# ASSESSMENT OF THE ROLES OF VARIOUS CEMENT REPLACEMENTS IN ACHIEVING THE SUSTAINABLE AND HIGH PERFORMANCE CONCRETE

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***ABSTRACT***

*Nowadays, concrete is considered as one of the most important and widely used materials in construction industry. Anyway, the production of the Portland cement (PC) as a necessary constituent of concrete can basically lead to the dangerous impacts on our environment by such as releasing the consequential amount of $CO_2$ that is one of the green house gases responsible for global warming. The emission $CO_2$ ($ECO_2$) level for PC is cited as nearly one ton per ton. It means that production of one ton of PC can lead to produce about one ton of $CO_2$ and other green house gases. Decreasing in use of PC and its replacement with industrial byproducts as cement replacements will have positive effect on environmental, social and economical aspects of each society which are essential in Sustainable Development(SD). The purpose of this paper is to review on the specifications,production method and the degree of effectiveness of some industrial byproducts such as GGBS, Silica Fume and PFA as the cement replacement in achieving high performance and sustainable concrete which can lead to not only improving the performance of the concrete but also reduction of $ECO_2$ by reducing the amount of PC, and that how they can affect in economical, environmental and social aspects possitively.It also intends to recommend some remedial program to increase the willingness of using these types of industrial by-products.*

***KEYWORDS:*** *sustainable concrete, high performance concrete, Portland cement, green house gases, cement replacements*

## I. INTRODUCTION

Nowadays, concrete is one of the most highly used materials in the world. It was estimated; the concrete industry produces annually about 12 billion tons of concrete and uses about 1.6 billion tons of Portland Cement (PC) throughout the world [1]. Anyway, production of PC as one of the fundamental constituents of concrete, leads to release of consequential amount of $CO_2$ that is one of the common green house gases responsible for global warming. Concrete production has some fundamental negative effects on the environment. It means concrete production not only consumes large amount of natural materials such as limestone and sand, but also producing each ton of PC will make the release of one ton of $CO_2$ into the environment. Therefore these environmental impacts of concrete can play the most important role in the sustainable development of the cement and concrete industry in this century [2].

Sustainable Development (SD) means development which meets the needs of the present without comprising the needs of the future generations [3]. Whereas the limestone is considered as one of the essential constituents to the production of PC, one of the biggest concerns to the sustainability of the cement industry is diminishing amount of limestone in some geographical regions [4]. If limestone is

limited, concrete construction and the occupation related to the concrete industry will be reduced. So this issue made the concrete technologies to focus on reducing the amount of PC application in concrete production by replacing it by some industrials byproducts known as green concrete materials. So, one of the applicable concrete technologies which will especially improve the environmental aspects of concrete by reducing the $CO_2$ emission and the economical aspects by making the high performance concrete is using industrial by-products known as cement replacements.
Concrete industrial byproducts known as cement replacements are measured as the materials that lead to reduction of natural resource application such as limestone for cement production, generate less $CO_2$ and make the concrete more durable, recyclable and environmental friendly product.
The aim of this paper is to investigate on the specifications, production method and the degree of effectiveness of some industrial byproducts such as GGBS, Silica Fume and PFA as the cement replacements in achieving high performance and sustainable concrete which can lead to not only improving the performance of concrete but also mitigating of $ECO_2$ by reducing the amount of PC, and that how they can affect in economical, environmental and social aspects of concrete possitively compared to PC concrete.It also intends to recommend some remedial program to increase the willingness of using these types of industrial by-products.

