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A Graduate Research on the Cost Effective Analysis and Environmental Impact of Using Industrial Byproducts as Supplementary Cementitious Materials in Building Construction

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For more than forty years, Dr. Fazil T. Najafi has worked in government, industry and education. He earned a BSCE in 1963 from the American College of Engineering, in his place of birth, Kabul, Afghanistan, and since then came to the United States with a Fulbright scholarship earning his MS in civil engineering in 1972 and a Ph.D. degree in transportation in 1977. His experience in industry includes work as a highway, structural, mechanical, and consultant engineer and construction manager for government groups and private companies. Najafi went on to teaching, first becoming an assistant professor at Villanova University, Pennsylvania in 1977, a visiting professor at George Mason University, and then to the University of Florida, Department of Civil Engineering, where he advanced to associate professor in 1991 and then full professor in 2000 in the Department of Civil and Coastal Engineering. He has received numerous awards including a scholarship award (Fulbright), teaching awards, best paper awards, community service awards, and admission as an Eminent Engineer into Tau Beta Pi. His research on passive radon-resistant new residential building construction was adapted in HB1647 building code of Florida Legislature. Najafi is a member of numerous professional societies and has served on many committees and programs, and continuously attends and presents refereed papers at international, national, and local professional meetings and conferences. Lastly, Najafi attends courses, seminars and workshops, and has developed courses, videos and software packages during his career. His areas of specialization include transportation planning and management, legal aspects, construction contract administration, and public works.

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A graduate study on cost effective analyses and environmental impact analyses of using waste cementitious materials in building construction

Abstract

Concrete is the most dominating construction material across the globe. In the last two decades the concrete production has increased dramatically, which caused an increase in Portland cement production since it is the core of reaction that gives concrete its strength. Cement production generates a significant amount of Green House Gas (GHG) contributing to global warming.

The purpose of this research is to review literature that proves efficiency of the usage of waste cementitious materials and to develop a comprehensive program to extrapolate the cost effective analyses of using these materials in construction and developing an environmental friendly alternative. This research will also document any existing methods available in applying the cost effectiveness of different projects involving Supplementary cementitious materials (SCM). A comparison among different SCM including concrete projects are analyzed for economy and environmental impact.

This research is focusing on waste SCM and concrete management for optimizing the construction costs. The ways for reducing the greenhouse gases (GHG) are one of the assumed benefits of this research. The future research can be in developing an ecofriendly concrete with greater strength and durability with less energy consumption.

Keywords

Concrete, Supplementary cementitious materials, Greenhouse gases, Efficient energy consumption

Introduction

Portland cement has been a dominant binder in construction, since the development of it over 175 years. [1]

Ordinary Portland cement (OPC) is a widely used material in any kind of construction. OPC happens to be the main binding material in construction industries across the globe. It is because the cohesive & adhesive properties. These properties make OPC capable of uniting the different construction materials and give a compacted assembly. [2.]

OPC manufacturing is a closely controlled chemical combination of calcium, silicon, aluminum, iron and other ingredients. [2]

The main compounds formed in mixing are:

- triclcium silicate (3CaO.SiO2)
- Dicalcium silicate (2CaO.SiO2)
- tricalcium aluminates (3CaO.Al2O3)
- tetracalcium aluminoferrite (4CaO.Al2O3.Fe2O3) [2]

About 1.56 billion tons of OPC are produced each year across the globe. Global consumption of Portland cement concrete is about 3.8 million cubic meters per year. Figure1 and figure 3 show us the exponential increase of cement production and consumption.[3&4] This process of production of cement and concrete is energy intensive and is responsible for the emission of carbon dioxide. To reduce the dependence on the cement utilization, the construction industry is turning its focus on Supplementary cementitious materials (SCM). [2]

The SCM is also referred to as the pozzolanic materials because of its binding capabilities. The SCM's that are discussed in this study are granulated blast furnace slag, fly ash, silica fume. [2]

About 850–900 kcal/kg (in the dry process) and 1300–1600 kcal/kg (in the wet process) is consumed in cement production. The global average electricity consumption is close to 111 kWh per ton of cement production. The amount of raw materials used in 1ton production of OPC is 1.5 ton and energy required to produce is 4.0 kJ energy. The gradual depletion of fuel energy and natural stone from our planet is due to cement manufacturing process. [2]

