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Review Article

Role of binary cement including Supplementary Cementitious Material (SCM), in production of environmentally sustainable concrete: A critical review

S. Samad [a], A. Shah [b,*]

[a] Civil Engineering Department, City University of Science and IT, Pakistan
[b] Civil Engineering and Environmental Design, City University of Science and IT, Pakistan

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Abstract

Concrete is the most widely used construction material in the world. Cement is the major manufactured material used in the production of concrete. It is an established fact that the manufacturing of one tonne of cement produces about one tonne of CO_2, which is a major Green House Gas (GHG), contributing to Global Warming, Climate Change and Ozone layer depletion. In this paper, the environmental impact of cement manufacturing has been assessed on the basis of literature review. The use of Supplementary Cementitious Materials (SCMs) such as Pulverized Fly Ash (PFA) and Ground Granulated Blast Furnace Slag (GGBS), Rice Husk Ash (RHA) and Silica Fumes (SF) have been used for reducing the weight of cement in the concrete mixes to achieve, the desired compressive strength of concrete for use in construction projects. Various trial mixes have been used with partial substitution of cement with PFA and GGBFS and SF to achieve the desired high strength concrete for structural uses. The addition of the SCM has reduced the cement proportion in concrete, thereby making it relatively sustainable. The results have been assessed on the basis of reduction in the embodied energy of the concrete. The paper presents a holistic review of concrete by using binary cement, incorporating Ground Granulated Blast furnace Slag (GGBS), Pulverized Fly Ash (PFA) and Silica Fumes (SF).

Keywords: Greenhouse gas; Global Warming; Concrete production; Supplementary Cementitious Material

Contents

* Corresponding author. Fax: +92 91 2609500.
E-mail addresses: hodcivil@cusit.edu.pk (S. Samad), drshah965@gmail.com (A. Shah).
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1. Introduction

Sustainability of Built Environment (SBE) is based on three major principles, namely Resource Conservation, Life Cycle Costing (LCC) and Human Friendly Designs (HFD). In resource conservations, the concept of 3Rs (Reduce, Reuse and Recycle) is very commonly employed in the construction and manufacturing sectors now (Bramley and Power, 2009). Concrete is the most important building material in the world due to the fact that, it is versatile and gives architectural freedom. According to The Concrete Centre (2010a,b,c), the amount of embodied CO_2 (ECO_2) of concrete is a function of the cement content in the mix designs. The ECO_2 impact of concrete is around 100 kg CO_2 per tonne. For sustainable concrete construction, the embodied CO_2 content of concrete is considered. Portland cement is the main constituent in concrete production from the ECO_2 perspective. In the production of Portland cement, a huge amount of CO_2 is produced. To reduce the embodied CO_2 of concrete, Portland cement can be partially replaced with Supplementary Cementitious Materials (SCMs) such as Ground Granulated Blast furnace Slag (GGBS), Pulverized Fly Ash (PFA), Rice Husk Ash (RHA), Silica Fumes (SF) etc. The SCMs have been used extensively over the last few decades in the production of concrete. Most of the use of SCM has been motivated by offsetting the cost of concrete production and reducing the construction cost. But more important consideration in the use of SCM, is sustainability dimension of concrete, as with increased use of SCM, we are expecting to reduce substantial volume of CO_2 emissions, thereby mitigating the environmental impact of concrete production.

The Sustainable Development Goals (SDGs) were established by the UN for the period 205–2030. The SDGs are comprised of 17 goals and 169 targets, which address the social, economic and environmental dimensions of development (UN, 2015). The SDG goal 9, is based on Industry, Innovation and Infrastructure, which also demands robust and resilient infrastructure by retrofitting the existing one and construction of new one in the developing and Least Developing Countries (LDC). Hence the construction industry has to grow, exponentially with the demand for new infrastructure. The cement consumption as a result would also increase manifold leading to more Green House Gases (GHG) emissions in times to come. To offset the detrimental impacts of cement production, the research for exploring more Supplementary Cementitious Material (SCM) as partial replacement of cement would continue with more rigour in future.

One of the important considerations of measuring the sustainability of building material is Embodied Energy. According to Cement and Concrete institute (2011), "*Embodied energy (EE) is the energy consumed for raw material extraction, transportation, manufacture, assembly, installation, disassembly and deconstruction for any product system over the duration of a product's life*". Apparently a material with low Embodied Energy is regarded more sustainable. A more relevant measure of sustainability is Embodied CO_2 (ECO_2), which is the total amount of CO_2 produced in the extraction and transportation of raw materials and their manufacture into the final product. It is often expressed as CO_2 per unit mass, or CO_2 per unit volume. (kg CO_2/tonne or kg CO_2/m^3). Indicative values of ECO_2 for the main cementitious constituents of reinforced concrete for the year 2010 are presented in Table 1 (UKQAA, 2010)

The comparison of values given in Table 1, shows that SCMs have very small amount of ECO_2 as compared to the Portland Cement, which make it very suitable material for sustainable concrete.

The current average worldwide consumption of concrete is about one tonne per year for every living human-being and due to this extensive use, concrete has a relatively large environmental footprint. Worldwide, the cement industry accounts for approximately 5% of man-made CO_2 emissions. Approximately 40% of this is from burning coal and 60% from the calcination of limestone.... (Sustainable Concrete, 2011). The CO_2 emissions per tonne of concrete production for rolling concrete mixes have increased by 7% in 2010 compared to 2009 but are lower than the 1990 base line. This increase is the result of higher average cement contents in the rolling concrete mix in UK. The CO_2 emissions for the production of rolling concrete mixes for three years are given in Fig. 1 (Concrete Centre, 2010a,b,c).

Table 1
Embodies CO_2 of Portland Cement, GGBS and PFA (UKQAA, 2010).

