A Comprehensive Review on Supplementary Cementitious Materials - Progress, Environmental Impact, and Future Sustainability Challenges

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Abstract

Cement is widely used material in construction industry. High performance concrete arranges extensive supplementary materials and Portland cement which detect the use in construction industry. This study investigates different supplementary cementitious materials, when these supplementary materials are mixed with cement, they increase their compressive as well as mechanical strength. Materials like metakaolin, blast furnace slag, silica fume, laterites, fly ash, rice husk ash, Nano-materials, blended cement and sugar-cane bagasse. In fresh concrete properties the mechanical strength estimates development of elastic modulus, strain due to shrinkage, in compressive strength and flexural strength. Conventional concrete like blast furnace slag and fly ashes have been used for many decades assemble the impacts on cement hydration and concrete properties. Supplementary cementitious materials are the key components of cement and the replacement of cement with other supplementary materials is a widely adopted industrial process and study the effects of CO₂ emission and absorption for precast cement production and their environmental impacts. The reduction of CO2 emissions through Supplementary Cementitious Materials (SCMs) involves partially replacing Portland cement with eco-friendly materials such as fly ash, slag, rice husk ash, or metakaolin to lower the carbon footprint of concrete production. Since cement manufacturing is highly energy-intensive and releases large amounts of CO2 from limestone calcination, using SCMs helps conserve energy and reduce greenhouse gas emissions. Besides environmental benefits, SCMs improve concrete's durability,

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strength, and resistance to chemical attack by refining its microstructure through pozzolanic reactions. The research helps to summarize the progress and availability of different supplementary materials, their environmental impacts on cement performance and durability and some challenges which faced by construction industry and achievement of sustainable supplementary material.

Keywords: cementing material, construction industry, fly ash, laterite

INTRODUCTION

Ordinary Portland Cement (OPC) is the fundamental component of construction industry work as binding agent in concrete [1]. It is commonly used in construction industry and in different infrastructure projects. OPC is formed with the composition of different components like a large amount of lime is used first and mixed with laterite iron ore than process of grinding start. The cement making process is done by clinker which is made up of 4 minerals like C3S, C2S, C3A and C4F. These minerals are added in clinker to form ordinary Portland cement and react with water and form a strong mechanical bond some quantity of gypsum is added into it [2]. When cement paste is added into water it grows a hard line and steadily increase its compressive strength, four cementitious products like calcium sulfate, sore cement, phosphate bonding and sodium silicates are the hardening modes of cement [3].

Large amount of OPC sold outside of North America which is mostly blended in clinker [4]. clinker is responsible for cement production up to 20-40%. The world population is increasing gradually the demand for construction is increase tremendously. Another cement is blended cement used in construction which is made up of OPC and different composites. Blended cement come into sight as an encouraging way to produce cement and reduce environmental impacts [5]. The strength and hydration of concrete hang on on the curing process after placing and uniting plastic concrete. Hydration continues for years with favorable temperature and water conditions, but ceases once water is lost. Curing techniques and duration significantly impact mortar and concrete properties, with strength largely influenced by cement hydration. Proper curing maintains moisture content and temperature, enabling desired properties to develop. As we know most of our

construction is very expensive and have negative environmental impacts like CO₂ emission in environment. Every one pound of cement production produce 0.9% CO₂ emission and about 5-7% of global CO₂ emission as well [6]. To address these concerns there is need to explore alternative suitable supplementary materials which replace conventional cementitious material to enhance the stability durability mechanical strength, tensile strength and flexural strength. These materials are fly ash, silica fumes, blast furnace slag, metakaolin, laterites, rice husk ash Nano-materials etc. [7].

Blast furnace slag

Blast furnace slag is an industrial by-product [8]. It is extensively used in concrete as supplementary material due to its high hydration and large surface area. BFS is obtain from iron making process, its physical and chemical properties help to analyze cement hydration process [9]. The mechanical properties of blast furnace slag recycled aggregates of concrete investigated at high temperature to test its tensile strength, compressive strength and elastic modulus Recent research explore that the recycle aggregates, BFS and other natural crushed stones to progress the concrete quality [10].

