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Trends and developments in green cement "A sustainable approach"

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ABSTRACT
It is evident from the history of cement that it's a vital construction material but its hazardous effects on environment cannot be ignored. Cement production causes serious environmental damages from its production to disposal which includes carbon dioxide emissions, noise/vibration pollution and damage to natural rocks (during extraction of raw materials from quarries). Cement is considered to be the third largest (man-made) source of greenhouse gas due to emission of carbon dioxide in atmosphere. The harmful effects of cement are encouraging the construction industry to use new cementitious materials without compromising cost and quality. Efforts are being made to develop supplementary cementitious materials using domestic, agricultural and industrial wastes and also recycled materials. This review study presents a concise review of current efforts for production and use of cement. This paper will also highlight some important green alternatives for cement which include energy effective, low carbon production, no carbon cements and inorganic materials.

Keywords: Cement, Carbon, Hazardous Effects, Energy, Cementitious Materials

1. INTRODUCTION

Cement is very important ingredient in concrete production which is a basic construction material. Imagining the modern world without these two important construction materials (cement and concrete) is very tough. Ordinary Portland cement is an extensive and strategic building material[1]. Till today the construction industry is greatly dependent upon cement, so that the global production of OPC is 3.6 billion metric tons (MT) every year[2] and this figure is expected to reach above 5 billion MT by 2030. Almost half of the annual production of OPC is used to make concrete and other half is being used for other applications like grouts, floor boards, rendering, coatings and stabilization purposes[3].

Construction industry is facing a lot of challenges from hazardous nature of cement due to CO_2 emissions, depletion of natural raw material resources and incorporation of environmentally friendly materials. Cost of cement production increases due to increased green tax and scarcity of raw materials.

Apart from all the efforts made by different organizations globally to reduce to reduce CO_2 emissions from past few decades but still OPC production is contributing 6% of the global CO_2 emissions[4]. In order to control carbon footprints, World Business Council for Sustainable Development (WBCSD) developed Global Cement & Concrete Association (GCCA) which includes world's major cement manufacturers[5]. The most important agenda of this initiative is to do the critical analysis of environmental damages and resource depletion by cement production globally and spread awareness to take preventive actions in order to decrease the harmful effects of cement production.

Encouraging people worldwide to reduce CO_2 emissions is supported by governments and environmental protection organizations because release of greenhouse gas is a serious threat to the environment that is responsible for climate change. Few laws and regulations were enforced such as taxes (green tax, extraction and quarrying tax etc.) aiming to reduce industrial activities contributing to greenhouse gas emissions. Despite of all these efforts CO_2 emissions (produced by cement and construction industry) could not be reduced due to the ever-growing demand of cement for construction[5].

In order to make cement industry sustainable, improvements in manufacturing process requires OPC mixture to use recycled materials, low carbon emissive fuels, incorporating clinker with other material (with low carbons and cementitious properties), carbon entrapping manufacturing process. The most secure, economical and effective Carbon Capture & Storage (CCS) method is development of negative carbon cements or enrapturing CO_2 during production of cement for large scale application. These solutions given can be used if they satisfy three conditions:

i. Excellent performance in short and long term use.
ii. Effectively satisfies different standards for different functions and applications.
iii. Availability of raw materials in bulk near processing plants.

This paper examines and summarize different materials for substitutions in cement that are being used or under research to reduce carbon emissions. This paper will also outline interaction of fuel derived from wastes (domestic, industrial and agricultural etc.) to reduce carbon footprints and some advanced technological cement replacement.

1.1 Portland cement production in the world

Cement production varies from country to country depending upon availability of raw materials. Those countries who could not produce cement or where the production could not fulfill their demands need to import the cement from other countries. As stated earlier, that the world is producing 3.6 billion MT of cement each year and China is the biggest manufacturer of cement which can be seen in Figure 1. Cement is the second most used product globally after water. Cement industry is abruptly increasing in countries with a great demand of infrastructure like India, Pakistan and China[6]. Figure 2 shows a forecast that there is a constant increase in cement production from 1990 to 2050.

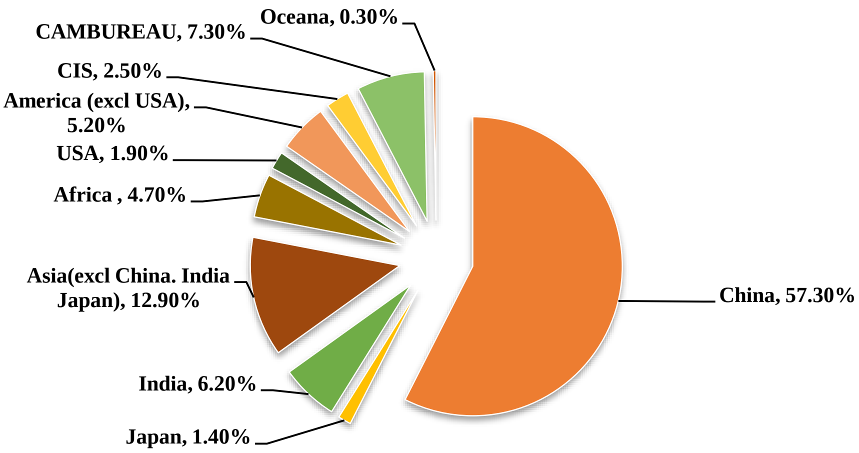

Figure 1: Current global cement production[4]