Materials	Embodied CO_2 kg/tonne
Portland Cement Type 1 Cement (CEMI)	913
Ground Granulated Blast furnace Slag (GGBS)	67
Pulverized Fly Ash (PFA)	4
Lime stone	75

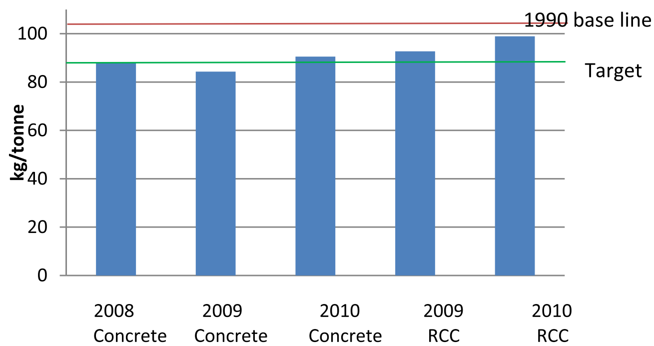

Fig. 1. CO_2 emissions for production of rolling concrete mix (The Concrete Centre, 2010a,b,c).

According to The Concrete Centre (2010a,b,c) Portland Cement is the largest energy demanding sector of the concrete industry and is responsible for almost 74% of the energy used in concrete manufacture. The cement sector and Ground Granulated Blast furnace Slag sectors have committed to voluntary Climate Change Agreements (CCA), with focus on reducing of cement use in concrete production by using SCM. These sectors have made an agreement with the Government of UK, to commit for energy reduction programs and will carry financial penalties if not achieved. The cement sector improved its CCA performance by 44.8% between 1990 and 2010 which exceeds the agreed target of 30%. The Ground Granulated Blast furnace Slag (GGBS), sector achieved a 16% energy reduction between 1999 and 2010 by improving the process of grinding.

2. Binary cement in concrete manufacturing using GGBS

GGBS is a by-product obtained during the manufacture of iron in the blast furnace. GGBS is economically available in large quantities, requiring storage facilities and therefore, it is suitable for use in ready-mix concrete, in the production of large quantities of site batched concrete and in precast product manufacturing. Blast furnaces are fed carefully with controlled mixtures of iron-ore, coke and limestone, at a temperature of about 2000 °C. The iron ore is reduced to iron and sinks to the bottom of the furnace. The remaining material that floats on top is the slag. The slag is rapidly quenched in large volumes of water. This process of quenching optimizes the cementitious properties and produces granules similar to coarse sand particles. The granulated slag is dried and ground to a fine powder that is called GGBS. It is off-white in colour and has a bulk density of 1200 kg/m^3. The first commercial blended Blast Furnace Slag Cement was produced in Germany in 1865 and currently over 200 million tonnes per annum of blast furnace slag cement is used around the world. According to Higgins (2006), UK uses about two million tonnes per year of GGBS as cement. According to Jones (2011) GGBS affect the properties of Concrete both in fresh and hardened states. The typical constituents of GGBS and Ordinary Portland Cement are given in Table 2 (Hanson, 2010)

Hooton (2000) found that the slump of GGBS concrete is unaffected as compared to PC concrete but slag concrete is much easier to compact by vibration and is therefore considered to be more workable. Due to the improved workability of slag concrete, the entrapped air content is lowered. The GGBS concretes are easy to finish because of the higher fines content but at higher replacement levels and ambient temperatures (<15 °C) setting times can be extended up to one or two hours. GGBS concrete with higher replacement (50% and above) or placed at lower temperature needs extra curing, if bleeding and finishing times are extended significantly. Hooton (2000) concluded that the setting time of GGBS mixtures can be extended up to one or two hours at high replacement levels and low ambient temperatures (<15 °C). In hot weather at a temperature above 20 °C, the finishing time can be extended by only a few minutes. For all concretes curing against the loss of moisture is essential and for GGBS concrete placed at low temperature, extra curing is required.

In hardened state, the GGBS affect the mechanical properties of concrete. Dhir *et al*. (2005), indicated that the influence of the concrete on compressive strength is in proportion to the effect on other engineering properties and are in line with the current design assumptions for concrete. It was also found that the Eurocode 2 (EC-02) equations for predicting the shear strength of reinforced concrete beams, based on compressive strength are appropriate for the range of concrete mixes considered which included PC/PFA and PC/GGBS mixes. It was suggested that there is no need for further reviewing the design procedures relating to flexure or shear for using concrete mixes containing GGBS and PFA with regard to the relationship between compressive strength and other engineering properties. In their research, it was shown that the compressive strength in the equation for calculating the shear strength of reinforced concrete beams given in BS EN 1992-1-1, is valid for all types of concrete and constituents including GGBS and PFA.

In Fig. 2, the comparison of compressive strength of concrete containing slag at 7 and 28 days with PC concrete is shown by the Slag Cement Association (SCA,2003). In Fig. 3, the comparison of flexural strength for Slag cement concrete and PC concrete has been presented. Johari *et al.* (2011) found that at the age of one day, the relative

Table 2
Typical constituents of GGBS after Hanson (2010).

Constituents	Percentage in GGBS	Percentage in Portland Cement
Calcium oxide (CaO)	40%	60–67%
Silica (SiO_2)	35%	17–25%
Alumina (Al_2O_3)	16%	3–8%
Magnesia (MgO)	6%	0.1–4%
Other - Fe_2O_3, etc.	3%	0.5–6%

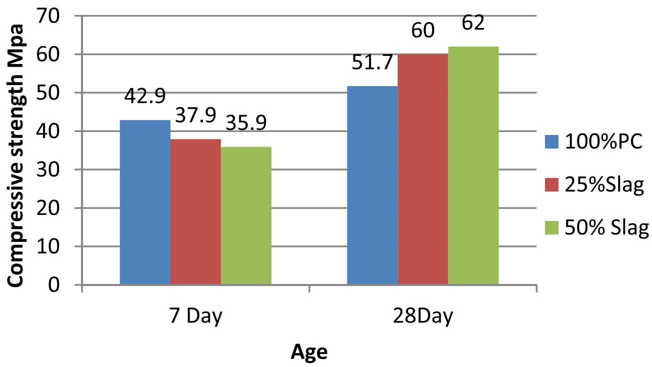

Fig. 2. Effect of Slag on Compressive strength of slag cement concrete after (SCA, 2003).

