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Assessment of the Combined Effect of Silica Fume, Fly Ash, and Steel Slag on the Mechanical Behavior of Concrete

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Abstract: Every ton of cement produced emits half a ton of carbon dioxide, so there is an immediate need to limit cement use. Cementitious materials such as fly ash, silica fume, and steel slag can be substituted for cement in making concrete more rigid and stronger. This research work has been done to analyze the change in compressive strength in concrete, reducing the use of cement and coarse aggregate, in the case of varying percentages of cement replacement circumstances. To get this job done, there's been conducted a variety of laboratory tests changing the partial cement replacement proportions with silica fume and fly ash and partial aggregate replacement with steel slag in the concrete mix. The test result showed that 15% silica fume, 10% fly ash, and 30% steel slag replacing proportion withstand more compressive load than the normal cement concrete mixture. The SEM test also supports the compressive strength test result by showing the internal bonding between the materials in the replaced binder-aggregate specimens. On the other hand, the flexural strength test came out with the best proportion of 15% cement replacement with fly ash and silica fume along with 10% coarse aggregate replacement with steel slag. The XRD patterns of the materials used also enumerate the standardization and testing procedures. The usage of sustainable cementitious materials like fly ash, silica fume, and steel slag incorporates the motivation behind reducing the industrial byproducts/wastes generated in such an amount that hampers our mother nature. The overall representation of this research will emancipate the initiatives taken toward greener and more sustainable construction.
Keywords: Concrete binder; Fly ash; Silica fume; Steel slag; Sustainability.

1. Introduction

The building and construction industry is a significant actor that helps to satisfy the demands of houses, hospitals, and educational establishments, among other advancements. However, it also consumes a lot of raw materials and natural resources. Construction of buildings and building operations have significant direct and indirect negative environmental effects [1]. Without taking into account water, concrete may be regarded as the world's most popular building material. The most important component of concrete is cement. It is made using a dynamic process that involves high-temperature treatment and releases around half a ton of CO_2 for every ton of cement [2]. Researchers have been looking at ways to use industrial by-products as supplementary cementitious materials (SCMs), which can take the place of some of the cement, to lessen the environmental effect of the manufacturing of concrete in recent years. To reduce carbon emissions through the production of these construction materials, a ground-breaking drastic movement needs to be drawn in the process and construction phases. The manufacture and use of cement and concrete, excluding carbon capture and storage (CCS), are two major sectors where very significant incremental reductions in global CO_2 emissions may be achieved [3].

1) As the partial replacement of Portland cement clinker, the use of low-carbon supplementary cementitious materials should be increased by a significant amount.

2) The mortars and concretes are to be mixed with an efficient proportion of Portland cement.

For the partial replacement of cement and to reduce CO_2 emission in the construction sector, we introduced here the replacement agent fly ash and silica fume with cementitious properties to culminate the concrete in one place acting as the sustainable binder. Among the various SCMs, silica fume, fly ash, and steel slag have shown great potential due to their pozzolanic and/or hydraulic properties. Silica fume is a by-product of the production of silicon and ferrosilicon alloys, while fly ash is a by-product of coal combustion in thermal power plants, and steel slag is a by-product of the steel manufacturing process. Fly ash is used in the production of cement, bricks, paving materials, floor tiles, and wall panels, and also in agriculture, and road construction. Depending on how much CaO it contains, fly ash is either classified as Class C or Class F ash. Around 600 million tons of coal ash are produced annually in the globe now, with fly ash making up around 500 million tons, or 75–80 percent, of this total. Currently, ash is used in various ways across the globe, ranging from 3% to 57%, but the average global use of ash only accounts for 16% of the total ash [4-6]. This silica fume is used to make additional silicon alloys, including calcium silicon, ferromagnesium, and ferromanganese (ACI 226-3R-87) [7]. The annual global consumption of silica fume surpasses 1 million tonnes [8-10]. The majority of steel slag is highly concentrated in Fe1-O and other metal oxides. It has good electrical conductivity characteristics as a result. It can be used as aggregate in concrete in place of natural particles [11]. These compounds can be used in concrete to increase its mechanical qualities while also lowering the quantity of cement required. The incorporation of steel slag is also present here to partially replace the coarse aggregate in the concrete mixes.

Despite the growing interest in SCMs, more research is needed to determine how using silica fume, fly ash, and steel slag together may affect the mechanical behavior of concrete. Evaluating the combined impact of silica fume, fly ash, and steel slag on the mechanical behavior of concrete is the primary goal of this study article. The goal of the study is to determine the ideal ratios of these SCMs to produce concrete with the appropriate mechanical qualities while using less cement and having a smaller environmental effect.