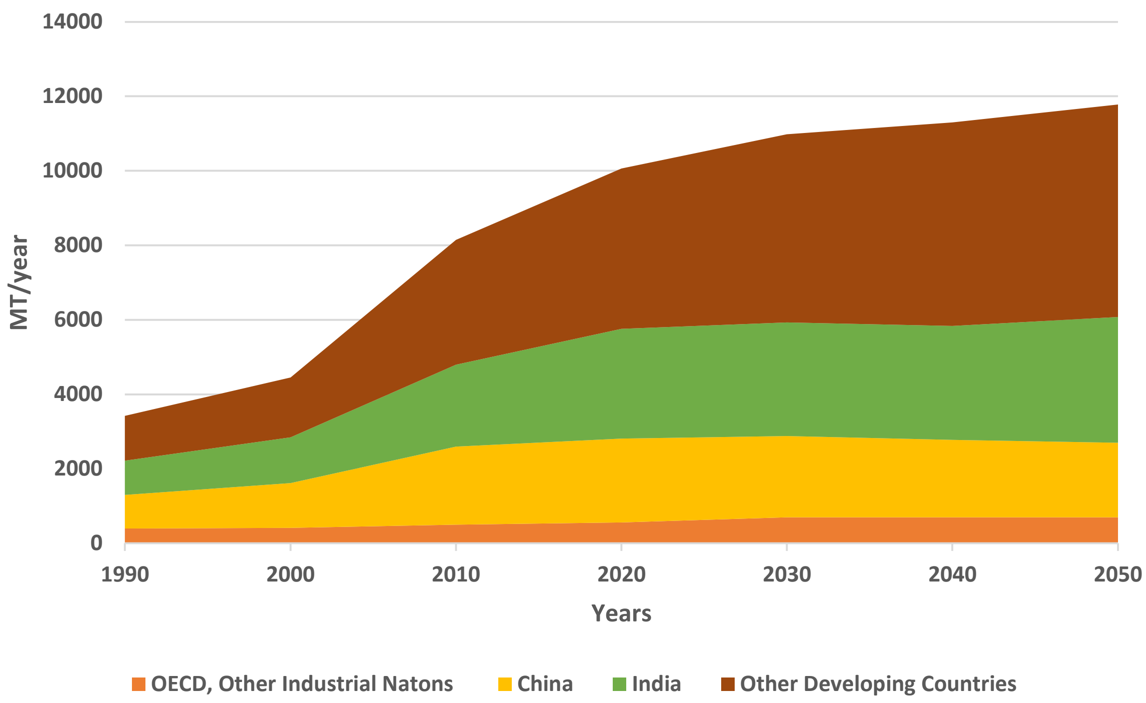

Figure 2: Estimated global cement production 1990-2050[6]

1.2 Energy use and CO_2 emissions (Present & Future)

It has been estimated that 900 gram of CO_2 evolves when 1000 gram of cement is manufactured[7] which gives 3.24 billion tons of CO_2 annually during the processes of quarrying, pyro-processing, grinding and transportation[8]. The major portion of CO_2 is emitted during manufacturing process of cement and includes:

a. From calcination (decomposition of $CaCO_3$ and CaO).
b. During burning of cement ingredients in kiln at high temperatures. Combustion of fuel emits CO_2 and amount evolved depend upon fuel being used such as oil, gas, coal, petroleum coke or biomass as shown in Table-1. A theoretical calculation shows that heat required in clinker making process is 1.75 ± 0.1 MJ/kg but due to different inefficiencies in cement making process actual heat requirements become high which in turn evolves more CO_2[9].

Table 1: CO_2 emissions depending upon kiln process and fuel used (kg/kg)[4].

Clinker Ratio (%)	Calcination Process	Dry Kiln Process				Wet Kiln Process			
		Coal	Oil	Gas	Waste	Coal	Oil	Gas	Waste
55	0.275	0.54	0.51	0.45	0.34	0.665	0.58	0.54	0.32
75	0.3	0.71	0.65	0.6	0.48	0.878	0.74	0.68	0.41
(Portland) 95	0.48	0.9	0.80	0.76	0.51	1.1	0.94	0.91	0.58

Rotary kiln used in pyro-processing also contribute towards CO_2 emissions. There are different types of rotary kilns used in cement manufacturing industry such as:

i. Dry with preheater and precalciner kiln
ii. Dry with preheater and with precalciner kiln
iii. Long dry kiln
iv. Semi wet/dry kiln
v. Wet

Cement manufacturing should always consider the type of kiln with minimum CO_2 emissions. Figure 3 shows amount of CO2 evolved in kilograms per ton of clinker heated between years 1999 and 2005.