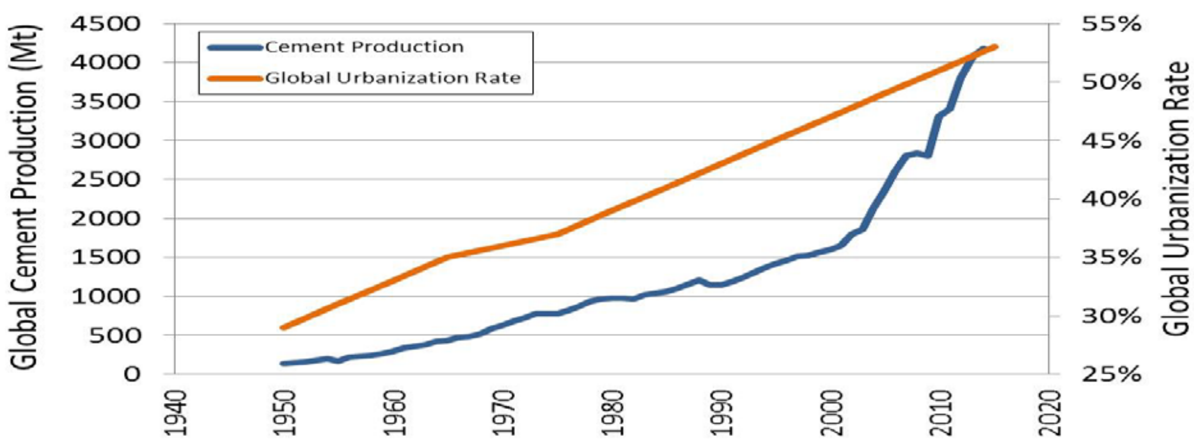

Figure1: Global cement production

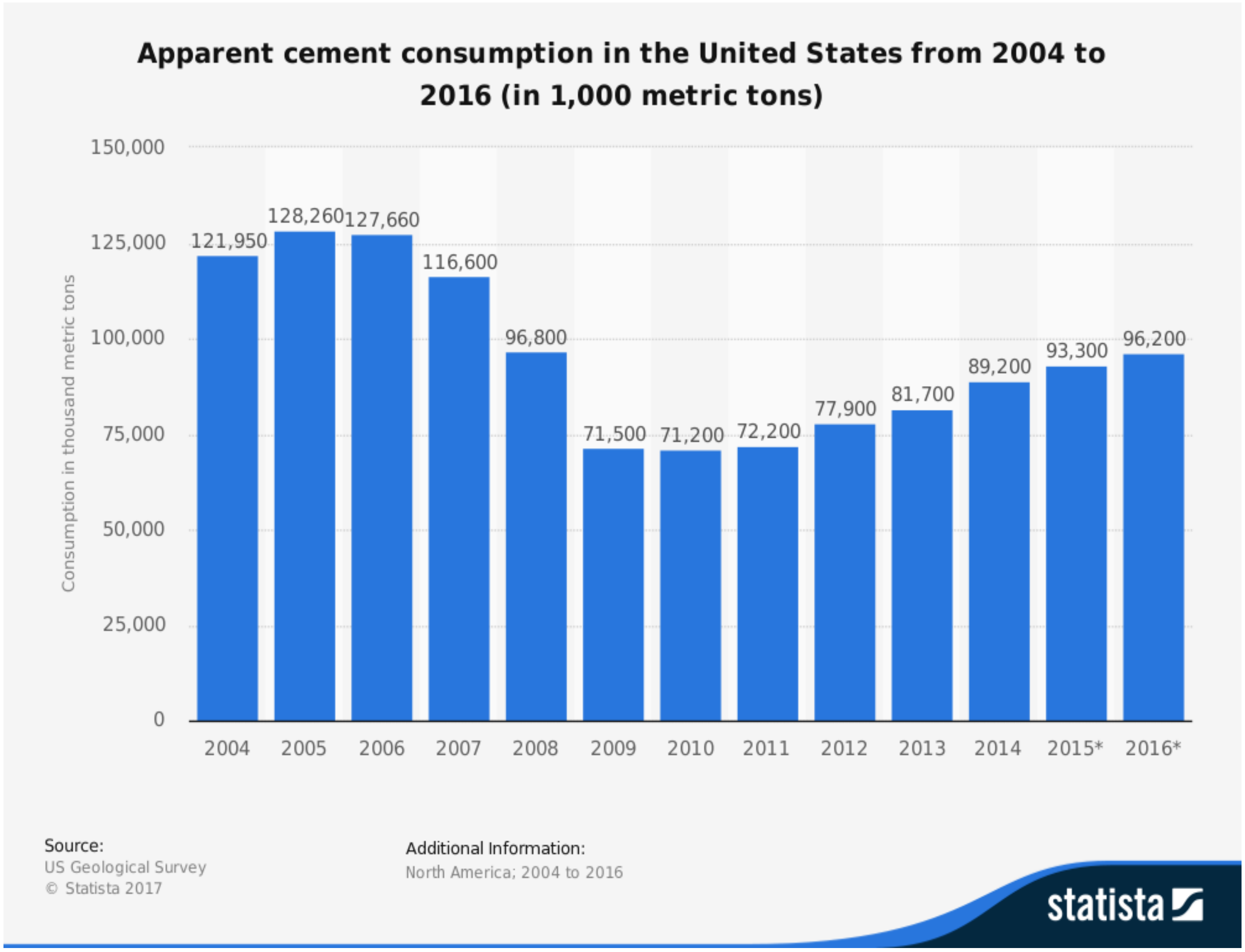

Figure 2: Cement consumption

Goal and objective

A range of materials is used in the building sector. A part of this study is to investigate and understand energy consumptions, CO_2 emissions and cost reduction in the usage of the SCM. These materials are in reuse as waste supplementary cementitious material in concrete (e.g. fly ash, silica fume, slag). The regular use of these materials in construction industry will lead to less energy consumption, reduction in CO_2 emissions and costs. A wide range of study is on progress on the SCM but only focusing on its mechanical or durability aspect. [5] This study will be beneficial to many people including policy makers, building material producers, environmental engineers, environmental researchers and building designers.