As other supplementary materials are used in construction industry to enhance cement properties BFS is one of them as it increases hydraulic properties and enhance compressive strength, durability and workability of concrete. Reactivity of BFS depends on properties of slag, which is different from slag source. Blast furnace is used as sprayed concrete for tunneling projects and under-ground construction. Blast furnace slag is a byproduct of iron making process, mixture of iron ore, coke, and limestone is reacted with blast furnace at 1500 degree, for the reduction of iron oxides in the ore molten iron is scraped together at the bottom of blast furnace. Because of its low-density slag slides on the top of iron and separated easily in the skimmer. It was also evaluated that the use of blast furnace slag as alternative cementing material improved uniform qualities of concrete mixture. The application and efficiency of Ground Granulated Blast Furnace Slag (GGBFS) in mortar and concrete manufacture.

The blast furnace slag has widely used in cement as supplementary material and concrete because of its high hydration qualities. The physical and chemical features of blast furnace slag were analyzed to observe cement hydration process. It was also evaluated that the use of blast furnace

slag as alternative cementing material improved uniform qualities of concrete mixture. The use of ground glassy blast-furnace slag in concrete for its technical benefits, including reduced heat evolution, higher strength, and reduced chloride ion penetration. However, it emphasizes the importance of early curing to minimize adverse effects. Slag can also reduce costs and energy demands in cement product [11-15]. The motorized properties of ground granulated blast furnace slag blended-concrete at high temperature. Different studies investigated that the compressive strength, splitting tensile strength, elastic modulus and stress strain behavior. They concluded that mechanical strength of ground granulated blast furnace slag blended-concrete increased significantly by reducing degradation phenomenon.

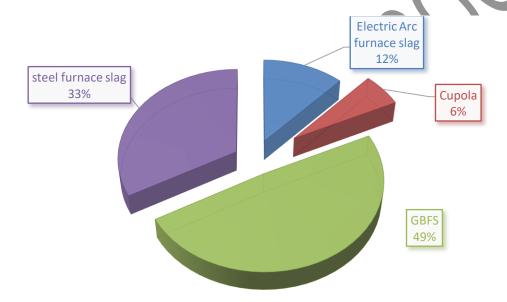


Figure 1, Sustainable construction material blast furnace slag.

In this fig. we explain the Emerging countries are experiencing rapid industrialization and urbanization which accumulate industrial waste that can be recycled into environmentally friendly building materials. This paper explores the applications of granulated blast furnace slag, steel furnace slag, electric arc furnace slag and Cupola in the creation of infrastructure and concrete composites. Waste slags have potential as sustainable building materials and identify gaps in material characterization. experimental viability and physico- mechanical behavior.

Table-1 Properties of blast furnace slag [16].

Properties	BFS specificat	ion Requirements
Insoluble residue	1.5%	1.5% (max.)
Fineness (m ² /kg)	340	275(min
Sulfide sulfur	1.7%	2.00 (max)
Loss on ignition	1.0%	3.00 (max.)
Moisture content	1.0%	1.0 (max)
Chloride content	0.05%	0.10 (max.)
Glass content	90%	67 (min.)

Silica fumes

Silica fume is industrial by-product of silicon and ferrosilicon very fine particles used as supplementary material in concrete. Due to fineness and large surface area they make reactive Pozzolanic material. It enhances concrete properties like mechanical strength, abrasion resistance and reduces impermeability reduce bleeding and protects material from corrosion. It was evaluated that the efficiency of silica fume is not constant at all requirements. To determine the efficiency two methods are used "general efficiency factor and percentage efficiency factors. The geopolymer and zero waste are such building materials that protect finite natural resources and reduce carbon dioxide emission to control climate change to certain extent as mention in table.