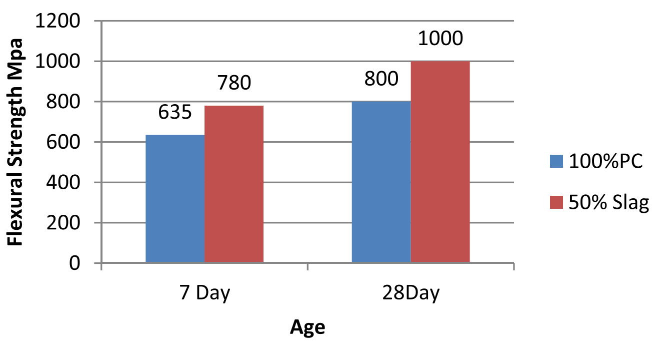

Fig. 3. Effect of Slag on Flexural Strength of slag cement concrete after (SCA, 2003).

strength of GGBS with 20%, 40% and 60% replacement was 72%, 45% and 4.6% of the Portland cement concrete respectively. The lower early age strength was due to the slower reactivity of GGBS and due to its delusion effect.

Khatib and Hibbert (2005) found that the early age strength gain of concrete containing GGBS decreases with increasing percentage of GGBS in concrete but the strength between 28 days and up to 90 days, increased as compared to the PC concrete. The replacement level of GGBS up to 60% was beneficial and beyond that the strengths were very low. The comparison of compressive strength at different ages between GGBS and the PC concretes, by Khatib and Hibbert (2005) is given in Fig. 4. Concrete was casted for equal water/binder ratio of 0.5 and the specimens were cured in water at 20 °C. It was concluded that 60% GGBS replacement of PC in concrete causes, an increase in compressive strength.

The 90 day flexural strength values of different mixes prepared by Khatib and Hibbert (2005) are given in the Fig. 5. The flexural strength of concrete containing 60% GGBS was higher than the control mix. The flexural strength of concrete containing 40% GGBS was reduced while that 80% GGBS reduced considerably.

According to Soutsos *et al.* (2004), at elevated temperature, the early age strength of concrete made with GGBS for equal 28 day compressive strength can be greater than that made with Portland cement only. This is a direct result of the activation of the GGBS caused by the elevated temperatures present in in-situ concrete. They proved that early age strength of GGBS concrete cured under adiabatic conditions can be as high as 250% of the strength of the companion specimen cured at 20 °C in a water tank. Adiabatic temperature rise due to the hydration of cement is the temperature rise which occurs if the fresh concrete is stored in a perfectly insulated environment and to achieve this state concrete was stored in an environmental chamber which was controlled at nearly the same temperature as that of concrete. Chu (2007) concluded that from a structural point of view, GGBS replacement reduces heat of hydration, enhances durability, including higher resistance to sulphate and chloride attack, when compared with normal concrete. On the other hand, it also contributes to environmental protection because it minimizes the use of cement during the production of concrete. Hooton (2000), found that the use of GGBS in concrete enhances

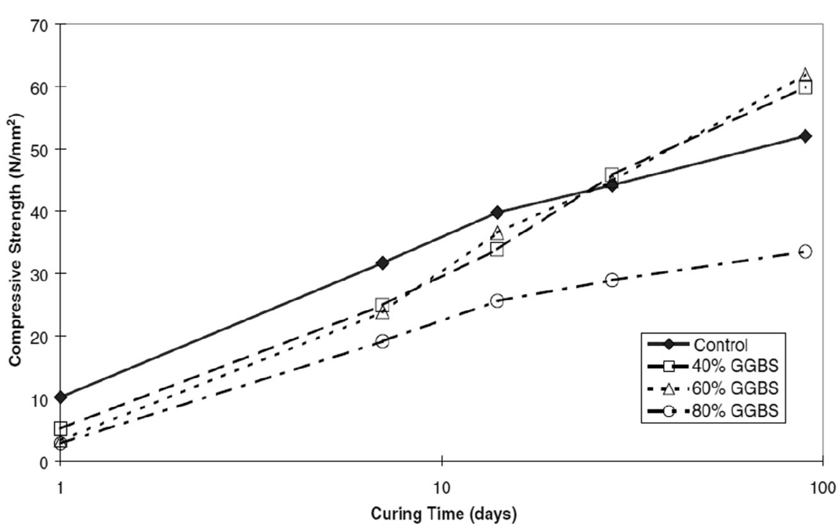

Fig. 4. Effect of GGBS on Strength Development (Khatib and Hibbert, 2005).

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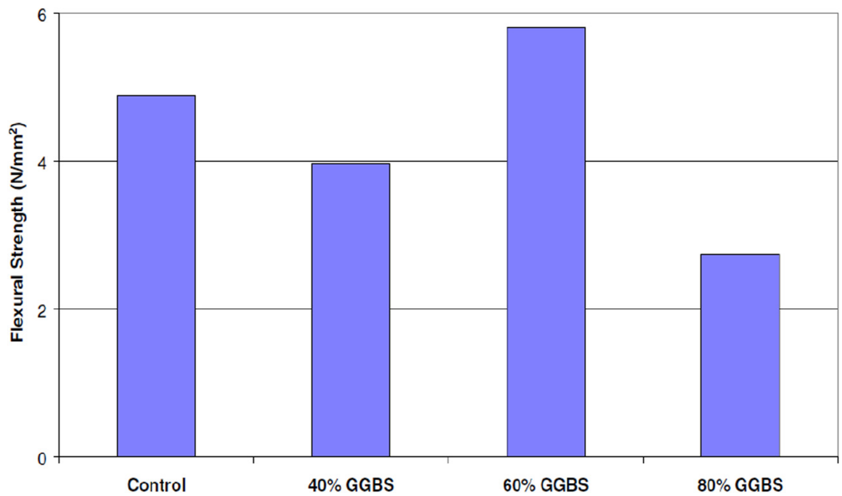