Embodied energy

The embodied energy of Portland cement concrete is low in comparison with other materials used in construction as can be seen in the figure 3. [6]

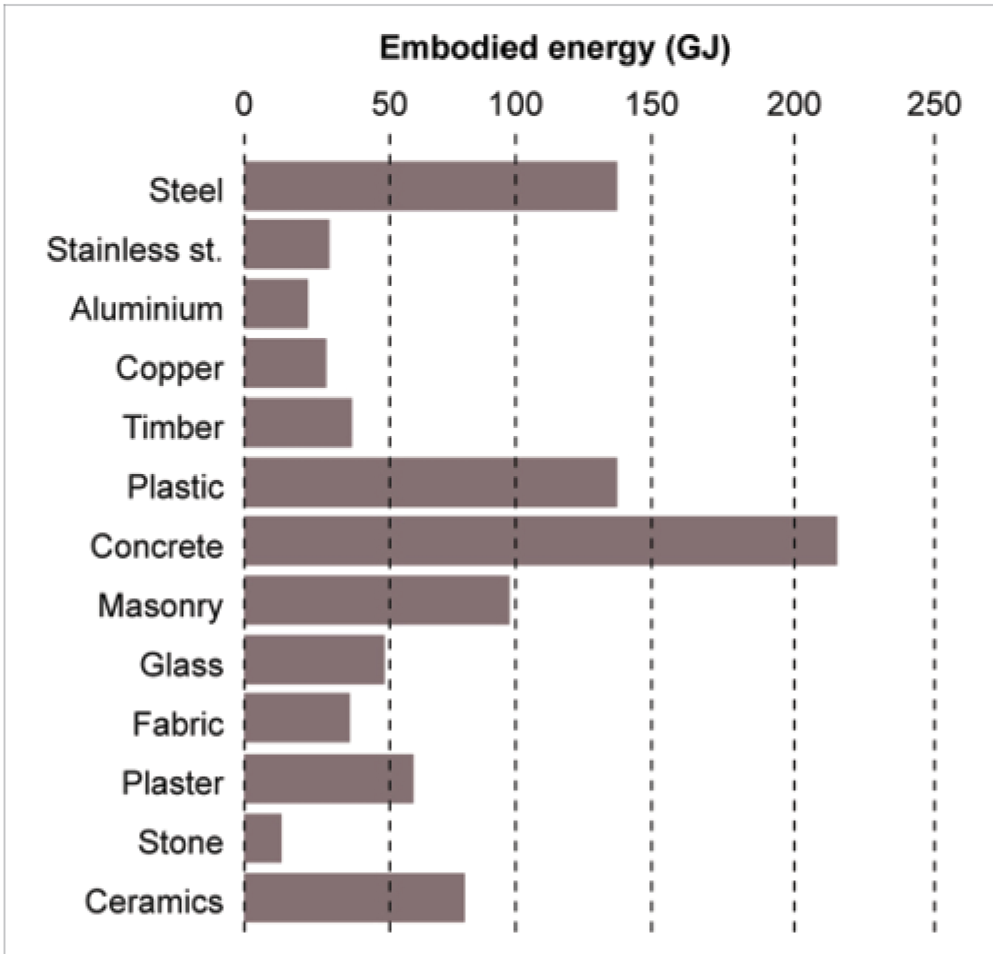

Figure 3: Embodied energy of common building materials

The sum of all energy consumption which includes the energy used for material exploitation, production, construction, installation, maintenance and demolition is the embodied energy of building materials. Figure 3 gives us a brief description of the embodied energy values for different materials used in construction [6]. The materials used in building construction should be reusable and recyclable, which intend will lead to low embodied energy and low CO_2 emissions. [7]