The Portland cement was replaced with some readily available industrial waste such as slag, Metakaolin, silica fumes, coal ash and fly ash. It was shown that silica fumes are an exponentially Pozzolanic substance. Furthermore, it was also concluded that the use of ferrosilicon industrial byproduct improved the mechanical properties of concrete. Silica fume react with lime in presence of water to make itself Pozzolanic reactive and reduce the porosity of concrete. High dose of silica fume increases setting time and decrease workability due to its large surface area (Mazloom *et al.*)

20040. By using scient metric review techniques was used to examine various finding of existing literature regarding the usage of building materials.

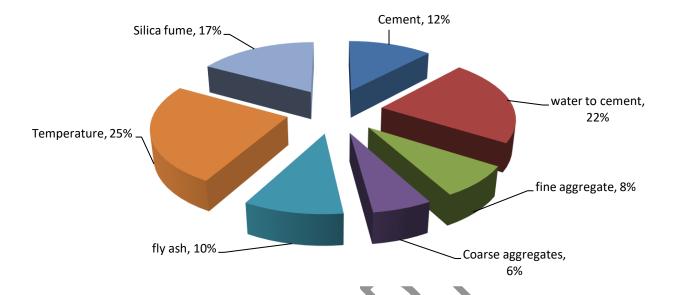


Figure 2, Demonstration of permeability of self-compacting concrete containing fly ash and silica fume [17].

In this fig we discussed about the three predictive models for self-compacting concrete (SCC) to increase the permeability of chloride ion. Using more parameters and hybrid AI techniques was recommended in Kumar et al.'s study on chloride penetration resistance in SCC including FA and SF exposed to different temperatures. However, aspects like the water-to-cement ratio and cement volume were overlooked, which reduced the validity of the model to understand all the percentage values are mention in the table as well.

The silica fumes help to improve the material properties and provide some environmental benefits. The geopolymer and zero waste are such building materials that protect finite natural resources and reduce carbon dioxide emission to control climate change to certain extent. The Portland cement was replaced with some readily available industrial waste such as slag, Metakaolin, silica fumes, coal ash and fly ash. It was shown that silica fumes are an exponentially Pozzolanic substance. Furthermore, it was also concluded that the use of ferrosilicon industrial by-product improved the automatic properties of concrete the tensile strength play a crucial role in concrete making process it is a strongest match of concrete to attain compressive strength [18].

Cracking in concrete is possible when tension is created and also causes serviceability and durability problems. It is investigated that when silica fume is added in concrete a remarkable refinement has noticed in mechanical properties of concrete and investigated the effects of silica on the properties of concrete. But still the process of finding distinctive conclusion concerning the optimum silica fumes substitution percentage level for prevailing the maximum strength of concrete. Silica fumes have glassy and spherical shape and have high silicon dioxide contents. When mixed with concrete it will reduce abrasion damage and increase chemical resistance, also reduce segregation. lubricant in nature and have ball bearing-effects silica are very efficient fore tension zone between aggregates and paste and provide maximum particle packing and reduce permeability. In commercial zone it will help in the increment of element higher strength and long service life for structure and provide easier pumping in tall buildings. Silica fumes and recycled concrete are mixed together for high performance Addition of silica fumes in concrete will speed up the hydration process and due to its high strength, it will build up high flexibility. In Silica fumes spherical particles are present which have high contents and make it Pozzolanic reactive due to its extreme fineness the addition of silica is notable in chloride ion. Silica fumes provide early strength, compressive strength, flexural strength, modulus elasticity, increase toughness, high bond strength and also durability. In concrete about 10% silica fumes is added to maintain slump [19-23]

Metakaolin

Metakaolin is a natural by- product obtained from heating of kaolin which is grey-white in color [24]. It is one type of clay originated from calcination process and clay should be utilized in Metakaolin as Pozzolanic material. About 600-900°C temperature is needed to produce Metakaolin [25-27]. The cementing ability of Metakaolin as alternative material as demand for concrete has been increasing due to world population. The use of this as supplementary material exhibited environmental benefits which can reduce the cost of concrete production. The highly Pozzolanic material Metakaolin is stable under normal environmental conditions and increases the compressive and flexural strength. This material also reduced shrinkage and permeability.

