contains silica and alumina, which are the most vital components of cement-replacing materials.

4.4.12 Rice husk ash

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

4.4.13 Coffee husk ash

The chemical composition of coffee husk ash has significant values of Al_2O_3 and SiO_2, which are major components of cement. It can replace cement by approximately 10%, and concrete produced from coffee husk ask has good potential as an environmentally friendly cementitious material that reduces pollution and provides a sound coffee waste management option.

4.4.14 Termite hill clay

Calcined termite hill clay powder is a pozzolanic material containing 38.82% SiO_2, 23.98% Al_2O_3, and 11.68% Fe_2O_3. As such, termite hill clay powder calcined at 650°C satisfies the American Society for Testing and Materials' requirements for use of calcined natural pozzolan in concrete. Moreover, classified as natural pozzolana class N, the material can produce a cementitious compound that has binding properties upon reaction with calcium hydroxide obtained from the hydration of cement. Therefore, calcined termite hill clay powder is a suitable replacement for up to 11.3% of cement in the production of concrete, which implies that it can reduce CO_2 emissions by 11.3%.

4.4.15 Water hyacinth biochar

Water hyacinth biochar, a carbonaceous solid material obtained through a pyrolysis process from solid waste materials, has extremely low thermal conductivity, high chemical stability, low flammability, ability to absorb water, and high capture and storage of CO_2. It can be used as a partial cement-replacing material in concrete construction up to 5% of cement by weight. In addition, every ton of biochar used in a building envelope means that the equivalent of approximately one ton of CO_2 is prevented from re-entering the atmosphere.

4.5 Advantages of cement-replacing materials

4.5.1 Environmental advantages

The cement industry is an energy-intensive industry with energy typically accounting for approximately 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 currently under greater scrutiny because of the large volumes of CO_2 emitted. This industrial sector is thought to be responsible for 5–7% of total CO_2 anthropogenic emissions. Concern over the impact of anthropogenic carbon emissions on the global climate has increased in recent years due to increased awareness of global warming. In addition to the generation of CO_2, the cement manufacturing process produces millions of tons of cement kiln dust waste product each year, contributing to respiratory and pollution health risks. To produce one ton of clinker, the typical average consumption of raw materials is 1.52 tons.

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

4.5.1.1 Energy saving

The cement industry plays a significant role in global energy consumption. 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 production methods, which are wet methods that consume more energy than dry methods. For instance, in the dry method, a temperature of 1450°C is needed to produce clinker, which accounts for 97.2% of the total, and the remaining temperature is needed for finishing and raw material grinding, with shares of 0.9 and 1.9%, respectively.

4.5.1.2 Reduction of CO_2 emission

Sustainable development of the cement and construction industry is one of the biggest challenges today. The production of one ton of Portland cement releases approximately one ton of CO_2 into the atmosphere in the manufacturing process. The cement industry contributes approximately 5% of the total atmospheric CO_2 emissions globally. In fact, we are now concerned with the environmental impact of civil engineering structures. Judicious use of cementitious materials as a partial replacement for cement can significantly reduce the CO_2 footprint of concrete structures. Most of the CO_2 emissions and energy use in the cement industry is related to the production of clinker; 63% of the 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.

4.5.1.3 Economic advantages

The production of cement is energy intensive and depends on the availability of raw materials near the cement manufacturing area. The process is mainly classified into three categories: 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 more than 97.3% of the fuel consumed and approximately 30% of the electric power used. Approximately 40% of the electric power is consumed in the finish grinding process and 30% during 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 consumes more than 97% of fuel, suggesting that it is the most expensive part of cement production.

5. Concrete and sustainability

Currently, sustainability is an important issue worldwide and is affected by cement and concrete technology. The construction industry, particularly cement and concrete, is responsible for the production of 7% of the world's total CO_2 emissions. Green concrete capable of sustainable construction is characterized by the application of industrial wastes to reduce the 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.

Cement is integral to infrastructure development in many 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 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 from chemical spills, and stream sediment loading. Global problems are the effects of mineral use and anthropogenic greenhouse gases contributing to global warming. Dust emission sources include kilns, crushers, grinders, clinker coolers, and material handling equipment, which are used in crushing and pyroprocessing. In addition, pyroprocessing is a considerable source of emissions, such as cement kiln dust, gases such as CO_2, sulfur oxide, and 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 effects of concrete is adding recycled materials to the concrete. Increased environmental awareness and dwindling resources in conjunction with regulations by governments/regional councils 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 an exploiter of natural resources. As such, it bears a special responsibility to contribute to sustainable development. 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; and (3) improving the durability of structures such that they need to be replaced less frequently through careful concrete mix design and prudent choice of admixtures.

Conflict of interest

The authors declare no conflict of interest.

Author details

Abebe Demissew Gashahun
Construction Technology and Management Academic Program, School of Civil and Water Resource Engineering, Debre Markos Institute of Technology, Debre Markos University, Debre Markos, Ethiopia

*Address all correspondence to: abebe_demissew@dmu.edu.et

References

[1] Hewlett P. Lea's Chemistry of Cement and Concrete. Elsevier Science & Technology; 2004

[2] Naik TR, Moriconi G. Environmental-Friendly Durable Concrete Made with Recycled Materials for Sustainable Concrete Construction. University of Wisconsin Milwaukee; 2006

[3] Comparison of different waste materials used as cement replacement in concrete. 2019. DOI: 10.1088/1755-1315/357/1/012010

[4] Gashahun AD. Assessment on cement production practice and potential cement replacing materials in Ethiopia. 2020;**12**:22-28

[5] Akadiri PO, Chinyio EA, Olomolaiye PO. Design of a sustainable building: A conceptual framework for implementing sustainability in the building sector. 2012:126-152. DOI: 10.3390/buildings2020126

[6] Alconpat R. Use of supplementary cementitious materials (SCMs) in reinforced concrete systems—Benefits and limitations. 2020;**10**:147-164

[7] Demissew A, Fufa F, Assefa S. Partial replacement of cement by coffee husk ash for C-25 concrete. 2019;**10**:12-21

[8] Marchetti E. Use of Agricultural Wastes as Supplementary Cementitious Materials. 2020

[9] Ramezanianpour AA. Cement replacement materials. n.d

[10] Lahri A, Dixit S. Alternatives to cement in concrete—A review. 2015;**6**:50-56

[11] Just H. How to make concrete more sustainable. 2015;**13**:147-154. DOI: 10.3151/jact.13.147

[12] Struble L, Godfrey J. How sustainable is concrete? In: pp. 201-211

[13] Cachim P, Velosa AL, Ferraz E. Substitution materials for sustainable concrete production in Portugal. 2014. DOI: 10.1007/s12205-014-0201-3

[14] Ioannou S. Alternative cementitious solutions for sustainable concrete in the Gulf region. 2019

[15] Meyer C. Concrete and Sustainable Development.2002. pp. 1-12