## II. LITERATURE REVIEW

Concrete is one of the most widely used building materials in roads, buildings and other infrastructures. On average, approximately 1 ton of concrete is produced each year for every human being in the world [5]. Due to this global extensive use, it is necessary to evaluate the environmental impact of this material correctly.
The construction industry has a direct and fundamental impact on world resources, energy consumption, and $CO_2$ emissions. We have to accept that PC is both resource- and energy- intensive material - every tonne of cement requires about 1.5 tonnes of raw material, and about 4000 to 7500 MJ of energy for production [6].
In the 21st century concrete construction, with the aim of causing the least harm to our environment, Fly Ash, slag and Silica Fume, and etc have been considered not only as partial PC replacement, but also as necessary and essential constituents of concrete.
Fly Ash story begins 2000 years ago when the Romans built the Colosseum in the year 100 A.D. At that time, the ash produced from Volcanoes was used widely in the construction of Roman structures [7]. Using fly ash as a pozzolanic material was identified as early as 1914, although the earliest significant study of its use was in 1937 [8]. As pozzolan greatly improves the strength and durability of concrete, the use of ash is a key factor in their preservation. Fly Ash has a successful history of use around the world, for over 80 years. The most prestigious projects of recent times have relied on Fly Ash concrete, including high-rise structures, dams, roads, nuclear power stations, bridges and tunnels [9]. In 1999, Kinuthia did an experimental investigation related to the workability of concrete including combinations of PFA and Metakaolin as PC replacement. Their research aim was to investigate the potential of using PFA and MK as supplementary materials with PC in connection with the flow properties of concrete [10].
The first testing for using silica fume in PC concrete was in 1952 and it wasn't until the early 1970s that concretes containing silica fume was used in some usage [11]. During the carrying out the stricter environmental laws during the mid-1970s, silica fume was collected for the purpose of PC replacement instead of sending it to the landfill. Clearly, the silica fume had been taken into accounts for using in the concrete due to very high strengths and low porosities based on the early work done in Norway. Since then silica fume have been used as one of the world's most valuable and versatile admixtures for concrete production. In 1987, Yogendran tried to alter the properties of concrete regarding its strength by using silica fume. They founded that 15% replacement of cement by silica fume for high strength is optimum amount [12].
GGBS is not a new product. It has already been used worldwide since the mid 1800s. Thirty-eight years after PC invention by John Aspdin in 1842, GGBS was discovered by Emil Langin [13]. One of its first applications in construction industry was for construction of the Paris Metro in 1889. In Britain, yearly about over 2 million tons of GGBS is utilized [13].

The objectives of this paper is to investigate the specifications, production method and the degree of effectiveness of some industrial byproducts such as GGBS, Silica Fume and PFA as the cement replacement in achieving high performance and sustainable concrete and that how they can affect on essential aspects of SD [economical, environmental and social aspects] possitively compared to PC concrete.

## III. CONCRETE

For more than 200 years, concrete has been adopted due to its long durability and reliable nature [4]. Besides the durability, concrete also has high energy performance, flexibility and environmentally friendly specifications. Environmentally friendly specification of concrete can be achieved while protecting the environment [14]. To achieve it, the concrete industry should take recycling industrial by products such as Fly ash, Silica Fume, GGBS and etc into account. By adding these cement replacements in an optimum percentage, the environmental impact will be reduced together with the energy efficiency and durability of concrete [15]. Hence the cement and concrete industries can lead to the sustainable development by innovating and accepting some technologies that can cause minimizing the emissions of the green house gases to the environment.

According to United Nations (UN) in 2007, it was estimated that about 28 billion ton of $CO_2$ were emitted worldwide in 2004. Those included with the manufacture of PC would have a huge impact on sustainable development of concrete industry. Generally because in 2004 cement production caused about 7% of GHGs (mainly $CO_2$) through the world or about 2 billion ton of GHGs [16].

Therefore, since the PC is considered as the main concrete constituent in producing $CO_2$, specified percentage of PC should be replaced by some industrial by-products known as cement replacement to reduce $CO_2$ emission of the concrete and also to improve the sustainable characteristic of concrete.

## IV. SUSTAINABLE DEVELOPMENT

Development (SD) is the development which meets the needs of the present without compromising the needs of future generations [17].

Some purposes of SD can be as following:

- Resource conservation: To conserve the non-renewable resources such as fuel, mineral and etc to ensure sufficient supply for present and future generations.

- Built development: To integrate environmental considerations into planning and development to respect the natural environment.

- Environmental quality: To prevent or reduce processes such as land filling which can lead to environment degradation and develop the culture of reusing and recycling process.

- Social equity: To impede development that increases the gap between the rich and the poor, and to encourage for reach to the social equality.

Inhabitation needs of the sustainability are based on three aspects including environmental, social and economical. At current time, the SD can be achieved through the partial integration of these three aspects. But the alternative face of SD is the full integration of these aspects such that:

- Economic exists entirely within the society as all parts of the human economy are achieved through interaction among people.
- Economy and society merely depend on the environment because if something is un-environmental then the society will be affected.
- When the society affected, then it will be uneconomical for the nation to create sustainable development [18]

Figure 1 and 2 indicate the face of SD at current time and alternative face of SD in the future respectively.