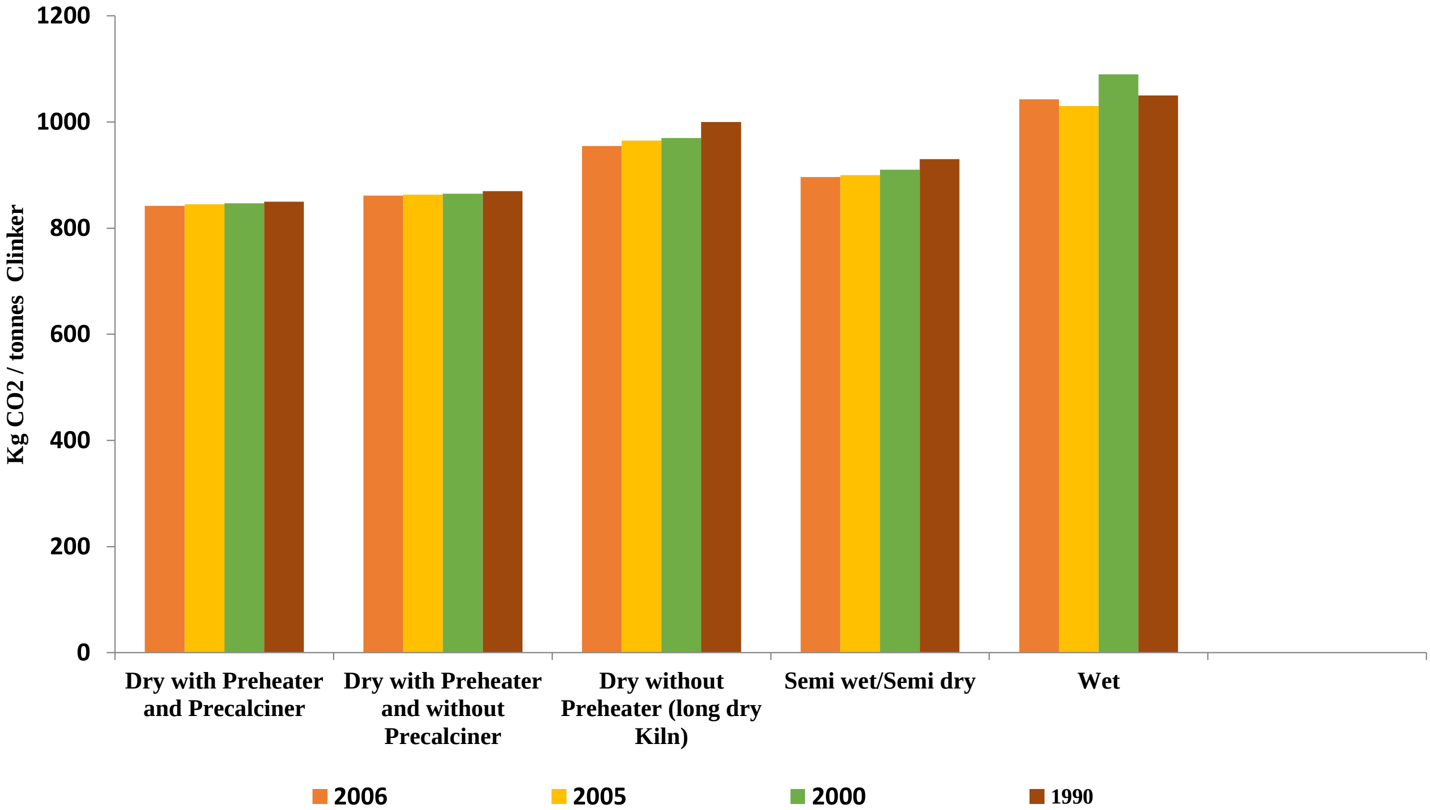

Figure 3: Amount of CO_2 evolve globally with different kiln types[6]

The Global Cement & Concrete Association (GCCA) suggests that how cement industry can move towards betterment by introducing new advanced technologies for both new and existing cement manufacturing plants, encouraging major cement manufacturers to use green alternatives by using low carbon fuel and clinker substitution. These recommendations by GCCA regarding green alternatives should be practically implemented in support of the government for the betterment of cement industry and environment. Figure 4 shows the estimation of CO_2 emissions till 2050, meaning that if no improvement will be made in the cement industry as a consequence CO_2 emission will be 5 times in 2050 compared to 1990. As the world is moving towards environmentally friendly products, construction industry should do the same. These steps will not only help to save the environment against different hazards but also will have a beneficial impact on economical production (by the possible reduction in greenhouse gas tax on the cement industry). Figure 5 shows the cost reduction that can possibly be achieved by reducing carbon footprints.

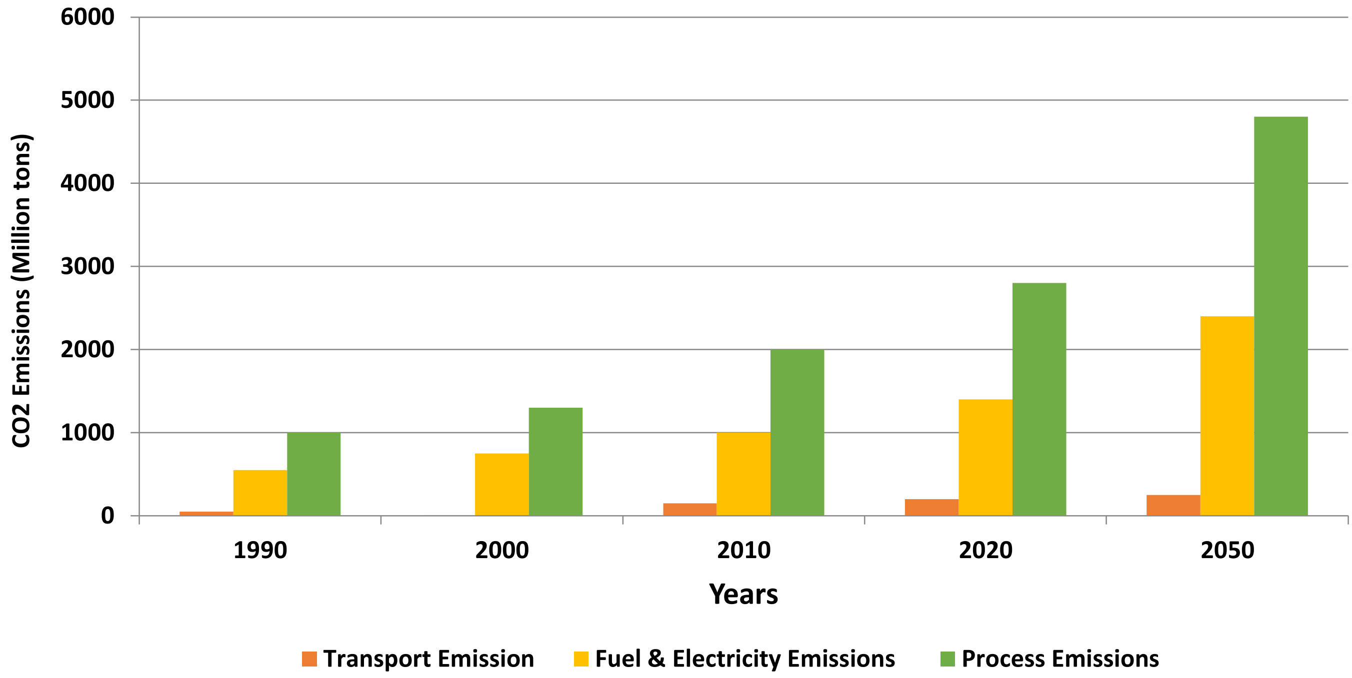

Figure 4: Global CO_2 emissions in cement production[6]