Despite of low embodied energy the production of cement and concrete do not come without issues. The manufacturing of OPC consumes 10–11 EJ of energy yearly. Due to the CO_2 emission in the process of concrete and cement production, the cement industry is actively seeking alternatives to reduce both energy use and greenhouse gas emissions.[5] The Figure 4 talks about the greenhouse gas reduction due to the utilization of SCM.[8] Table 1 and figure 5 talk about the top cement producing nations across the globe. [(3&9)]

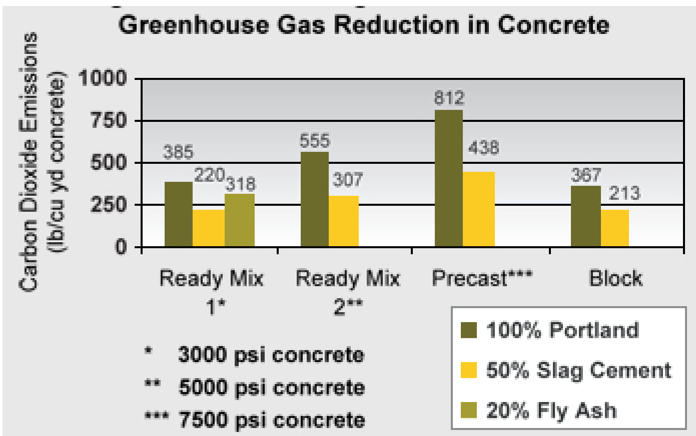

Figure 4: Effect of slag cement on embodied greenhouse gas reduction in concrete

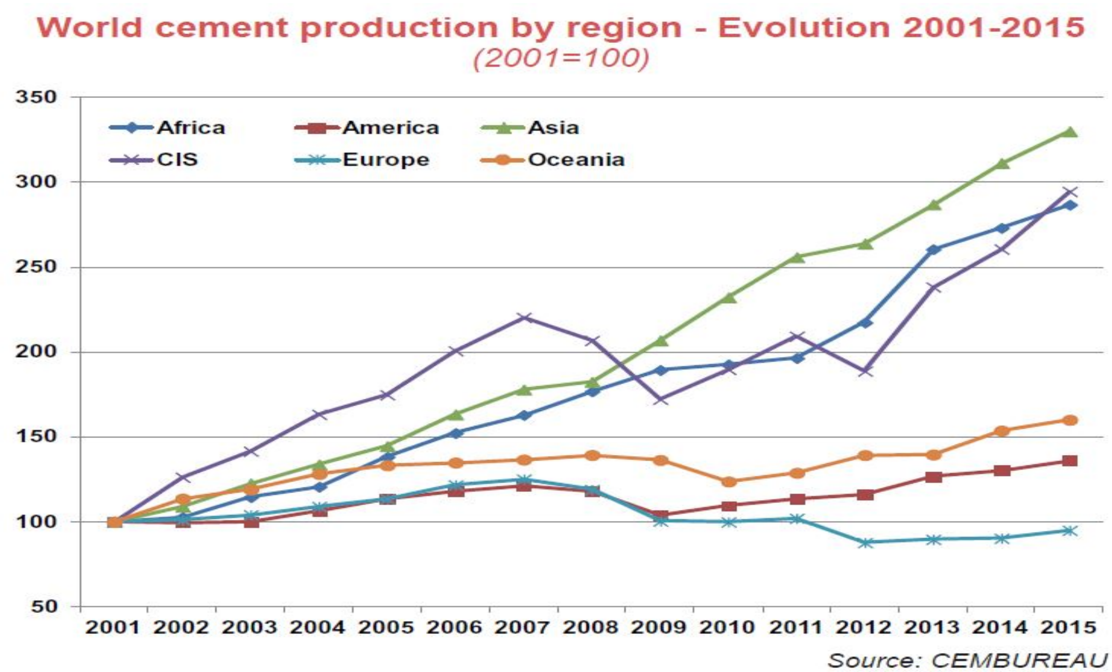

Figure 5: World cement production by region

Table 1: Top cement producing nations in 2014

Country	Cement production (Mt)
China	2500
India	280
U.S.	83
Iran	75
Turkey	75
Brazil	72
Russia	69
Saudi Arabia	63
Indonesia	60
Vietnam	60
Japan	58
Egypt	50
South Korea	48
Thailand	42
Mexico	35
Pakistan	32
Germany	31
Italy	22