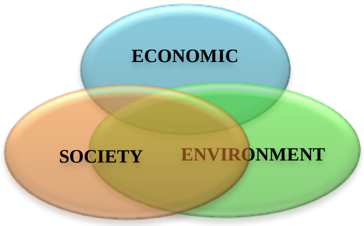


**Fig1.** Face of SD at current time

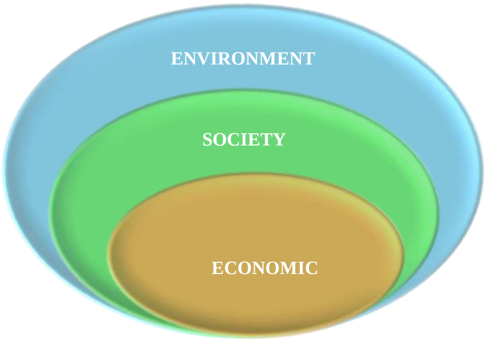


**Figure2.** Alternative face of SD in future

Reusing some industrial by products as the cement replacement in concrete production is considered as sustainable consumption pattern which has a feedback loop after the consumption stage. The pattern will not lead to the waste which means it follows the reusing and recycling process. Figure 3 demonstrates the sustainable consumption pattern. Reusing process in sustainable consumption pattern can save substantial amount of embodied energy which would otherwise be wasted. So using industrial by-products like POFA, PFA, GGBS, Silica Fume, and etc in building construction can have significant impact in saving high embodied energy due to their reusing. This significant reduction in embodied energy can lead to mitigation of global warming; reducing resource consumption such as limestone in cement production and reduction of biodiversity and in the long term consideration can improve built environment and human health

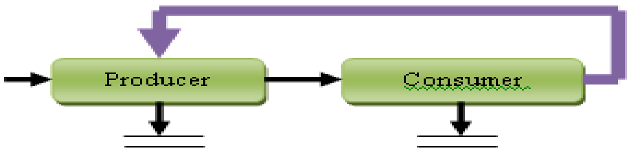


**Figure 3.** Sustainable consumption pattern

## V. Ground Granulated Blast-Furnace Slag

Most GGBS is a by-product from the blast-furnaces used for manufacturing iron. The way of its production is that the blast-furnaces are fed with carefully controlled mixtures of iron-ore, coke and limestone, with temperatures of about 1500$^o$ C. The slag is rapidly put out in volumes of water. The process of putting out improves the cementitious properties and produces granules similar to coarse sand particles.

The 'granulated slag' is become dry and ground to a fine powder that is called GGBS [19]. It has off-white color and a bulk density of 1200 kg/m$^3$.

Table 1 shows the chemical compositions of GGBS produced in UK.

**Table 1:** Chemical compositions of GGBS

| | |
|---|---|
| Calcium oxide (CaO) | 40% |
| Silica ($SiO_2$) | 35% |
| Alumina ($Al_2O_3$) | 16% |
| Magnesia (MgO) | 6% |
| Other- $Fe_2O_3$, etc. | 3% |

### 5.1 Specifications of GGBS

- It is available in large quantities and suitable for use in Ready- Mix concrete and production of large quantities of site batched concrete and in precast product manufacturing.
- GGBS has its own reactive components, e.g. Calcium Oxide arising from burning of limestone in the furnace. GGBS has to be handled very carefully. Solution of GGBS and water is highly alkaline, which can be seriously dangerous for body skin.
- Activation of the GGBS alkalis and sulfates result in GGBS hydration products.
- Some of these GGBS hydration products mix with the Portland cement hydration products to form further hydrates that have pore-blocking effect.

### 5.2. Benefits of Concrete Produced by PC+GGBS

- Energy consumption and CO2 emissions of the concrete can be reduced 43% and 50% respectively by using of blended cement with 60% GGBS in production of concrete of strength class C25/30 [20].
- Chloride resistance of the GGBS concrete is more effective than PC concrete that makes the concrete more high performance and is beneficial for exposed elements such as bridge across buildings, roof car parks, etc.