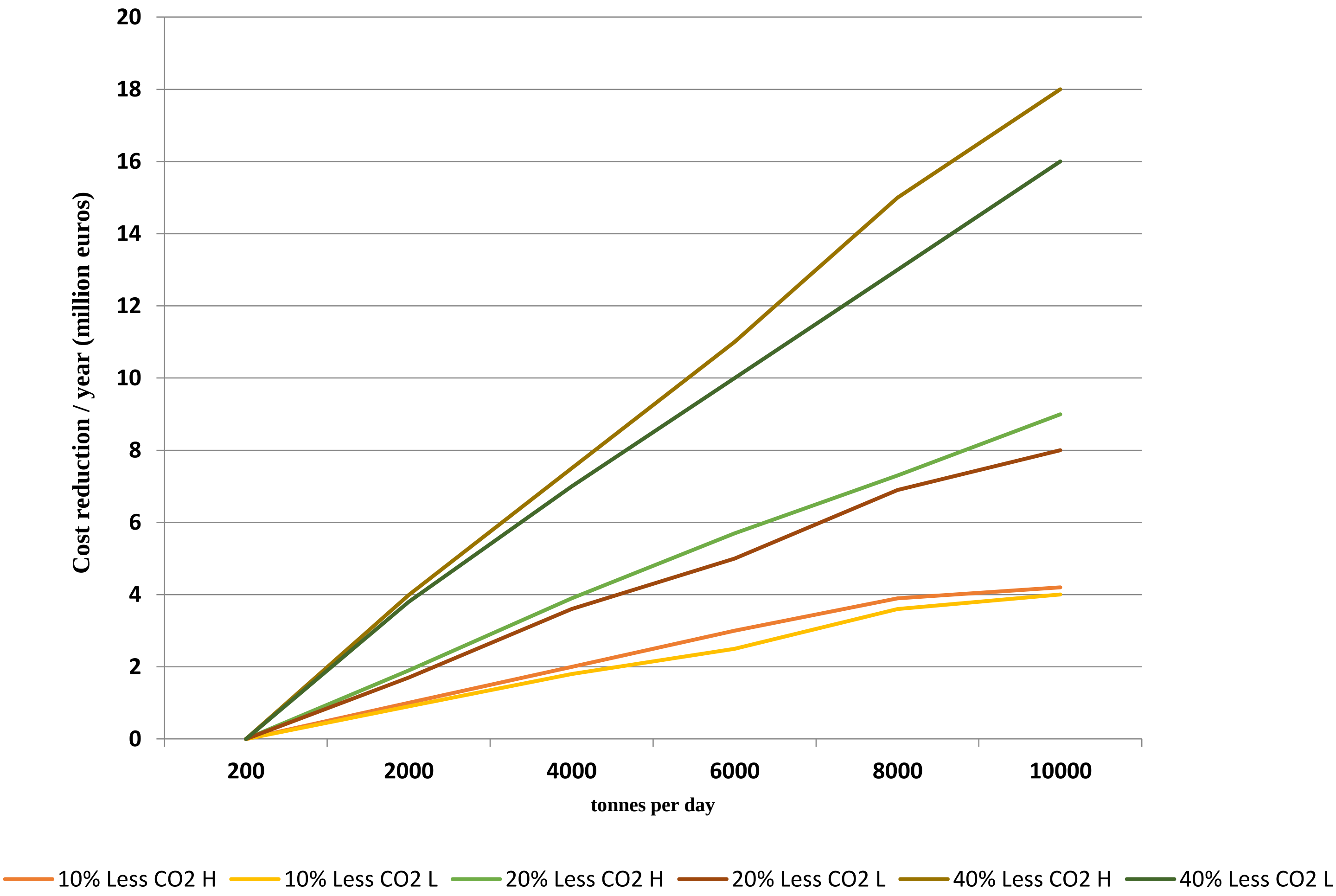

Figure 5: Cost reduction in cement industry by reducing CO_2 emission[4]

2. GREEN CEMENT & GREEN CHEMISTRY

As the name suggests, green cement is an environmentally friendly type of cement that can help save the environment because of low CO_2 emissions during its production. Green cement is produced by advanced technological processes in which the greenhouse gas emissions are minimized. Green cement does not involve cement production only, but also cement use and cement disposal altogether know as green chemistry as shown in Figure 6. These green chemistry processes include following procedures to be taken care of:

A. Cement Production

i) Source of energy for cement production for manufacturers
ii) Greenhouse gas emission from unit processes
iii) Type and properties of raw materials being used
iv) Transportation of raw materials from quarrying site to production plant
v) Production process should be efficient to add waste materials with ease

B. Cement Use

i) Material strength, durability and life.
ii) Ability of cement produced to form composite material
iii) Energy required for cement paste forming, placing and hardening

C. Cement Disposal

i) Ability of cement produced to be recycled
ii) Number of times it can be repaired
iii) Energy requirement and cost for repair or replacement