Environmental Impacts: Risk of improper disposal of Waste Materials

The application of waste materials in cement and concrete industry will highly improve surroundings we live in and prevent environmental pollution. A proper management system is required for the waste utilization. Fly ash is usually dumped in a specialized fly ash landfills and proper lining has to be built to prevent trace elements in the fly ash from leaching into drinking water supplies. The study by EPA has found that living near such enclosures like ash ponds increases the risk of damage from trace toxic materials like cadmium and lead. [10]

The proper disposal of silica fume and fly ash, an industrial by product waste, is one of the major issues for environmentalists worldwide since dumping of silica fume as a waste material may cause severe environmental problems and hazards. Hence, the use of waste SCM in concrete reduces the environmental burden by relieving a waste problem and contributes to the durability of concrete. [10]

Calcination and fuel combustion in the process of cement production generates Green House Gas (GHG). The use of SCM in concrete can be a major help in reduction of greenhouse emissions. This inclusion can make it possible to reduce the CO_2 emission in atmosphere towards eco-friendly construction technique. [10]

These emerging environmental impacts demand detailed knowledge to progress towards sustainable practices. The embodied energy of various human created objects has been used as a defacto scale to assess the environmental impact and reduce unsustainable practices. The next step to better understanding the environmental impacts is embodied CO_2 analysis, which relates with the issue of climate change. [11]

Sustainable construction

Due to the increasing awareness about climate change, the focus has been increasing in the area to develop more sustainable buildings and constructions. This is increasingly being encouraged for upcoming infrastructure.[12]

Since we spend 89-90% of our time in the built environment, it is wise to make it sustainable. It is crucial to build and environment that is healthy and pleasant for human living despite the resource and pollution issues surrounding the construction sector[12]. There is a 70% increase in the greenhouse gas emission between the years 1970-2004 as per The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).[13]

The buildings contribute to one third of the greenhouse emissions, mainly because of the use of fossil fuels. All the efforts in the past have been. Past efforts to address these emissions have had a mixed record of success[14]. There is wide variety of studies have already been done on SCM for the last 50 years; none has shown that recycled materials are unsuitable for structural use. This opens a completely new range of possibilities for the reutilization of materials. This reuse of materials is a good solution to the problem of excess materials.[14]
To create a better world, sustainability is very necessary for our future generations, which will be by enhancing environmental performance.it is the intersection of economic, social and environmental impact all put together. Sustainability shown in Figure 6 will provide a livable and cleaner planet without compromising the needs of the future generations.[15]

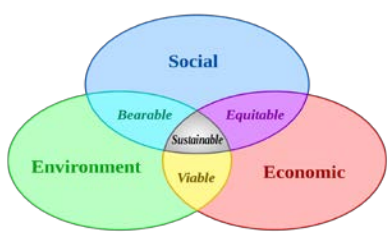

Figure 6: Sustainability

In the recent times, about 10-50% of cement is being replaced by SCM. The future interests in pushing this boundary to a higher extend to create binders either entirely or almost from waste SCM. The additional shortcoming of Portland cement in various applications gives this research the additional motivation.[1]

Supplementary cementitious materials

Fly ash, ground granulated blast-furnace slag and silica fume are materials when used with OPC contribute to the hardening properties concrete. Most of these materials are byproducts of other industrial processes. It is desirable to use these materials judiciously in energy perspective and environmental aspect. These materials can be used as partial replacement or addition part, depending on the required for the construction.[16]

Fly ash

Fly ash is the by-product of combustion of pulverized coal in the electric power generation plants. During combustion in the furnace, volatile matter and carbon are burnt off and the residue is Fly ash. The various mineral impurities present in coal are clay, feldspar, quartz and shale fuse. It primarily contains silica, alumina, iron and calcium. Fly ash particle sizes vary from less than 1 µm to more than 100 µm with the typical particle size measuring under 20 µm. Therefore, they mix well with OPC because of its size being angular.[16]