As we add amount of metakaolin in cement then it increases the compressive strength per day. It was investigated that metakaolin partially replacement of cement also reduced environmental damages. The incorporation of Metakaolin in concreting mixture serves as cementitious material.

Due to low-cost production and easy availability, the application of metakaolin as cementing material is increasing. Poor and high reactive kaolin were tested at different temperatures for different times. Some evidences show that the poor kaolin is used to produced highly reactive Metakaolin. Metakaolin are used as supplementary material in construction industry because they help to reduce permeability of hardened cement and reduce CO_2 emission. The use of this as supplementary material exhibited environmental benefits which can reduce the cost of concrete production. The highly Pozzolanic material Metakaolin is stable under normal environmental conditions and increases the compressive and flexural strength. This material also reduced shrinkage and permeability. It was investigated that metakaoline partially replacement with cement also reduced environmental damages [28,29].

Table-2Chemical composition of MK [30].

Chemicals	Percentage (%)
SiO ₂	62.62
Al2O ₃	28.63
Fe ₂ O ₃	1.07
MgO	0.15
CaO	0.06
Na ₂ O	1.57
K ₂ O	3.46
TiO ₂	0.36
LOI	2.00

Cement wasreplaced up-to 20% of MK. Presence of MK reduce capillary action (water penetration into pores: Due to increase in intense humidity cause durability problems. Reduction in absorption increase MK contents by capillary action [31]. Pore structure of concrete provides a useful demonstration to measure the rate of absorption, and this process is publicly described [32-42] Cement is partially replaced by MK at different percentages and to determine elasticity testing of cylinder of different sizes at various should be deter minded. Metakaolin improves the compressive, flexural and tensile strength of concrete to exploit the supplementary material like

Metakaolin in concrete and recompense the environmental and economic issues caused by cement production [43].

Table-3 Physical properties of MK [44].

Particulars	Values
Appearance	Off-white powder
PH (10% solids)	0.4-5.0
Bulk density (kg/L)	0.4-0.6
Specific gravity	2.6
Loss of ignition	1.5
Lime reactivity	1050mg Ca(OH) ₂ /g

Laterite

Laterite is a soil type rich in iron stilica and aluminum oxides and rich type of residual products [45]. Laterite are used as predecessor in manufactured feasible geopolymer. Replacement of construction material like stone, bricks and concrete blocks incumbent in recent years. use of soil blocks can be well-organize the flaws of water absorption, strength and durability can obstruct the huge application in construction industry. Without external stabilization the compressed soil blocks are un stable and have low strength that limit the applications of high rain. Laterite soil extensively exists over a large surface area based on physical nature, chemical composition and geological characteristics which pivot different factors like origin process, atmosphere, surface properties, weathering that influence these factors. Laterite soils sometimes have unfavorable physical and chemical properties like standard gradation low ratio and high plasticity not always abide with specification of high-volume roads [46]. Sand effect on cement properties which engage the blocks, Use of these blocks are produced to determine density, compressive strength and tensile strength. The use of lime for neutralization that can help to investigate the mechanical and thermal properties. Lime is an important factor for representing cement growth. For the accessibility

overall the world laterite becomes visible as highly skilled candidate for alkali-polymer binder production. The durability and compressive strength of laterite cement increase the low permeability of soil contents and magnesium sulphate solution. In the beginning the compressive strength of the cement is decreases for 3 days due to Pozzolanic reaction takes place slowly and gradually increases with the passage of time

Table-4 Physical properties of laterites

physical properties	Laterite Aggregates
Moisture contents (%)	0.52
Aggregates impact values	28.70
10 % fine values	10.20
Aggregate crushing value	30.70
Specific gravity	2.54
Elongation index	8.00
Flakiness index	8.50
Water absorption	1.07

Fly ash

Fly ash is the finely divided residue that is gained from combustion process of coal and exhausted gases chamber. Fly ash is obtained from burning conditions and collection mechanism makes it Pozzolanic reactive. Use of fly ash in hydraulic cement Attempts to concerning a number of applications in construction industry [47]. Use of fly ash with high fineness and low carbon contents will reduce the water demand of concrete. Fly ash concrete improve the workability of concrete reduce cohesiveness and segregation of concrete.