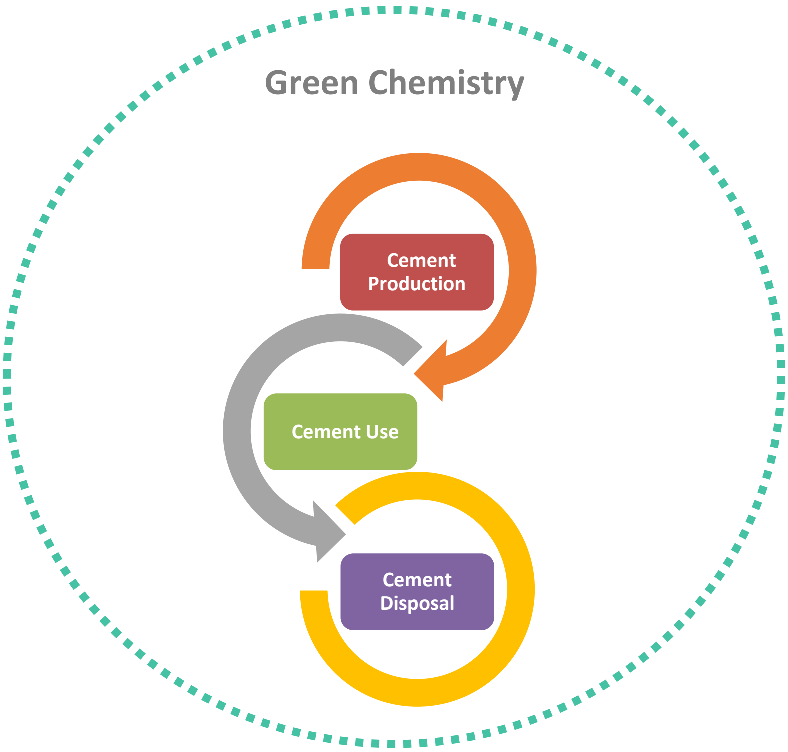

Figure 6: Green Chemistry for Cement Production[10]

Figure 7 shows one of the green cement production methods in which CO2 produced is either captured three major processes.

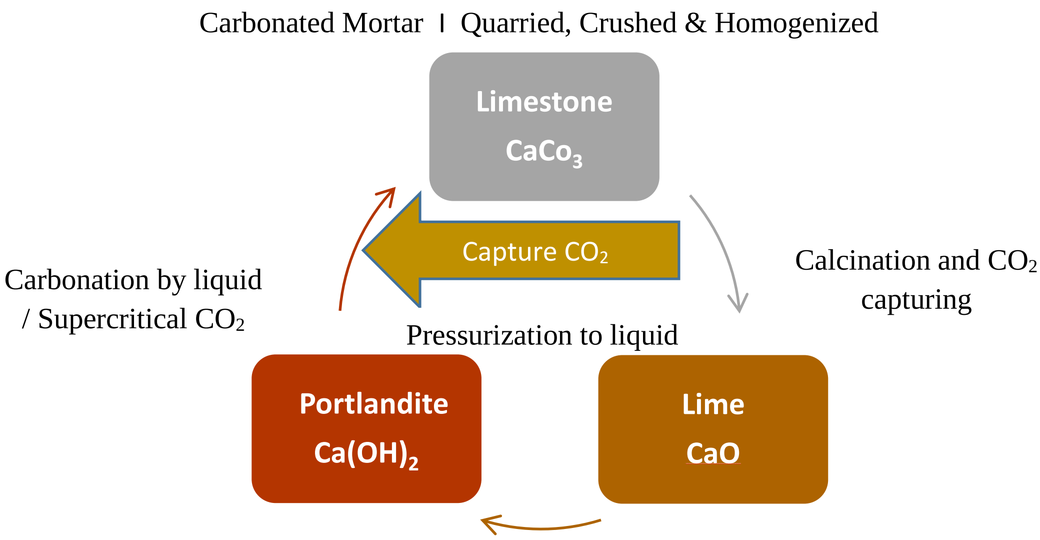

Figure 7: Green cement production method[11]

2.1 Resource efficient cement

Reduction in energy requirement also plays an important role in green cement production. Cement manufacturer uses advanced technologies to cut down production cost of cement and emission of CO_2 thus making cement manufacturing process economical and environmentally friendly. This largely reduces the emission of hazardous gases at the cement industry levels[12]. Timely update of the cement production processes depends upon the manufacturers and involves improvement or replacement of manufacturing equipment in the plants. Fuels from the wastes such as wood, trees, plastic, sewerage (industrial and municipal) sludge etc. are playing a big role in producing resource efficient green cement[13]. The use of waste fuels reduces the costly conventional energy demand and thus reduces the production cost. Researchers are focused on reducing CO_2 emissions using waste fuels in order to fulfill the cement requirements of the modern world and to protect the environment at the same time.

During pyro-processing clinker is burnt by using coal or coke, but instead of these if waste substitute is used such as biomass will reduce CO_2 emissions than that of coal. But the major disadvantage of using these fuels is that they alter chemical composition of cement by introducing different components during burning process. This change in chemical composition that can affect different properties of cement such as delayed setting times or very low early strength[14]. But this disadvantage can be superseded by monitoring and controlling the production processes and changing it according to requirements. Nowadays, many countries are using alternative fuels in cement manufacturing plants on large scale[15].

2.2 Supplementary Cementitious Materials (SCM)

SCMs are mostly used as fillers or as pozzolanic materials with cement. These materials are used because they hydrate just like Portland cement but produce silicate blend in large quantity that comes in contact with large quantity of lime during cement hydration process resulting in producing no or minimum carbon dioxide. These materials are as follows:

a. Ceramic waste
b. Condensed silica fume
c. Fly ash
    i. Class C
    ii. Class F

d. Grits
e. Ground granulated blast furnace slag (GGBS)
f. Lapindo mud
g. Geopolymers

These supplementary materials are used in cement and concrete manufacturing that might have gone to landfill sites. Moreover, when these materials replace some amount of cement then energy requirements and emissions related to cement are reduced. All the above-mentioned materials reduce CO_2 emissions in different amount depending upon their properties and bonding with cement particles.

a. Ceramic Waste

Ceramic Waste Powder (CWP) is a waste material which partially replaces cement. It improves workability, compressive strength and durability of when used with cement for concrete manufacturing[16].

b. Condensed SF

Condensed SF mostly popular as micro silica. This material possesses pozzolanic and cementitious properties. It can reduce an appreciable amount of CO_2 emissions but very difficult to obtain as compared to fly ash or GGBS. They provide large surface area to get hydrated like cement. Cement having an optimum (5%-15%) amount of silica fumes can improve strength of cement as a binder or concrete[17].