Fig. 5. Effect of GGBS on flexural strength (Khatib and Hibbert, 2005).

durability, if properly proportioned and cured. Further it is effective in improving the resistance to chloride, sulphate and alkali-silica reaction. GGBS concrete reduces the diffusion of chloride and oxygen and the time to depassivate the steel is increased. Based on the data developed by Hooton (2000), typically 50% replacement level or less was considered sufficient to obtain equivalent performance to a sulphate resisting Portland cement. He proposed longer curing period for concrete containing GGBS and when slag concrete is placed at lower temperature than 15 °C, it should be protected against excessive loss of moisture after initial screening and prior to final finishing and application of curing.

The environmental profile for the production of one tonne of GGBS, compared with typical values of Portland Cement (PC), is presented in Table 3 (Higgins, 2006). The raw material for GGBS is slag which is produced as a by-product of iron. Only the energy used for processing and grinding of slag to GGBS has been considered. This slag if not utilized, will otherwise go to land fill as waste disposal. The replacement level and the need for extra cementitious content are the important factors in selecting the most sustainable material for concrete production. GGBS is highly cementitious and can usually replace Portland cement by 50% or more.

With the substitution of SCMs like GGBS and PFA in various proportions, Higgins has given the reduction in GHG, primary energy use and mineral extraction as given in Table 4 (Higgins, 2006).

Thomas (2009) used 35% GGBS slab structure of West Thames college extension. As PC production is responsible for 6% of the global carbon emissions, its partial replacement with GGBS was of environmental benefit as less cement was quarried and it saved the waste product of the steel industry to be land filled. The delivery cost of the blended cement concrete was 2–3% cheaper than the standard concrete mix. Architecturally, the light colour of GGBS concrete provided a nice finish to the fair-faced walls, columns and slabs. Formwork striking times were extended to account for slower strength gain. Vertical forms were delayed from one to two days and slabs cast in subsequent weeks were delayed to at least 11 days rather

Table 3
Environmental Burden for the manufacture of GGBS after Higgins (2006).

Source	Measured as	Impact	
		Manufacture of 1 tonne of GGBS	Manufacture of 1 tonne of PC
Climate change	CO_2 equivalent	0.05 tonne	0.95 tonne
Energy use	Primary energy	1300 MJ	5000 MJ
Mineral extraction	Weight quarried	0	1.5 tonnes
Waste disposal	Weight to tip	1 tonne saved	0.02 tonnes

Table 4
Calculated environmental impacts for 1 tonne of concrete After Higgins (2006).

Impact	100% PC	50% GGBS	30%PFA
Greenhouse gas (CO_2)	142 kg (100%)	85.4 kg (60%)	118 kg (83%)
Primary energy use	1070 MJ (100%)	760 MJ (71%)	925 MJ(86%)
Mineral Extraction	1048 kg (100%)	965 kg (92%)	1007 kg (96%)

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than a week for PC concrete. Overall these were acceptable prices to pay for the financial saving and environmental benefit.

In Shard, the tallest building of European Union, 75% GGBS was used in the base slab. GGBS was used not only to reduce the propensity for early-age cracking but also to reduce embodied CO_2. An innovative approach was used on this project to allow construction above and below ground to start simultaneously (Parker, 2012).

3. Binary cement in concrete manufacturing using Pulverized Fly Ash (PFA)

According to the information given by the United Kingdom Quality Ash Association (UKQAA, 2004), PFA is a by-product obtained at power stations and is a solid material extracted by electrostatic and mechanical means from flue gases of furnaces fired with pulverized bituminous coal. It is carried by the exhaust gases and recovered as fly ash with fine particles. According to Thomas (2010), the use of fly ash as supplementary cementing material in concrete has been known from the start of last century but the first research in fly ash was conducted at the university of California by Davis *et al.* (1937) and the first significant utilization of fly ash in concrete began with the construction of the Hungry Horse Dam in Montana in 1948. The production of the material has been changed to reduce the gaseous emissions in recent years but has not affected the nature of PFA except it has increased the loss on ignition (LOI). According to Sear (2011) in “Future trends for PFA in cementitious systems” the ash production in the UK is falling overall. The UK produced about 5,300,000 tonnes of PFA which is fairly consistent for a number of years but has significantly reduced now. The Lafarge Combustion Plant Directive (LCPD) led to closure of number of Coal Fired Power stations by 2015. The coal fired power station products sold in the UK in 2009 are shown in Fig. 6, and application of PFA products in UK is given in Table 5 (Sear, 2011).

The requirements for PFA for use in blended concrete according to BSEN 450-1(2012) are given in Table 6

3.1. Properties of concrete produced with PFA blended binary cement

According to Joseph and Ramamurthy (2009), fresh density of concrete is reduced with increase in replacement level of cement by fly Ash and its workability is increased. Fly Ash particles are usually spherical in shape and reduce the water demand for a given value of slump. The spherical shape of fly ash reduces the friction between the aggregates and between concrete and the pump line and thus increase the workability and pump-ability of concrete. Fly ash in concrete increases the fine volume and decreases the water content and so reduces the bleeding of concrete (Ash Utilisation Division, 2011).