Table- 5 Physical requirements of fly ash

Characteristics	Requirements		

Soundness by auto-	0.8
calved test expansion in	
% (max.)	
Strength activity index	75
with Portland cement in	
7 and 28 day in % (min.)	
Water requirements in%	105
control in max.	
Partial retained on 45	34
micron %	

To find compressive strength of fly ash assemble and non-assemble machines are used. Machine learning is used for testing the material we use as waste product (fly ash) which give accurate information and precise data. This study collects appropriate data and told about description of the study and helps to learn their methodologies.

Rice husk ash

RHA is a by -product obtained from milling process. First the burning process start we can burn at 600–800-degree temperature as the burning increase silica quantity in RHA increased. Silica is very important because they contain silicon and oxygen atoms. In rice husk ash about 85-0-90% silica is present and works as binding agent in concrete and protect from air damages. RHA in powder form mixed with concrete because we use RHA as supplementary material in concrete Then RHA is mixed with water and other components as it is mix it fills the gaps between cement particles and reduce the pore size and increase its strength, it concrete compressive as well as flexural strength. Reactivity of RHA is due to large amount of amorphous silica is present in it, and have substantial surface area. Small particle size of RHA makes it Pozzolanic reactive increases its workability and strength [48]. Combustion methods are used to make ash from husk these are self-made combustion method and oven combustion in laboratory. Self-combusting method consist of two stoves and one combustion chamber. RHA burned from both controlled and un-controlled methods.

Table-6 Physical properties of Rice husk ash

Particulars	Properties

Appearance	Very fine
Specific gravity	2.3
Odour	Odourless
Particle size	45 micron
Mineralogy	Non- crystalline
Shape texture	Irregular
Color	Gray

Nano-material

The use of various nanoparticles such as Nano TiO₂, Nano Al₂O₃, Nano Fe₂O₃, Nano ZrO₂ as partial replacement material in concrete left significant impact on the compressive strength of hardened concrete matrix. The determination of this study is to explore the compressive strength and the resistance in nanomaterial concrete. This also help to investigate testing raw material concrete, concrete mix designs (use as partial substitution material) and also resist the nanomaterial concrete resist sulfate attack. Application of nanomaterial in concrete has go through countless concentration to increase conventional concrete properties. The size of nano material we used should be less than 200nm. Due to their Nano size applications we use should be estimated 500nm. When nanomaterial is added into concrete it will reduce cement contents and increase binding effect. Nano silica, nano alumina, carbon nanotubes, polycarboxylate, Nano clay and Nano kaolin are used in nano material concrete. A Nano particle like Nano-iron helps to increase strength and provide strongest match potential. Nano-silica determines low resistance and complications. Nano-titanium used as self-wipe in concrete. Nano technology has magnified the consciousness of Nanomaterial features and finds a better way to create progressive concrete material.

Table-7Some utilization of nanomaterial in construction industry

Nanomaterial	Applications	Properties
used	in	
	construction	
Al ₂ 0 ₃	Asphalt	Increased serviceability
nanoparticles	concrete	
Carbon	concrete	Crack prevention
nanotubes		
Titania	concrete	Self-cleaning, increase
nanoparticles		hydration
Silica	concrete	Reinforcement of strength
nanoparticles		UV
Copper	Steel	Corrosion resistance
nanoparticles		
Iron oxides	concrete	Increase compressive
nanoparticles		strength and abrasion
	. (<i>\</i>	resistant
Clay	Bricks and	Increase surface
nanoparticles	mortar	roughness and
		compressive strength

When nano-particles are added into cement the durability of cement increases. In different research the experimental work supervise that the size of Nano material should be less than 100 nm in size when mixed with concrete. Due to the presence of different particles in concrete the microstructure of Nano-silica become denser and more consistent than other conventional concrete [48].