c. Fly Ash

Fly ash is a byproduct obtained from industrial waste of pulverized lignite as fuel. It is a very fine powder with a large surface area. This material can be obtained in two different varieties:

i) Class C fly ash is obtained by burning lignite or coal. This material has lime content more than 10%. It has both cementitious and pozzolanic properties[18].

ii) Class F fly ash is a product obtained during heating of anthracite or bituminous coal. It contains CaO in less quantity such as less than 5%. This material only possesses pozzolanic properties[18].

d. Grits

This material is mainly composed of $CaCO_3$ without amorphous material. Grits with 10% replacement with cement does not show an appreciable improvement in strength but can be improved with more finer grit material. Using grits as partial cement replacement will avoid its dumping in landfills and can contribute towards making cement industry sustainable[19].

e. Ground Granulated Blast Furnace Slag (GGBS)

This material is obtained as a byproduct during manufacturing of iron or steel. It can be used in conjunction (replacement) with cement or other pozzolanic materials. Compressive strength and tensile strength of cement mortar decreases by with increase in the quantity of contents of GGBS[20].

f. Lapindo mud

Lapindo mud is obtained from erupting mud volcano. Eruption of volcanic mud has a bad impact over the environment of the places of eruption Extensive research efforts in the past focused on making use of this material has shown that lapindo mud and OPC has similar chemical composition. Moreover, it is now revealed that primary constituents (Si, Al, & Fe) in lapindo mud are greater than OPC. Replacing 10% cement with lapindo mud can increase compressive strength of cement mortar by 26%[21].

g. **Geopolymers**

Geopolymer composition mainly includes byproducts and waste. Geopolymers play an important role in manufacturing of geopolymer concrete by replacing an amount of cement with different geopolymers. Concrete having geopolymers protect it from corrosion and fire etc.[22].

Generally, using the above-mentioned materials in an optimum quantity by replacing partial cement can reduce some percentage of cement required and thus reduces the CO2 emission to a favorable extent as shown in Table 2.

Table 2: Percentage Reduction in CO_2 Emissions by using SCMs

Supplementary cementitious material	Ceramic Waste	Condensed Silica Fume	Fly Ash	GGBS	Lapindo Mud	Geopolymers
Reduction in CO_2 Emissions	29%[23]	15%[4, 9]	14%[24, 25]	22%[24, 25]	28%[26]	80%[27-29]

2.3 Green inventions and initiatives in cement industry

Worldwide, many researchers and cement manufacturers are with the idea of sustainable cement production thus helping to retain green environment. Some honorable mentions are:

1- Corporation of California, (USA) named as Calera has been working to make $CaCO_3$ from seawater to mix with CO_2 to be used as OPC with a great reduction in CO_2 emission[30].
2- Calix, an Australian company tried to modify cement properties by making it more reactive. CO_2 can be captured during the complete process[31].
3- Ceratech, Virginia USA manufactured a new product named as Ekkomaxx with complete replacement of cement with fly ash and additives. According to the company's claim, this product has no CO_2 emissions[31, 32].
4- Solidia Technologies, a US company developed a new process named as "Reactive hydrothermal liquid-phase densification". This process develops a similar product like cement by using slightly different raw materials as used in cement production heated in kilns at a low temperature to evaluate less carbon dioxide[33].
5- A scientist in University of Arizona has invented a new material named as Ferrocrete which is known to be a carbon negative material. It was prepared by using the wastes and byproducts of different industries such as glass steel[34].

3. COMPARATIVE PROPERTIES OF SUPPLYMENTARY CEMENTITIOUS MATERIALS

Most commonly used partial cement replacement materials are silica fume, fly ash and GGBS. Due to advance technologies we have an improved and bulk access to these materials. Before their use, we should establish an optimum amount to be replaced with cement in order to have full benefits. So, these three materials effect properties of concrete when replaced partially with cement, an overview is given Table 3.

Table 3: Effect of silica fume, fly ash and GGBS on properties of concrete

Property	Silica Fume	Fly Ash	GGBS
Percentage by weight of cement	Between 0-10% [34]	Generally 25 % [35]	Between 20% to 80% (40% in general) [35, 36]
Workability/Slump	Reduced (It can be improved by using plasticizers) [37]	Improved due to better cohesion [38]	Reduced (It can be improved by using plasticizers) [34]
Self-Compaction	Reduced [39]	Improved [38]	Reduced [34]
Mechanical Properties	Great improvement in strength, density and modulus of elasticity [40-42]	Initially lowers strength gain but increases late strength[43]. Higher replacement can give appreciable reduction in compressive/flexural strength [44-46]	Initially lowers strength gain but increases late strength[47, 48]
Sulphate Attack Resistance	Not very effective [49]	Very effective and reduces damages due to sulphate attack [50]	Most effective amoung all SCM's [47]
Alkali-silica Reactivity	Reduced [51]	Reduced [51]	Reduced [47]
Carbonation Depth	Increases with increase in replacement content [52, 53]	Increases with increase in replacement content[46, 53]	Increases with increase in replacement content [47, 53]
Permeability	Reduced[37, 43]	Reduced [54]	Reduced
Chloride Ion Penetration Resistance	Increases with increase in replacement content [37, 55, 56]	Increases with increase in replacement content[55, 57]	Increased [40, 58]

The most critical property of concrete is the compressive strength. Being the most important ingredient of concrete, cement decides the compressive strength behavior of concrete Figure 8, 9 and 10 show the effect of silica fume, fly ash and GGBS respectively on compressive strength of concrete when used as partial replacement material with cement.