Silica fume

Silica fume is produced because of the reduction of high-purity quartz with coal in an electric arc furnace. Silica fume is produced as an oxidized vapor from the 2000°C (3630°F) furnaces. After cooling down, its collected in cloth bags essentially as silicon dioxide in amorphous form. Only 5-10% of Silica fume is used as cementitious material. It is used usually to create high strength concrete and high degree impermeability.[16]

The use of silica fume as a partial replacement of fine aggregate will be environmentally beneficial as it is a means of waste product utilization.[10]

Blast furnace slag

The use of granulated blast furnace slag as a cementitious material started in the early 1900's. It was developed in Germany. About 30-45% of binder material in concrete can be replaced by granulated blast furnace slag. The Ground granulated blast-furnace slag is also referred to as the slag cement. It is made from Iron. It contains importantly the silicates and aluminosilicates of calcium developed during the molten state along with iron in a blast furnace. [16]

Suitability of concrete with waste cementitious materials in structures

The use of SCM can help reduce the dead weight of a structure by increasing the flexibility, workability with lighter weight. It improves thermal, fire resistance, and is better for sound insulation. The usage of SCM in concrete helps in reducing the concrete industry's CO_2 emission by 30 % and increases concrete industry's use of waste products by 20%. This leads to reduced environmental pollution and sustainable development. The overall material benefits are resource efficiency and energy efficiency. The properties that make it efficient are its recycled content and manufacturing process. These recycled materials used in concrete tend to lead to energy conservation. [17]

Methodology

Understanding sustainability in construction industry is one of the focuses of this research. There is a large consumption of energy and resources in the building sector which deep impacts on the environment. Construction is inevitable and concrete buildings are going to be built all over the world due to the economic reasons. As established earlier cement, production is one of the most energy-intensive processes in the world. For every ton of cement manufacture, 930 kg CO_2 is emitted.[18]
There is an urgent need to learn about the effective use of cement and concrete to develop a stronger, more durable, energy efficient and economically viable. It should be made mandatory to use the debris after the lifetime of a structure as a filling material in applicable places. The partial replacement of cement with SCM provides an important contribution for the green, durable and energy efficient concrete design. Based on the demand of durability and strength, these SCM's like fly ash and slag can replace up to 70 % of the binder.[18&19]

A brief study of CBA, LCA and CEA was done to understand the application. This study can help evaluate different scenarios for the reuse of the waste cementitious materials in terms of environmental impact and economic benefits.

The various options available as reuse that have been already studied have been listed below and the energy consumption is summarized in Table 2.[19 & 17]

- Disposal in a landfill after stabilization/solidification,
- Reuse as part of raw material in cement kiln,
- Reuse as part of aggregates for bricks, and
- Reuse as alkali in the Waelz process (Figure 7)[19].