Dhir *et al.* (1984) found that the there is a close correspondence between the strength of PC concrete and PC/PFA concrete at the age of 28 days. They designed the concrete for equal workability and 28-day strength 15–60 N/mm^2. PFA concrete was designed using known cementing efficiency factor and all the specimens were cured under standard curing conditions. Early age strength of PFA concrete is slower than PC concrete because the pozolanic reactions are slower than the hydration reactions and they start after about five days. At low water curing temperature of 5 °C the strength of PC concrete and PC/PFA concrete are very similar because the lower temperature are not able to slow down the pozzolanic reactions more than those of hydration reactions. At ages between 28 and 180 days, at

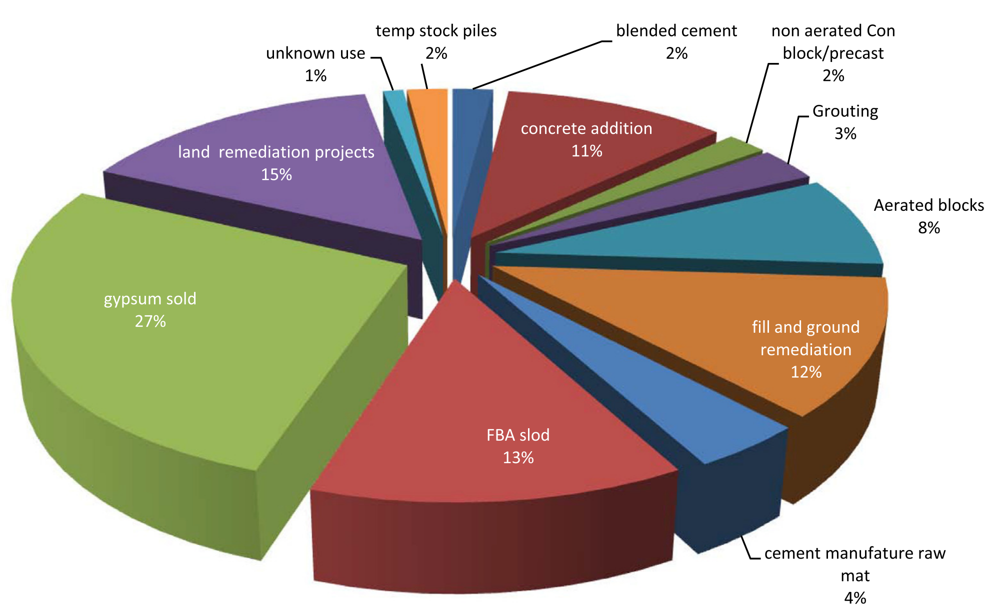

Fig. 6. Coal fired power stations products sold in the UK during 2009 (Sear, 2011).

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Table 5
Applications for PFA annual PFA production for UK after Sear (2011).

Application for PFA annual PFA production	Tonnes
Cement raw material	200,000
Blended cement	100,000
on aerated concrete blocks and precast	100,000
Grouting	150,000
Aerated blocks	400,000
Fill, ground remediation and other uses	650,000
Sent to land reclamation projects	750,000
Land filled material	1,600,000
Total	4.400,000

Table 6
Chemical requirements of Fly Ash as Characteristic values.

Property	Test reference	Requirements[a]
Magnesium Oxide	EN196-2	≤4.0%
Phosphate (P_2O_5)	ISO 29581-2	≤5.0%
Sulphate (SO_3)	EN196-2	≤3.0%
Loss on ignition for Cat A	EN196-2	≤5.0%
Chloride	EN196-2	≤0.10%
Free Calcium Oxide	EN 451-1	≤1.5%
Reactive Calcium Oxide	EN 197-1:2011	≤10.0%
Reactive Silicon Dioxide	EN 197-1	≤25.0%

[a] Requirements are given by mass of Fly Ash.

low temperature there is a decrease in strength of PC/PFA concrete. At 20 °C curing condition there is a significant increase in compressive strength of PC/PFA concrete at 365 day strength compared to PC concrete. For standard curing temperature of 20 °C, there was a close correspondence between the strength of PC/PFA concrete and the PC concrete. The concept of equal strength for equal maturity irrespective of the route to maturity for PC concrete does not apply to PC/PFA concrete and is dependent on the curing temperature. Dhir *et al.* (1998) found that PFA fineness affects the strength of concrete and the strength of PFA concrete is reduced by using coarser PFA. In order to take care of the effect of PFA fineness on strength, they developed a simple procedure of varying the water content, cement content or both. The acceptable variation of PFA fineness in BS- EN 450 (2012) has an effect on the concrete production and it can be adjusted by modifying the margin between the characteristic and mean strength. It was suggested that the '*k*' factor approach to mix design is not suitable for BS EN 450 PFA and simple adjustment to the mix proportions is appropriate. For durability tests, which include chloride diffusion, carbonation, sulphate Resistance, alkali silica reactivity, freeze thaw and abrasion, similar performance was achieved by BS-EN 450 PFA and BS 3892 part 1 PFA provided equivalent design strength was achieved. Safan and Kohoutkova (2001) reported that continuously water-cured concrete specimens provided a better rate of strength development compared to other curing conditions and the compressive strength affected by drying condition varies at different ages. Solanki and Pitroda (2013) performed flexural strength test on mini beams of size 100 mm × 100 mm × 500 mm. A concrete mix M20 grade was designed as per IS10262:2009 method. The water/cement ratio was 0.48 for all the mixes. Flexural strength test was performed at the age of twenty eight days. It was concluded that the twenty eight day flexural strength of concrete is increased up to 11.1% with 20% replacement level of PC by fly ash. The flexural strength test results are given in Table 7.

Kayali and Ahmed (2013) prepared concrete mixes by replacing PC with different percentages of Fly ash. The water/cement ratio was 0.38 for all the concrete mixes and the total amount of cementitious material content was kept constant for all the mixes and was equal to 450 kg/m^3. The concrete samples were cured with fog for seven days and then they were air dried till the age of 28 days for testing. Kayali and Ahmed, 2013 found that there was a decrease in the compressive strength of concrete made with fly ash and further decrease was observed with the increase in replacement level of fly ash. The same trend was also in modulus of elasticity of fly ash concrete compared with the PC. The effect of Fly ash on compressive strength and modulus of elasticity is shown in Fig. 7. They emphasized that these trends were for total cementitious content of 450 kg/m^3 and these trends may significantly vary, for different total cementitious contents.