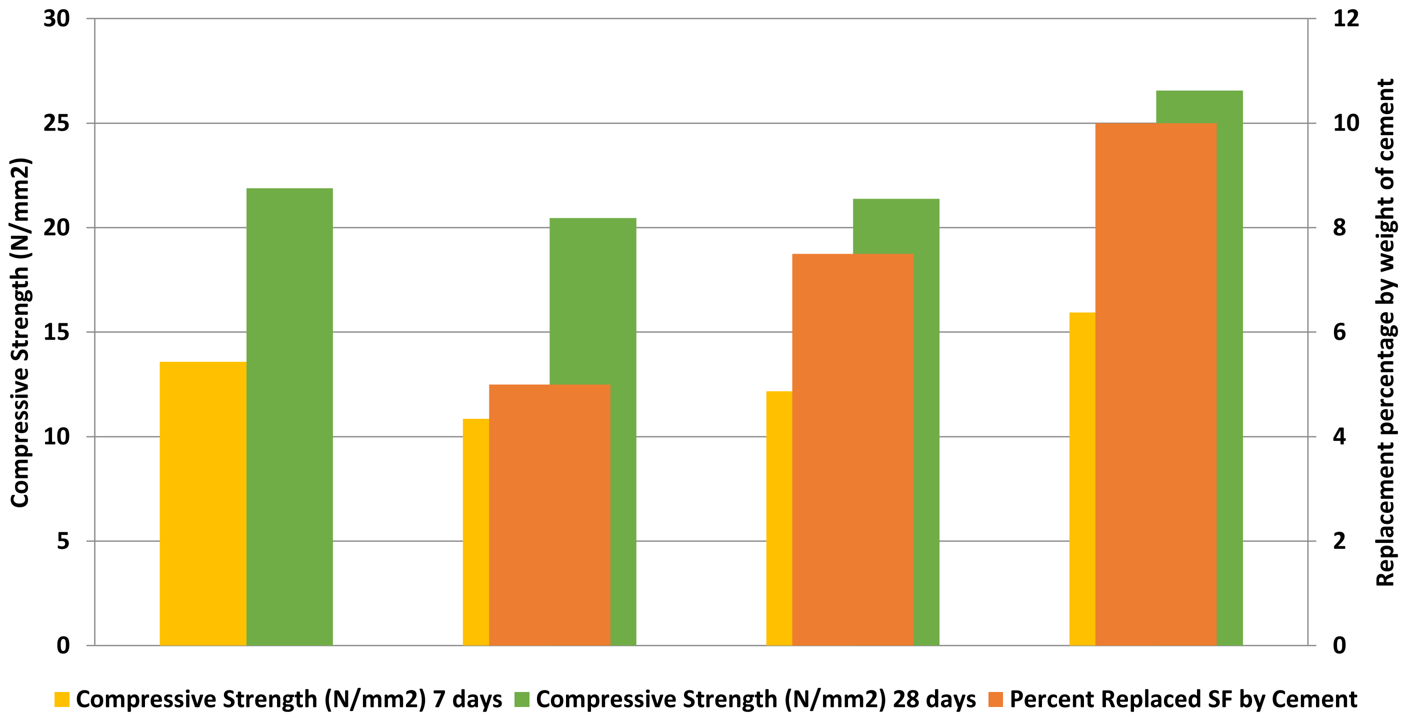

Figure 8: Effect of Silica fume on concrete compressive strength[59]

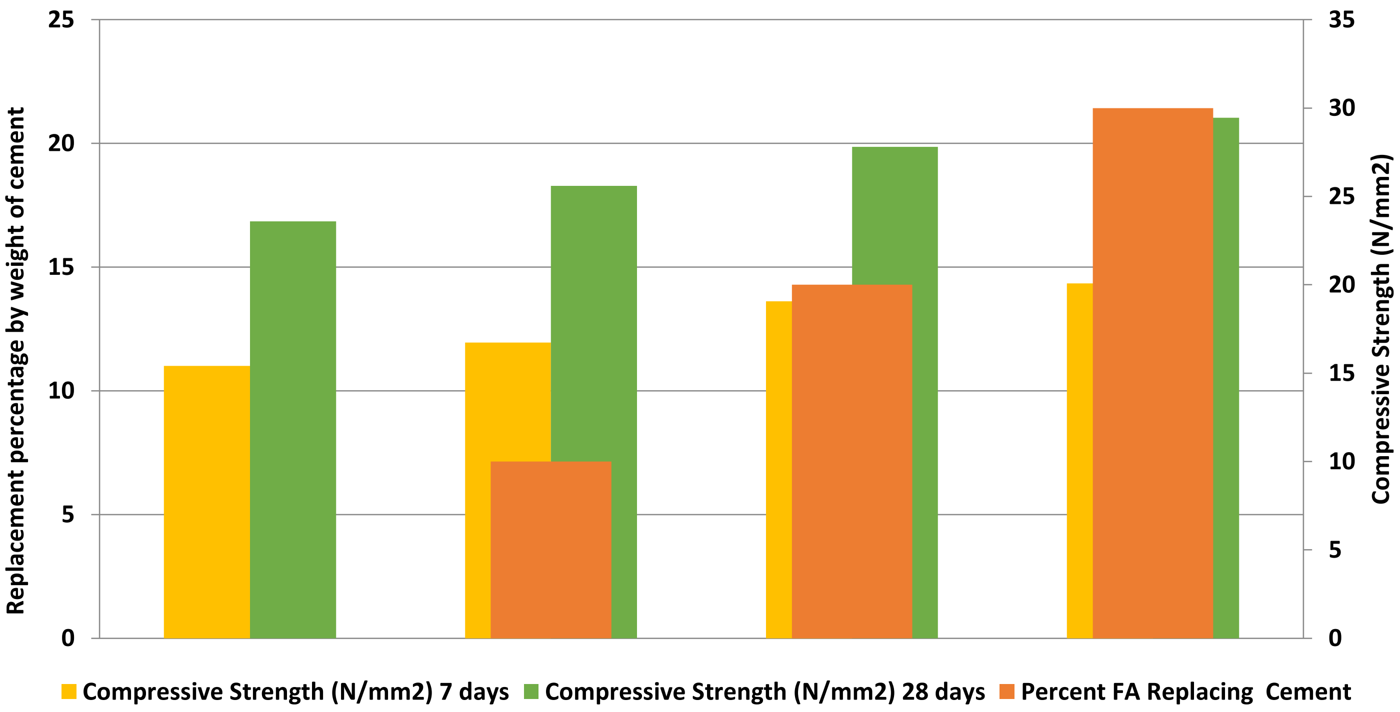

Figure 9: Effect of Fly ash on concrete compressive strength [60]