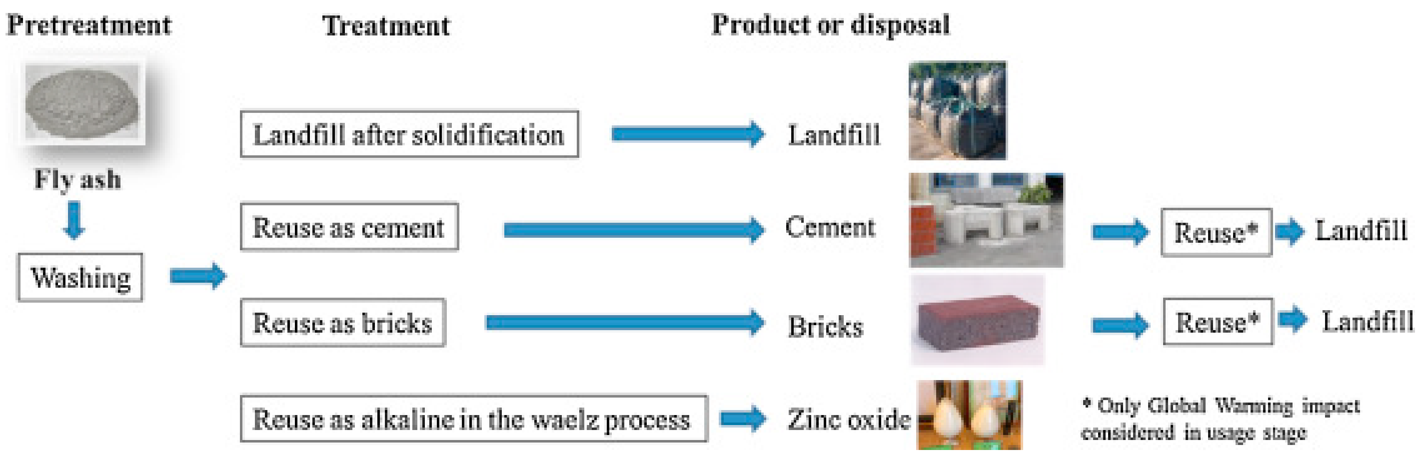

Figure 7: Different scenarios of reuse of fly ash

Table 2: Various reuse scenarios and the energy consumption

Energy flows per ton of fly ash treatment.					
Scenario	Description	Energy usage/t of fly ash	Amount	Unit	Sources
1	Landfill after solidification	Solidification	3.9	kWh electricity	Operated factory
		Activities on landfill:	55 l	l diesel	
2	Reuse as cement	Cement making	0.81	ton fuel oil	Chen et al. (2010)
			0.81	ton natural gas	
			3.776	ton coal	
3	Reuse as bricks	Extraction of material	0.707	l diesel	Siao (2010)
		Brick making	9.278	l diesel	
			33.16	kWh electricity	
			0.021	kg coal	
4	Reuse as alkaline	Waelz kiln	0.45	ton coal	Operated factory
		ZnO recycling process	75	kWh electricity	
			30	kg oil	
			95	kWh electricity	

Life cycle cost framework development

For better understanding, the economic aspect of the construction industry's life cycle cost, framework is necessary. This framework shown in Figure 8 includes all aspects like the performance, social economic, public and rehabilitation factors into account. It is necessary to develop a comprehensive approach to quantify and validate all the above-mentioned aspects. Although sometimes it is hard to fully understand and calculate these aspects.[20]

The idea behind life cycle cost analysis is that all costs involved in a construction, maintenance, rehabilitation, social, economic impacts and any other cost that is incurred during care and maintenance of a construction considered in the design decision process. Every aspect mentioned earlier in the life cycle cost process is combined with other aspects relevant to them in some way to calculate a final product. The two major costs usually are the user costs and agency costs. Some external costs are not directly related to construction or maintenance. These costs tend to be a little difficult to quantify, but it is necessary to include them and the modeling technique used.[20]

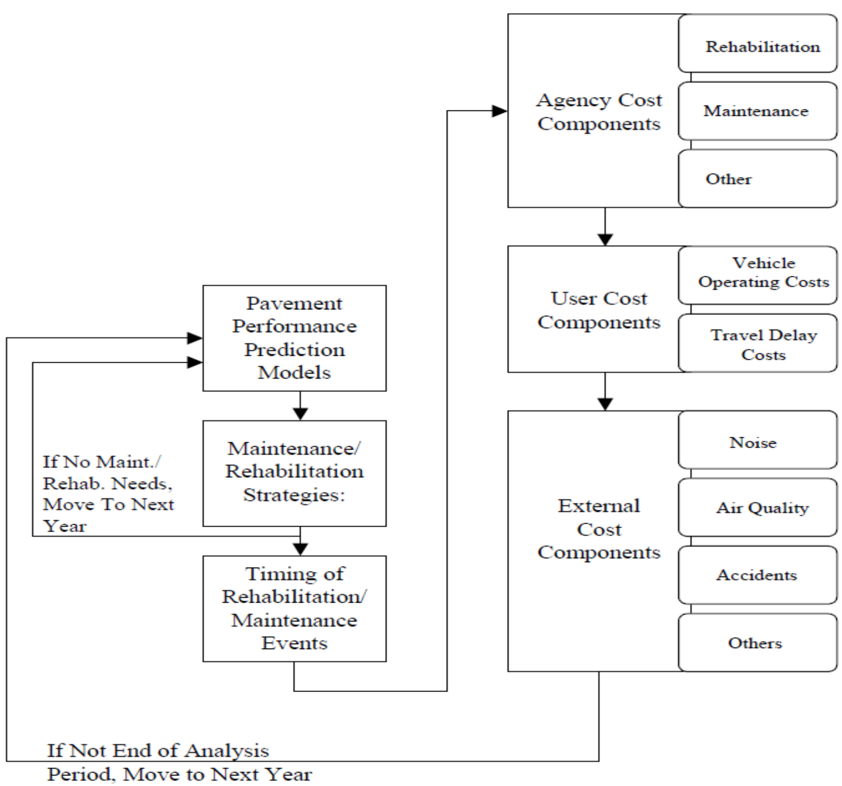

Figure 8: Addition of External Costs into Life Cycle Cost Analysis Framework

Environmental Framework

The demand of Sustainable practices has been on drive because of the Emerging environmental impacts. Every human made object has embodied energy. It has been used as a scale to assess environmental impact and reduce unsustainable practices. The pressing issue of climate change, embodied carbon dioxide (CO_2) Evaluation is the next big step in achieving a better understanding of environmental impacts. There is a direct link between embodied energy analysis by the component of emitted CO_2 from most energy sources.[11]