### 5.3. Comparison between GGBS and PC Concrete

- GGBS concrete has the better workability and can be placed and compacted easier than PC concrete. The term better workability makes the GGBS concrete high performance compared with PC concrete that can lead to the sustainable concrete.
- GGBS concrete has the early-age temperature rise that can lead to reduction of the risk of thermal cracking in large pours.
- GGBS concrete has lower heat of hydration that is preferable in most concrete construction projects.
- The fineness of GGBS particles can effect on the heat of hydration and strength positively
- The durability of concrete is increased by using GGBS with higher resistance to chloride ingress, reducing the risk of reinforcement corrosion, higher resistance to attack by sulfate and other chemicals and defending against damaging from Alkali Silica Reaction. Al of these specifications can cause GGBS as the material to make the concrete more sustainable with high performance.

## VI. PULVERIZED FUEL ASH (PFA)

It is a by-product acquired at power stations, where finely powdered (pulverized) coal is used as fuel, mixed with heated air and burned. It is transported by the exhaust gases and recovered as 'fly ash' with fine particles.

### 6.1. Environmental Benefits of PFA

- One ton of PC production causes the emissions of 0.89 to 1.1 tons of CO2 depending on the type of manufacturing process (average about 1 ton).

- Each ton of PFA can save 900kg of $CO_2$ emission on average when it is used as cementations products [21]. The $CO_2$ emission can be decreased to 680 kg per ton for a common PC+PFA concrete, containing 35% PFA compared with about 1ton per ton for PC-only binder.

## 6.2. Comparison between PC+PFA and PC Concrete

- PFA concrete obtained with good mix design has more chloride resistance, durability and structural performance compared with the common PC concrete.
- In quick construction or manufacturing of precast elements, PFA concrete is not suitable for using in compared with PC concrete due to its slower development of strength.

## 6.3. Level of Replacement

- The amount of replacement of PC with PFA depends on chemical properties of PC and PFA which should be cautiously chosen to achieve the best performance.
- Optimum level of PC replacement is ordinarily 35% for usually used PC in order to achieve a balance between the strength development and chloride resistance of the concrete.
- For higher amount of PFA in concrete, special mix design is needed in order to obtain good workability of green concrete, durability and structural performance. Table 2 indicates the comparison of PFA and PC concrete in general.

**Table 2:** comparison of PFA and PC concrete

| **Properties** | PFA Concrete vs. PC Concrete |
|---|---|
| **Workability** | Increased for the same w/c ratio |
| **Setting time** | Increased |
| **Bleeding** | Reduced in most cases |
| **Plastic Shrinkage** | Increased ( Early curing could prevent cracking |
| **Early age Strength** | Reduced for equal binder content |
| **Long Term Strength** | 30-50% greater than at 28 days |
| **Formwork striking time** | Increased for equal binder content |
| **Carbonation Resistance** | Similar to PC concrete |
| **Resistance to Chloride attack** | Much better than PC concrete |
| **Resistance to sulfate attack** | Better than PC concrete |
| **Resistance to freeze-thaw & abrasion** | Little less at early stage |

In concrete mixture, pores can be filled with filler instead of unhydrated cement. So this action can lead *to* the enhancement in durability and avoidance of cement wastage in concrete with PC+PFA.

## 6.4. Disadvantages of PFA

Some disadvantages of PFA are as follows:

- Fly ash with poor quality can have negative impacts on concrete lead to increasing permeability.
- Although slowly setting time of concrete by using fly ash can be considered as a disadvantage of fly ash, but it can actually be a benefit by reducing thermal stress.
- By using the fly ash in concrete, freeze-thaw durability may not be acceptable.

# VII. SILICA FUME

Silica fume is an industrial by-product obtained from producing silicon metal or ferrosilicon alloys. It is a very reactive material, including higher percentage of Silicon Dioxide in comparison with PFA (40%) and PC (20%) [22].

Its microstructure is dense and homogeneous, since the silica fume concrete has less CA $(OH_2)$ crystals in the hydration in compared with PC concrete. Therefore it has very high strength and durability which lead to the high performance concrete.
Silica fume is very fine and dusty, and it contains small amount of crystalline quartz. So, placing and curing the silica fume concrete needs special attention to safety.
Generally, the use of Silica Fume provides the most positive Sustainability impact of all the Supplementary Cementitious Materials (SCM). Silica Fume by a small volume SCM is requiring minimal production and transportation efficiencies. It has also a fundamental effect on extending the life cycle of concrete by reducing the concrete footprint. By long service life, durability and the potential to stand up to disastrous events, silica fume concrete can improve the sustainability matter in concrete industry which also leads to the high performance concrete (HPC). It has been identified as one of the most important advanced materials needed in the effort to rebuild the nations' infrastructures. HPC produced with silica fume has increased strength, durability, toughness, resistance to abrasion, corrosion and chemicals; and life cycle cost efficiencies.
According to the EPA report to Congress EPA, the kg $CO_2$ emissions per metric ton of Silica Fume was estimated about 14 kg which is very low compared with GGBS, PC and Fly ash [23]. Also the compressive strength efficiency ratio of silica fume concrete at 28 days is about 300%.
Silica Fume applications include:
Concrete, Cementitous Repair Products, Concrete Tile & Panels, FCB, Concrete Roofing & Wallboards, Shotcrete, Oil Well Grouting, Polymers & Elastomers, Repair Products and Refactory & Ceramics.