Dias *et al.* (1990) tested grade 25 and 35 concretes, where Portland cement was replaced with 15% and 25% class F PFA with very high fineness (i.e. percentage passing through 45 μm sieve is 85%). PC content was 345 kg/m^3 and 444 kg/m^3 for grade 25 and grade 35 concrete respectively. Water content for both grades was 200 kg/m^3 which made the water/cement ratio of 0.58 for grade 25 and 0.45 for grade 35 concrete. For PFA concrete mixes the water content was reduced to 190 and 185 kg/m^3 for 15% and 25% PFA mixes respectively. They found that the best performance of PFA mixes was in the reduction of charge passed in the indirect rapid chloride ion transport test and in the reduction of heat of hydration and temperature rise. In general, the results of PFA mixes were similar or better than the PC control mix. The strength ratio between PFA and PC mixes was slightly higher at 3 days than at 7 days after which the ratio increased again.

According to the findings of Jia *et al.* (2004), to achieve an excellent carbonation resistance of concrete, good

Table 7
Twenty-eight (28) day Flexural Strength of Concrete produced with partial replacement of cement by PFA (Solanki and Pitroda, 2013).

Fly ash replacement level	Flexural Strength (N/mm^2)	% change in Flexural Strength
0%	5.05	0
10%	4.48	−11.28
20%	5.61	11.08
30%	4.46	−11.68

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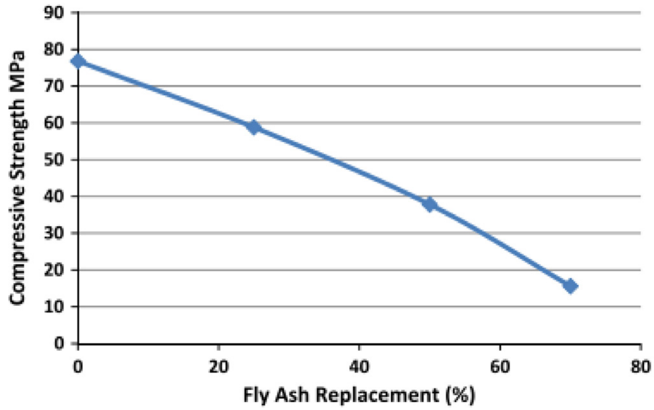
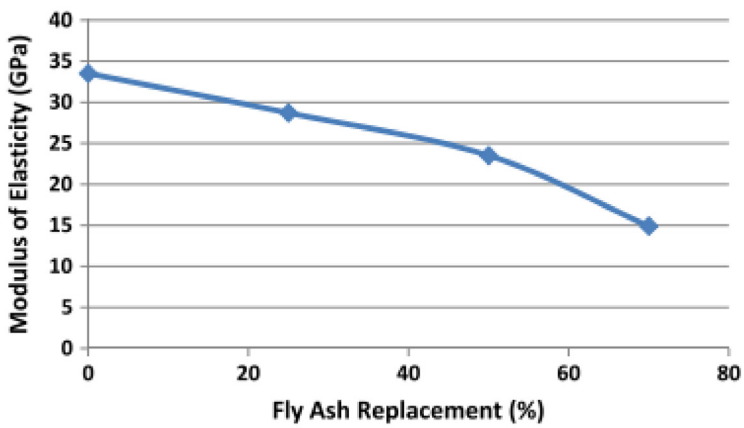


7a (Compressive Strength)



7b (Elastic Modulus)

Fig. 7. Effect on Compressive strength and Modulus of Elasticity with various proportions of PFA in Concrete produced with binary cement (Kayali and Ahmed, 2013).

curing is very important. Specimens were stored in a moist curing room maintained at 20 ± 2 °C for 1, 3, 7 and 28 days before they were exposed to the natural and accelerated carbonation environment. It was noted in the study that prolonging the initial curing time causes decrease in the carbonation depth of concrete. The linear relationship between compressive strength and carbonation depth is not suitable when cement is replaced by mineral admixtures in 20% or 35% proportions and the water–cement ratio is reduced to 0.40 or 0.37 because of the pozzolanic reaction. Sear (2010) reported that fly ash has been used for many years and can improve the sulphate resistance and chloride diffusion, prevent alkali-silica reaction and reduce heat generation. These beneficial properties of fly ash have been researched by many with more than a thousand papers. It has been increasingly recognized in recent years that using fly Ash as a cementitious binder reduces greenhouse gas emissions, enhances durability and extends the structures life. According to ScotAsh (2005), each tonne of PFA re-used in cement products saves an average 900 kg of CO_2 emission. In addition using processed PFA as an addition to concrete lowers the water demand, which in turn saves energy.

According to the United Kingdom Quality Ash Association (2010), about 400,000 tonnes of fly Ash are used in concrete production per annum and saves about 250,000 tonnes of CO_2 to the environment. Fly ash is also used by the cement industry in the production of blended fly ash cement so the overall benefit of the UK coal fired power stations fly ash is the reduction of about 600,000 tonnes of CO_2 per annum. This figure could be doubled because only about half of PFA produced is currently utilized. According to ScotAsh (2009), cement containing PFA typically cost 5% less than conventional blends. Cement contents are typically about 10% higher for 30% PFA mixes than PC mixes. For a typical mix of 300 kg/m^3 PC, contains 330 kg of PFA (30%) brings the price down by £ 1/m^3. In the Angel Building, London, self compacting (36% fly ash) concrete was used to eliminate the need for conventional methods of compaction, such as

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vibrating pokers. By using PFA workability of concrete was improved around difficult interfaces and the light grey colour of PFA concrete added towards the aesthetic of the building.