Derivation of CO_2 Emission Factors

Each fuel source has a quantity of CO_2 emissions associated with it. The United States of America generated about 4 trillion kilowatt-hours of electricity in the year 2015. About 67% of the electricity was generated from coal, natural gas, and petroleum, which are fossil fuels.[21]

Energy sources for electricity generation are [21]:

- Coal = 33%
- Natural gas = 33%
- Nuclear = 20%
- Hydropower = 6%
- Other renewables = 7%
- Biomass = 1.6%
- Geothermal = 0.4%
- Solar = 0.6%
- Wind = 4.7%
- Petroleum = 1%
- Other gases = <1%

Coal Coal used in electricity generation (sub-bituminous) has an emission factor of 91.2 g CO_2 /MJ [11] The calculation of emission factor for coal in electricity generation is = 91.2 x 0.33 = 30.096 g CO_2 /MJ

Gas Gas used in electricity generation has an emission factor of 54.22 g CO_2/MJ. [11] The calculation of emission factor from burning gas is = 54.22 X 0. 33 = 17.8926 g CO_2 /MJ

Geothermal The calculation of emission factor for geothermal in electricity generation is [11] $=3.7 \times 0.004 = 0.0148$ g CO_2 /MJ

The total electricity emission Factor is the sum of the above three (considering only coal, gas and geothermal)

The total emission factor for electricity is thus 30.096+17.8926+0.0148 = 48.0034 g CO_2 / MJ

Energy Source	g CO_2 / MJ
Coal, bituminous	
Coal, sub-bituminous	91.2
Coal, lignite	95.2
Coal, All NZ	90.4
All Petroleum Products	68
Petrol	66.6
Diesel	68.7
Heavy Fuel Oil	74.8
Light Fuel Oil	72.5
Electricity	16.43
Gas, average	54.52
Gas, Maui	54.22
Gas, treated	54.82
LPG	60.4
Geothermal	3.7
Biogas	101
Wood	104.2

Table 3: Table of CO_2 emission factor

The overall CO_2 content can be calculated for each material by applying CO_2 emission rates for various fuels used in the production of the building materials as summarized in Table 3. The energy analysis provides the energy source contributing to the final product. Energy analysis is the basic necessity before doing the CO_2 analysis. [11]

Valuable data from various available resources were studied to understand and included embodied CO_2 coefficients. CO_2 content needs to be analyzed for every energy input step of the analysis. This process has to be reiterated and recalculated for every new data that is being gathered. We need to try to avoid errors and omissions. In case of unavailability of date, proxies from close related operations can be used. This will improve the consistency of the process and lead to closer results.[11]

Conclusions

The reuse and recycling of materials will be a necessity to save resources, which will lead to decrease in energy consumption, CO_2 emissions and the cost economy behind it. Different energy sources have different impact on the environment. Some of the sources have less environmental impact to compare to others. The current focus of the world is on global warming, as climate change is its consequence. Because of which it is important to know the CO_2 implication of every energy source. Another factor understood from this study is that, energy associated with buildings is half the total energy usage in developed countries. That makes embodied energy and CO_2 emission data of building materials very valuable information. The integrated study into the innovative application of reusing various waste cementitious materials has proved very beneficial in the past and needs to be implemented in the future. Deep integration of environmental and economic effects in the application is required to discover superior alternatives. Although this study provided a promising future for the use of various cementitious materials and its environmental and economic benefits, the total life cycle cost needs to be analyzed further for better understanding and judgement. Life cycle analysis (LCA), Cost effectiveness analysis (CEA) and Cost benefit analysis (CBA) can be used in the future to compare these various application alternatives. Future research needs to be done with boundary conditions including health and ecosystem risk, social consensus, and acceptance of products in a detailed program. The research on the cost effectiveness and environmental impact analyses of using waste cementitious materials is relevant to the ASEE graduate division's mission. This mainly helps graduate students conducting special research or working towards their PhD dissertations. This would provide 1-on -1 teaching opportunities that enable students to receive advice from the faculty advisors, and will greatly impact student's learning for achieving measurable results.

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