Sugar-cane bagasse

Residue of plants after extraction of juice, it is a by-product obtained from combustion process of biomass from waste plants. First waste is collected than washed it into a water tank and then dried it by placing into sun and up-to 600°C it converts into ash. About 600 million tons of sugar-cane waste is acquired. Addition of biomass in cement can magnify the strength and durability

properties and have Pozzolanic activity due to presence of oxide contents. Sugar cane is obtained from sugar and utilized in alcohol and bio ethanol manufacturing and extensively used in industrial bio-products. To produce a pledge that engross the slighter energy and exhale less amount of energy and find a structure that work properly over time. This is possible to replace bagasse in cement material which helps to improve quality of cement and decrease construction cost. Ash contains 50 % cellulose 25% lignin and 25% hemicellulose, due to this workability of cement increases and compressive strength of material increase about 5%. If the percentage of material increased the compressive strength and tensile strength decreases.

Sugar-cane bagasse is tropical and sub-tropical crop. China is the third largest country that produces 2 million tons of sugar cane per year. Sugar cane issued in fertilizers and for glass ceramic material production, geo polymer, ceramic raw material, fe₂O₃ -SiO₂. Nanoparticles, silica aggregates, nonporous and silica aggregates to remove. Light weight aggregate like sugar-cane bagasse that have good Pozzolanic reactivity that approximately comparable to RHA and have a lot of studies that focused on the applications in cementing material and a lot venture have been made like conventional concrete, high performance concrete self- compacting concrete, recycled aggregate concrete, aerated concrete pavement concrete and light weight concrete.

In laboratory the investigation revealed that the bulk amount of bagasse pyrolysis produces 33-28% of charcoal for fuel compressed blocks and particles. The heat of combustion exceeded the maximum limit of carbocation. To prevail the bulk quantity of fine particles and fiber structure of bagasse and a rotating drum is required. Two stage techniques are used to combine furnace and closed pyro ligneous vapor and a heat carrier system that control the emission of carbon Bagasse can used as alternative wood source of charcoal manufacturing. Despite its relatively have high thermal value of 18.4kg with moisture content of 12%. Bagasse and cane garbage have excellent disadvantages in fuel. In dense populated locations bagasse-fired boiler can provide a significant health risk owing to air born fly ash. Implementing a suitable emission control is a castigatory step in reduction of pollution to fight excessive emissions under professional supervision must operate and maintain boilers and associated equipment efficiently by Calvin 1996).

Table-8 Physical properties of sugar-cane bagasse powder.

Physical parameters	Sugar-cane	bagasse	Treated	sugar-
	powder		cane	powder
			bagasse	
Specific gravity	0.6		0.55	
Bulk density	0.54		0.51	
Porosity	61		69	
Surface area	16		18	
Avg. particle size	0.7		0.65	
Moisture content	55.7		51.4	V
Loss in ignition	91.6%		91.22%	
Al2O ₃	2.3%		2.3%	
SiO ₂	1.1%		1.1%	
Fe2O ₃	0.23%		0.23%	

Toselect a perfect energy crop and transform it into biofuels required an important characteristics design which is suitable and cost-effective. A lot of properties of generated residue is present in sugar alcohol industry. Different studies have demonstrated that sugar cane bagassecan be used as small-scale pyrolysis. Large scale pyrolysis is not established for other feed stocks. To produce biofuel feed stock applications on large scale are used. Bagasse pyrolysis have a wide range of products that can be used in fuels and chemicals.