## VIII. COMPARISON BETWEEN GGBS, PFA AND SILICA FUME

Following data were derived from Environmental Protection Agency (EPA) [23]. It compares three Supplementary Cementitious Materials (SCM) or Recovered Mineral Components (RMC) including Silica Fume, PFA and GGBS together and also Portland Cement (PC) in terms of their environmental impacts ($CO_2$ emission and energy savings) and compressive strength.

**Table 3:** Comparison between PC, GGBS, PFA and Silica Fume

| [SCM / RMC] Recovered Mineral Component | CO2 emissions - kg per metric ton | Compressive strength efficiency ratio @ 28 days | Avoided CO2 emissions per pound substituting for cement | Energy Savings per pound substituting for cement |
|---|---|---|---|---|
| (Portlad Cement) | 959 | 100% | --- | --- |
| Slag (GGBF) | 155 | 90% | 0.60 lb | $ 0.05 |
| PFA class F | 93 | 65% | 0.97 lb | $ 0.08 |
| Silica Fume | 14 | 300% | 2.10 lb | $ 1.23 |

## IX. RESULT AND DISCUSSION

As I mentioned before, conventional concrete causes release of substantial amount of $CO_2$ through cement production. So, this kind of environmental issues of concrete makes construction industry obligated to use green concrete by adding some cementitious materials to mitigate them. Using Industrial byproducts instead of cement in concrete can be so effective to mitigate the disadvantageous impacts of cement production.
In this study various supplementory materials such as GGBS, PFA and Silica Fume have been investigated. Although all these materials are beneficial and can have effective impacts on increasing the strength and durability of concrete, and reducing the environmental impacts of concrete, their effectivenesses are different with each other. It means using optimum of one cementitious material can lead to concrete with higher strength or lead to reducing more $CO_2$ compared to other ones. So the role of some of them in achieving sustainable development (SD) is more significant than the

others. Figures 3 indicates how cement replacements affect positively on environmental, social and economical aspects of each scoiety which can help in achieving SD.