4. Binary concrete in concrete using Silica Fumes (SF)

Silica fume is a by-product of producing silicon metal or ferrosilicon alloys. Production of silica fume involves the reduction of high purity quartz (SiO_2) in electric arc furnaces at a temperature of more than 2000 °C. The smoke that results from furnace operation is collected and converted to silica fume. Silica fume is a very fine powder consisting mainly of spherical particles of diameter 0.15 µm. The average size of particle of silica fume is about 100 times smaller than an average cement particle. Silica fume is generally dark grey to black or off white in colour and can be supplied as a dense powder or slurry depending on the application and the handling facilities available. In the UK silica fume is supplied as slurry consisting of 50% silica fume and 50% water. Global consumption of silica fume exceeds one million tonnes per annum. The properties of silica fume and OPC are compared in Table 8.

According to Norchem (2012), in cementitious compounds, the chemical reaction of silica fume is called "pozzolanic" reaction. The hydration of Portland cement produces many compounds; including calcium silicate hydrates (CSH) and calcium hydroxide (CH). The CSH gel is the source of strength in concrete. When silica fume is added to the fresh concrete, it chemically reacts with the CH to produces additional CSH. The benefit of this reaction is increase in the compressive strength and chemical resistance. The bond between the concrete paste and the coarse aggregate, in the crucial interfacial zone, is greatly increased, which results in increase in compressive strength. The additional CSH produced by silica fume is more resistant to attack from aggressive chemicals then the weaker CH. The second function of silica fume in cementitious compounds is a physical one. As silica fume is 100–150 times smaller than a cement particle it can fill the voids created by free water in the matrix. This function is called particle packing and it refines the microstructure of concrete, creating a much denser pore structure. Impermeability is increased with the addition of silica fume in concrete.

Table 8
Comparison of the physical and chemical properties of OPC and Silica Fume (Detwiler and Mehta, 1989).

Properties	OPC	Silica Fume
Physical		
Specific Gravity	3.1	2.2
Mean grain size (µm)	22.5	0.10
Specific area (cm^2/g)	3250	200000
Colour	Dark Grey	Light to dark grey
Chemical Composition		
Silicon dioxide (SiO_2)	22.03	96.0
Aluminium Oxide (Al_2O_3)	4.03	0.10
Iron Oxide (Fe_2O_3)	3.67	0.60
Calcium Oxide (CaO)	65.19	0.10
Magnesium Oxide	0.88	0.20
Sulphite (So3)	2.86	–
Sodium Oxide (NaO)	0.12	0.10
Pottasium Oxide (K_2O_3)	0.20	0.40
Loss on ignition	0.98	1.70

According to The Concrete Society (1991), the average quantity of silica fume used in concrete is typically less than 8% of cement content but can be used up to 12.5% or more. BS EN 13263-1 (2005) and BSEN 13263-2(2005) applies for Silica fume in concrete. The water demand of concrete increases with the use of silica fume and is due to the high surface area of the material. To achieve maximum strength and durability, high-range water reducing admixtures are used in concrete containing silica fume. Concrete containing silica fume is more cohesive and reduces the risk of segregation. The slump of silica fume concrete is more than the PC concrete. Silica fume is a very reactive pozzolan because of its chemical and physical properties. Concrete containing silica fume can have a very high strength and can be very durable. Using silica fume, high early strength concrete can be achieved and has been used in tall buildings in USA and Asia. Time of striking formwork is not affected by the use of silica fume in concrete.

According to Wolsiefer (1991), silica fume lowers the concrete permeability and prevents chloride ingress to the reinforcement, while simultaneously increasing the electrical resistance of concrete to corrosion. Silica fume addition prevents the salt induced corrosion of steel bars. It was concluded that silica fume concrete has less creep than that of PC concrete at equal strength. Shrinkage of concrete is reduced by using silica fume. GGBS, PFA and silica fume reduce the environmental impacts significantly because their manufacturing does not require any quarrying of virgin minerals, they use much less energy in their manufacture as compared to PC and their use in concrete avoids them being land filled. Their use in concrete structures enhances the durability and can lead to longer service life. Due to the higher strength achievable by silica fume, overall volume of concrete can be reduced. SCM has positive effects on the properties of concrete including early-age properties, late hardening, drying shrinkage, or compressive and tensile strengths. The effects of these SCMs on properties of concrete, however vary significantly due to different sources. The trial batching by hit and trial can be the best way to develop concrete of desired properties. The specification of such SCM requires further standardization and more tests are required to enrich the database of such results (Owaid et al., 2012).

5. Binary cement in concrete manufacturing using Rice Husk Ash (RHA)

The top cover of the rice seed is comprised of mostly silica extracted from the soil. This thin sheet is burnt to form Rice Husk Ash (RHA). The large surface area and

Table 9
Chemical and Physical Properties of RHA (Mehta, 1992; Zhang and Mohan, 1996; Bui et al., 2005).

Chemical Properties	Zhang and Mohan (1996)	Mehta (1992)	Bui et al. (2005)
Composition (%)			
Silicon dioxide (SiO_2)	87.3	87.2	86.98
Aluminium oxide (Al_2O_3)	0.10	0.15	0.84
Ferric oxide (Fe2O3)	0.16	0.16	0.73
Calcium oxide (CaO)	0.55	0.55	1.40
Magnesium oxide (MgO)	0.35	0.30	0.57
Sulphur oxide (SO3)	0.24	0.24	0.11
Sodium oxide (Na2O)	1.12	1.12	2.46
Potassium oxide (K2O)	3.68	3.68	–
Loss on ignition (LOI)	8.55	8.50	5.14
Physical Properties			
Specific gravity	2.06	2.06	2.10
Mean Particle Size (μm)	–	–	7.4
Fineness 45 (μm)	99	99	–

non-crystalline nature of the RHA, makes very suitable pozzalonic material (Tashima et al.;2004). The fineness of the RHA, after grinding makes it very suitable for use in concrete. The RHA must comply with the current Standards of ASTM C 618-94 for its use in concrete. The chemical and physical properties of RHA are given in Table 9.