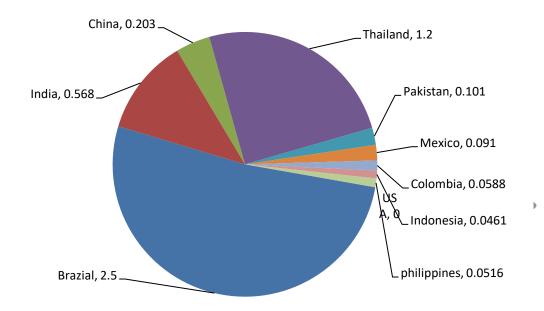


Figure 4, Utilization of sugar-cane bagasse's ash as cement.

This study helps to investigate usage of sugar cane bagasse as cement substituents in building sector, characterization and reaction mechanism. The SCBA affect fresh and hard hardened state attributes like strength, modulus and hostile environmental effects.

Blended cement

The research on chloride corrosion began three decades ago, when the demand of infrastructure was in noticed on reinforced concrete. The reduction of CO₂ emission by using by-products from other industries for cement production and conserve natural resources by the replacement of aggregates, waste material recycling and water in concrete production. This type of cement has significant effect on chloride ions, and produce deformational properties of concrete in blended cement. Blended cement is prepared to replace different ordinary Portland cement with cement powder. The hard blended cement is preserved under tap water for different time periods. The composite materials have more resistance and durability against neat blended cement materials. Hydration of blended cement 32 wt.% Na₂O-and Cao help to represent alternative supplementary materials and also used to reduce CO₂ emission (Moesgaard *et al.* 2012). In ceramic materials clay roof tiles, and Portland cement are suitable for fine material the thermal treated clay is one of the first clay in study used as pozzolanic material. Material are abolished due to many reasons like;

selection of non-accurate temperature mechanical and dimensional failure and reduction of durability. The morphology of pozzolanic material and clay Portland cement is almost same and the hydration phases are analyzed by scanning electron microscopy and XRD techniques. Use of blended cement binder to reduce the ecological footmarks of CO₂ emission produced during cement production. For better result thermal analysis, microstructural analysis, EDS analysis and compressive strength should be implemented.

Table-9 chemical composition-based EDS analysis of blended cement

Elements	Mass (%)	Atom (%)	Mass Norm (%)	Abs.error(%)	Rel.error(%)
Titanium	0.6	0.73	0.96	0.04	0.77
Sulfur	0.7	0.38	0.5	0.04	1.55
Iron	1.50	5.0	9.23	0.06	4.66
Calcium	2.38	11.34	14.32	0.2	4.04
Potassium	0.71	3.38	4.19	0.07	6.84
Silicon	7.88	52.3	47.99	0.38	4.55
Sodium	0.13	0.96	0.74	0.05	29.06

Reduction of CO₂ concrete

Environmental impacts in Concrete become an important matter of interest because concrete produce requiring sustainability. Emission of Carbon dioxide is used to find the parameters in concrete production and to identify environmental impacts. Cement and cement replacement supplementary materials like fly ash, blast furnace slag, metakaolin, rice husk ash, blended cement etc. are examined. The important construction material regards for 65% of building greenhouse gas emission comprise concrete and dispersed steel. In surrounding CO₂ emission produced by crucial construction materials accounts 40%. Concrete. Victor et al has demonstrated the methods to optimized cost of CO₂ emission in pre cost concrete roads bridges with the help of U shape sections The reduction of CO₂ emissions through Supplementary Cementitious Materials (SCMs) involves partially replacing Portland cement with eco-friendly materials such as fly ash, slag, rice

husk ash, or metakaolin to lower the carbon footprint of concrete production. Since cement manufacturing is highly energy-intensive and releases large amounts of CO₂ from limestone calcination, using SCMs helps conserve energy and reduce greenhouse gas emissions. Besides environmental benefits, SCMs improve concrete's durability, strength, and resistance to chemical attack by refining its microstructure through pozzolanic reactions. This approach not only supports sustainable waste management and resource efficiency but also promotes cost-effective, durable, and greener construction practices. [50].