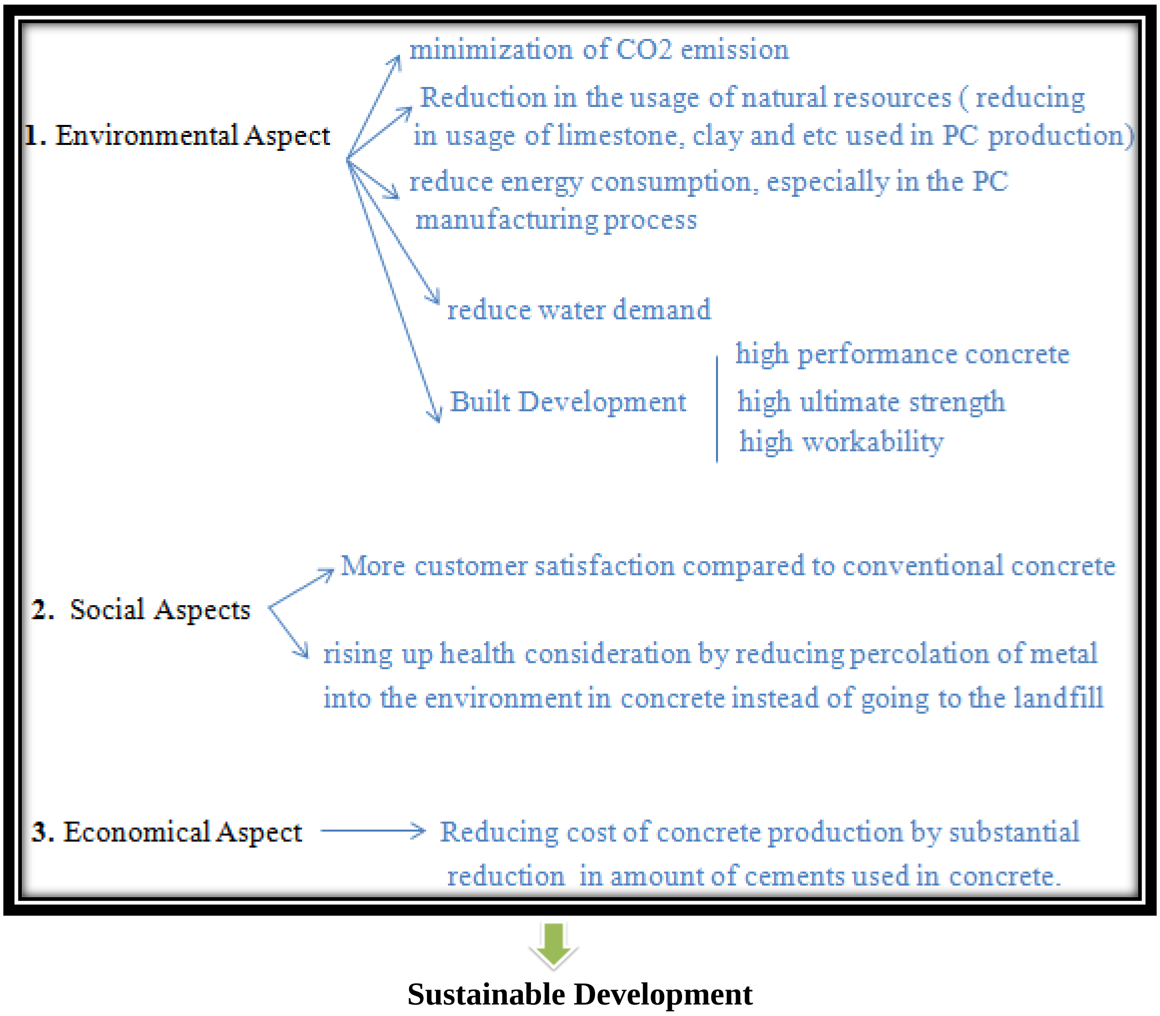


**Figure 3:** The effects of various cement replacements on environmental, social and economical aspects

Some of cement replacements may be more efficient in some aspects compared to others. For example, regarding minimization of $CO_2$ emission in concrete production and built development in achieving high performance concrete from environmental aspect, silica fume may be considered as a most efficient materials leads to 14 kg/ton $CO_2$ and 300% compressive strength compared with PC. Economical asspect of these by-products depends on their availability in the society and that how much their cost to be produced. So various cement replacement may have various impacts in different regions, situations and amounts.
Therefore, investigation and determining the optimum usage of these cementitious materials in concrete production by implementing different kinds of laboratory tests will lead to higher sustainable and performance concrete in the future.

## X. Conclusion and Recommendations

However these types of cement replacements have been used in concrete industry since many years ago but nowadays in many countries especially third world countries, conventional concrete is still used which can cause natural resource depletion and also huge emission to the air. So, this behavior in the long term period can lead to ozone depletion and have dangerous impacts on human health. The main issue of these cement replacement is their availability in the region and the way of their production which may cause higher cost for concrete production.

Beside unavailability, lack of knowledge and information, unskilled worker, irresponsibility and poor legal legislations can be also the reasons of not willing of using these kinds of cement replacements.
Due to environmental legislations, cost of disposal is high. Recycling of material not only saves the cost of disposal, but also helps to preserve natural resources. Accordingly, high optimum cementitious materials suggest a solution to the problem of enhancing the demand of concrete in future in a sustainable way and reduce environmental impacts and comply with a cost effectiveness and ecological behavior. The key principle of sustainable development is the long-term strategies to tackle the key environmental issues including climate change, improving air quality, regenerating towns and cities, and protecting the countryside and natural resources which should be contained in a continuous improvement programs.
So passing strict legislation regarding concrete production, improving the knowledge about the method implemented for using cement replacements, non-conformance penalties, training and education of concrete producer, designer and workers, and making them available by government for engineers and customer can be beneficial to be focused in the future plan of concrete industry in making more sustainable and high performance concrete.

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