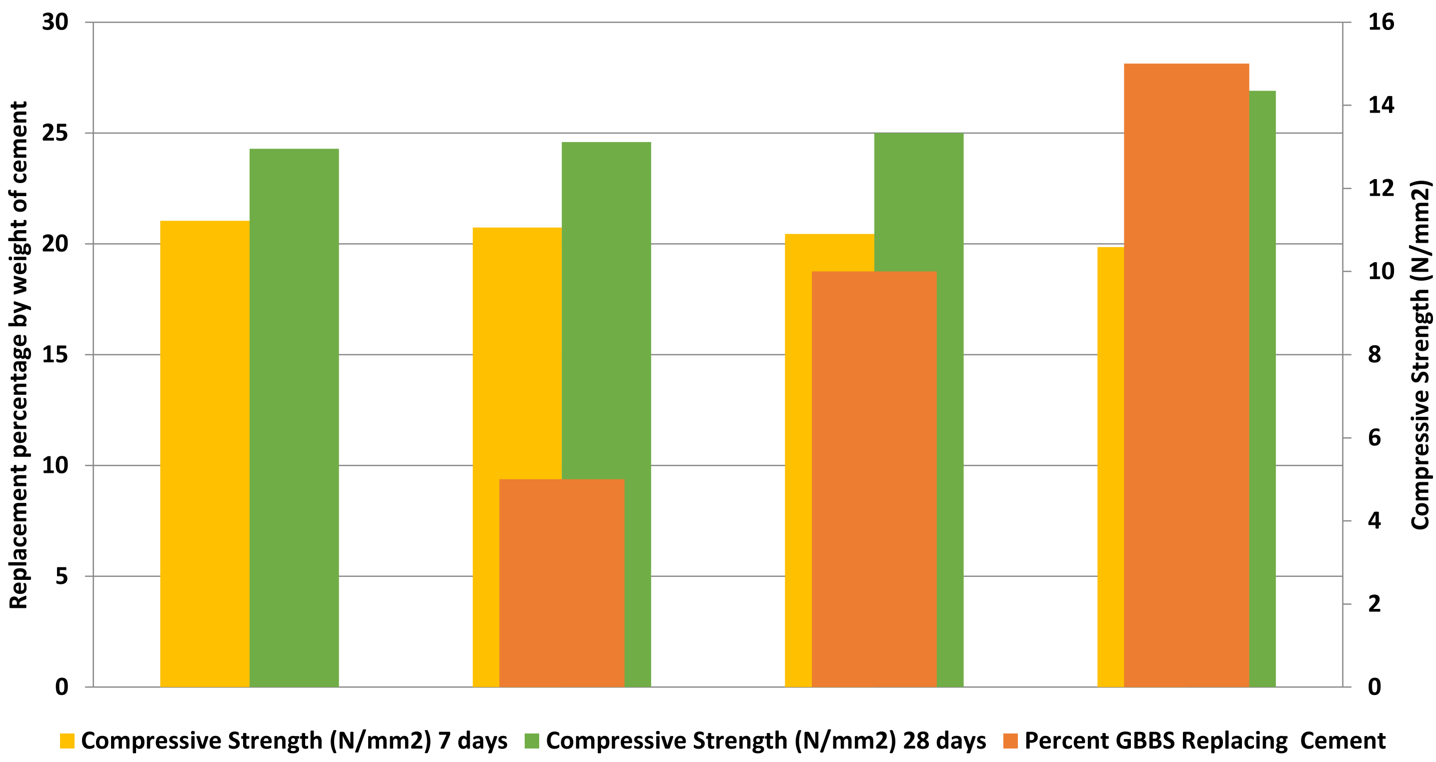

Figure 10: Effect of GGBS on concrete compressive strength[61]

Figure 8, 9 and 10 clearly show that an optimum percentage of cement replaced with SCMs improves the compressive strength of concrete.

4. CONCLUSION

Without any doubt cement is the most important and extensively used building material in construction industry Its use cannot be denied as it can produce a great number of versatile blends (such as concrete, mortar, grout etc.) when mixed with other construction materials.

A great amount of CO_2 is evolved in cement production each year that is growing day by day. This is posing a serious threat to the environment (climate change) and also leading to severe economic challenges (increase in usage and cost of fuel).

In order to make cement industry sustainable, energy effective and profitable; inevitable changes are necessary. The most important improvement that is needed to be done to reduce the CO_2 emissions (one of the major reasons of global warming) through cement and construction industry. necessary initiatives include improvements in cement production method, incorporating wastes and avoiding the use of naturally occurring raw materials as they are depleting exponentially) as partial cement replacement and using and low carbon fuels.

A new generation of materials are being introduced in the construction industry that have similar properties as those of cement and they have the potential to replace cement partially or completely. These materials need more research and support of the construction industry to make the practical use of these supplementary cementitious materials on large scale.

Global regulation in this regard is the need of the present time. This is only possible by the mutual consent of the governments around the globe. The prime focus must be improved production techniques, promoting use of low carbon fuels and waste materials in both cement and construction industry thus saving the depletion of natural resources. These regulations can be implemented in each country by general awareness and negotiations among the local stake holders.

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