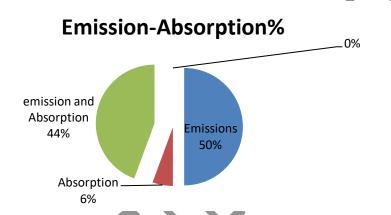


Figure 5, CO₂ emission-Absorption in concrete for precast

The figure tells about emission and absorption of CO₂ in concrete with percentages. If we consider the precast production of concrete the absorption will be 6%, emission will be 44% total will be 50% of emission and absorption during precast production of concrete. A very huge amount of energy is desired to produce cement so, coal is used as an energy source in cement production. Burn coal is utilized in form of powder and chomp about 450g of coal for the production of 900g of cement. CO₂ reduction by Supplementary Cementitious Materials (SCMs) refers to the process of lowering carbon dioxide emissions in cement and concrete production by partially replacing Portland cement clinker with environmentally friendly materials such as fly ash, silica rice fume, husk ash, sugarcane bagasse ash, slag, metakaolin. or Since Portland cement production is responsible for about 8% of global CO₂ emissions—mainly from limestone calcination and fuel combustion using SCMs helps minimize the carbon footprint of concrete without compromising its performance.

Incorporating supplementary cementitious materials (SCMs) like fly ash, slag, silica fume, and calcined clays into concrete mixes can reduce CO₂ emissions by approximately 10% to 70%

compared to conventional Portland cement, depending on substitution levels and material types. Life-cycle assessment (LCA) studies show that replacing 30–50% of cement with SCMs can lower emissions by 30–60%, with cradle-to-gate CO₂ savings reaching over 200 kg per m³ of concrete in some regions. These reductions are quantified through experimental mix designs and LCAs considering raw material processing, transport, and in some cases, carbonation uptake. Regional availability plays a key role: for instance, countries like India and Brazil use more SCMs due to access to industrial byproducts, while regions with declining coal or steel industries face SCM shortages, prompting a shift toward alternatives like calcined clay or natural pozzolans.

• Limitations

Supplementary cementing materials (SCMs) help enhance the properties and sustainability of concrete but also have certain limitations. These include issues such as limited availability and variable costs, inconsistency in properties due to differences in material processing and impurities, slower early strength development, potential risk of alkali-silica reactions, carbon footprint concerns, regulatory challenges, compatibility issues with chemical admixtures, and uncertainties related to long-term durability. To address these challenges, it is essential to carefully select SCMs according to project requirements, implement strict testing and quality control measures, and ensure collaboration between key stakeholders such as contractors, researchers, and material suppliers.

Future Perspectives

All supplementary cementing materials exhibit performance variability and differences in chemical and physical characteristics, often resulting in slow strength development, compatibility issues, and environmental concerns. Future developments should focus on advancing SCM characterization techniques and promoting innovation in SCM production processes. Improved compatibility testing between cement types and admixtures can simplify the selection of optimal materials. Additionally, conducting comprehensive life cycle assessments of SCM-based concrete will help evaluate their long-term environmental and performance impacts. Continuous efforts toward developing standardized testing

- methods and performance criteria will enhance reliability, consistency, and confidence in the broader application of SCMs within the construction industry.
- Continued effort for the development of standardized testing method strategies and their recital criteria for these materials can help to improve confidence and consistency in their applications.

Conclusion

Different supplementary cementitious materials are used in construction industry to improve performance of concrete. Use of these supplementary material help to improve mechanical strength, durability and reduce cost and environmental impacts. The cement and concrete industry are relaying on these materials have low cost and high availability from industrial waste streams. Research on supplementary materials is increasing and we are moving beyond the testing of small-scale sources and find the effect on their properties and find the effects of CO₂ emission during concrete production and their environmental impacts.

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