Sunil *et al.* (2016) have reported that up to 40% replacement of cement by RHA has no change on the compressive strength of concrete. They also showed considerable improvement in the compressive and flexural strength of concrete for 10% replacement level. Mehmud *et al.* (2016), showed that partial replacement of cement by RHA, doesn't increase the compressive strength of concrete at the early age, but at later age of 28 and 56 days, there is appreciable increase in the compressive strength of concrete. This is common in all types of concrete made with blended cement incorporating SCM. Due to increased surface with grinding, the water requirements of RHA blended cement concrete increases, which can be offset with the increased use of Super-plasticizers (HRWR), to achieve the desired workability and strength (Ghassan and Hilmi, 2010).

5.1. Effects of SCM on the durability of concrete

Different SCM such as Fly ash, Silica fumes, Slag, natural pozzolans (RHA) have varying effects on the properties of hardened concrete such as strength gain, Abrasion Resistance, Freeze-Thaw and Deicer-Scaling Resistance, Drying Shrinkage and Creep, Permeability, Alkali-Silica Reactivity, Chemical Resistance and Carbonation. The strength gain in case of Silica fumes has been observed as increased, whereas for other SCM, it is varying depending upon the dosage and level of replacement. The abrasion resistance is generally the same as control mix with no SCM. The permeability of concrete and subsequent freeze & thaw actions is reduced for SCM added concrete. The Alkali Silica Resistance (ASR) increased with the SCM concrete. The chemical reaction also increases with the addition of SCM (Scott and Safiuddin, 2015; Naik et al., 2007). According to Justnes (2016), reported that in most cases the durability issues like chloride ingress, carbonation, alkali aggregate reactions, sulphate resistance and freeze-thaw resistance are well addressed by SCM used as partial replacement of cement at the same level of water to binder ratio.

6. Conclusions

1. The three pillars of sustainability are economic development, social equity and environmental protection. The nations of world under various Summits, have committed to achieve these objectives through resource conservation in the design and construction of Sustainable Built Environment.
2. Concrete would continue to be the major construction material for creation of the built environment, hence the burden of resource extraction in the production of concrete would continue unless more sustainable and environment friendly means for concrete production are explored. In production of concrete, its major constituent cement, require 4GJ of energy during manufacturing of 1 tonne of Cement, which results in 0.89–1.1 tonnes of CO_2.
3. Various Supplementary Cementitious Materials (SCMs) are used as partial replacement of Portland Cement (PC), e.g. Pulverized Fuel Ash (PFA), Ground Granulated Blast furnace Slag (GGBS) silica fume, Rice Husk Ash (RHA).
4. According The Concrete Centre UK (2010), the cement sector has improved its Climate Change Agreement (CCA) performance by 44.8% between 1990 and 2010 which exceeds the agreed target of 30%.
5. GGBS replacement gives lower heat of hydration, enhanced durability including resistance to sulphate

and chloride attack when compared with normal concrete. On the other hand, it also contributes to environmental protection because it minimizes the use of cement during the production of concrete. Concrete made with slag cement has higher compressive and flexure strength compared to the PC concrete.

6. The strength gain is slow in the concrete containing GGBS but the long term strength of GGBS concrete is more compared to the PC concrete. All these beneficial effects of GGBS concrete depends on concrete mix proportions and curing conditions. A maximum replacement level of 50% is recommended for GGBS and the curing temperature of at least 20 °C is beneficial. The slump of the GGBS concrete is unaffected as compared to PC concrete and is much easier to compact. Due to the improved workability of slag concrete, the entrapped air content is lowered.
7. The influence of concrete on compressive strength is proportionate to the effect on other engineering properties and is in line with the current design assumptions for concrete. Literature review suggests that there is no need to review the design procedures relating to flexure or shear for using concrete mixes containing GGBS and PFA with regard to relationship between compressive strength and other engineering properties.
8. Early age strength of PFA concrete is slower than the PC concrete because the pozolanic reactions are slower than the hydration reactions and they start after about five days. At low water curing temperatures of 5 °C, the strength of the PC concrete and the PC/PFA concretes are very similar because the lower temperature are not able to slow down the pozzolanic reactions more than the hydration reactions.
9. For water/cement ratio of 0.48 and with 20% replacement of PC with PFA, the flexural strength is increased by 11.0% compared to the PC only concrete. According to the findings of Kayali. and Ahmed (2013), if the total cementitious content of concrete is kept constant and it is cured for a limited time, there is a decrease in the compressive strength and modulus of elasticity of concrete containing PFA, compared to the PC only concrete and this decrease in strength is increased with the replacement level.
10. According to Concrete Society (1991), The elastic modulus of PFA concrete is generally equal to or slightly in excess of that shown by PC concrete of the same grade". This statement is in contradiction with the findings of Kayali and Ahmed (2013) and it depends on the total cementitious content, curing and water/cement ratio.
11. Fly ash has been used for many years and is used to improve the sulphate resistance, reduce chloride diffusion, prevent alkali silica reaction and reduce heat generation. Fly ash is used as a cementitious binder to reduce greenhouse gas emissions, enhance durability and extend structure life. Each tonne of PFA re-used in cement products saves an average 900 kg of CO_2 emission. In UK the use of Fly Ash in concrete production per annum saves about 250,000 tonnes of CO_2 to the environment.
12. Rice Husk Ash (RHA), replacement up to 10% has given good results in improving the mechanical properties of concrete. However at a larger level of replacement beyond 30%, the compressive and tensile strength of concrete reduce. With finer RHA material, the water cement (binder) ratio increases, which is offset with the use of High Range Water Reducers (superplasticizers).
13. The SCM would continue to be used to reduce the cement use in the production of concrete, with more research on standardizing its specification, mix design method at global level. The binary cement incorporating SCMs, would continue to make Concrete more sustainable and environment friendly, with more developments.

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