Several earlier studies examined the use of specific SCMs in concrete, including fly ash, silica fume, and steel slag. The partial substitution of cement with 30% fly ash and 6% silica fume in 2021 was demonstrated by G.V.V. Raj Kishore in his studies, and it resulted in much greater strength than the other sample specimens he studied [12]. Rutwij Shah, on the other hand, calculated the substitution of coarse aggregate with industrial by-product steel slag in M30 grade concrete with a range of 40–60% partial replacement for greater compressive strength in 2021 [13]. In the work of Aditya Pathak, he deduced the pertinent proportion of silica fume and fly ash for the partial replacement of cement binder [14]. In the partial replacement of cement binder with steel slag, Maria Dolores Rubio-Cintas showed that the shrinkage of concrete is also dependent on the amount of steel slag usage [1]. Burhan Uzbas have shown the microstructural bonding between silica fume and cement particle to obtain the optimum level of strength compared to normal cement concrete and thus deliver a sustainable solution from the waste management perspective also [15]. In 2018, Farhat Abubakar et.al. has done an extensive experiment on the substitution of cement with fly ash in concrete. The findings demonstrated that the inclusion of fly ash increased the workability and decreased the water need for concrete mixes. Concrete's compressive strength rose with fly ash concentration up to a 20 percent level before beginning to decline at that point. The concrete's splitting tensile strength and flexural strength both followed a similar pattern [16]. In 2019, Xiaobao Luo et al. investigated the combined influence of silica fume and steel slag on the mechanical behavior of concrete. Their findings revealed that the addition of silica fume enhanced the concrete's brittleness, compressive strength, and compressive strength discreteness. Powered steel slag, on the other hand, lowered the compressive strength of concrete by 10% when the concentration of steel slag was less than 20% [17]. Incorporating silica fume and using various kinds of steel fiber reinforcements, Mehmet Gesoglu et al. discover, a significant change in the mechanical characteristics of the concretes independent of the w/b ratio [18]. In 2022, Mavoori Hitesh Kumar et.al. has done a rigorous experiment with a triple blend of fly ash, silica fume and steel fibre in concrete to see the upheaval changes in the mechanical properties of concrete. And their reported results showed that an optimum mix of 15% fly ash, 12% silica fume, and 1% inclusion of steel fibers achieved higher compressive strength by a 5.89% rise with improved workability results and showed a remarkable performance in terms of flexural and split tensile strength with an increment of 20.40% and 28.02% respectively [19].

Upon previous research data and to our knowledge, no prior studies have looked at the combined impact of all three SCMs noted as fly ash, silica fume, and steel slag, on the mechanical behavior of concrete, though. Especially, steel slag is added to the concrete mixtures to replace some of the coarse aggregates which is the utmost unique exposition.

Another important aspect of the above-mentioned concrete work has been studied in our work which focuses on the flexural strength behavior. The ANOVA table indicates that the water/cementitious ratio and silica fume concentration are important factors in CP's early flexural strength. Additionally, it was discovered that the ideal circumstances were a 0.35 water/cementitious ratio, a gradation with a low percentage of fine aggregates, a 5% FA content, and a 0% silica fume content at 7 days of curing. At the ideal conditions, the maximum flexural strength of 5.31 MPa was attained [20]. Under high temperatures and during flexure, the fly ash concrete consistently exhibited the same pattern of behavior as the concrete without fly ash. In comparison to specimens without fly ash, fly ash concrete that contained up to 20% fly ash performed better because it retained more of its strength [21].

The whole paper is arranged in several parts. The materials used for the lab tests and the methods we followed for conducting our work are discussed in the materials and methods section. The attained outcomes of our works are discussed in the results and discussion section. And finally, a conclusion has been drawn based on our outcomes.

2. Materials and methods

The cementitious materials we used here to develop a sustainable solution to waste management and environmental pollution issues. The materials used for binder replacement are fly ash and silica fume while the steel slag is partially replaced with the coarse aggregate in a controlled proportion. In our work, twelve (12) concrete mixtures were prepared in a cube molding formation, with a reference mixture without cement replacement and eleven (11) other types of specimens in which various proportions of mix design were applied. The following table 1 shows the physical and chemical properties of the materials attained through various lab tests:

Table 1. Materials' chemical composition, density, and specific surface area [22-24]

Materials	Chemical Composition						Density	Specific Surface Area
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	ΣOthers		
	%	%	%	%	%	%	gr/cm^3	cm^2/gr
CEM	20-22	4-8	4-6	55-60	2-3	2-15	3.01	>2800
GGBFS	32-36	11-12	0-2	40-42	7-8	1-10	2.91	4500-4700
Silica Fume	92-96	1-3	0-1	0-1	0-1	1-3	2.22	6500
Fly Ash	61-65	30-34	0-2	0-2	0-1	1-6	2.40	3500-4000

In table 2 below, the percentage of materials in the concrete mix is shown.

Table 2. Percentage of materials in concrete mix

Specimen No.	Binder (100%)			Fine Aggregate (100%)	Coarse Aggregate (100%)	
	Cement (%)	Silica Fume (%)	Fly Ash (%)	Sand (%)	Stone Chips (%)	Steel Slag (%)
SP-1	100	-	-	100	100	-
SP-2	85	5	10	100	90	10
SP-3	80	5	15	100	80	20
SP-4	75	5	20	100	70	30
SP-5	80	10	10	100	90	10
SP-6	75	15	10	100	90	10
SP-7	80	10	10	100	80	20
SP-8	80	10	10	100	70	30
SP-9	80	5	15	100	90	10
SP-10	75	5	20	100	80	20
SP-11	75	15	10	100	80	20
SP-12	75	15	10	100	70	30

The cement used in our work is Ordinary Portland Cement (OPC) for its long-term strength-gaining property. The steel slag is used as ground granulated blast furnace slag (GGBFS) which is the industrial by-product during the manufacturing of steel. The fly ash was obtained from a local coal plant. The selected percentages we used for cement replacement by silica fume and fly ash and coarse aggregate replacement with steel slag were defined based on the results obtained by Golweski & Charan [25-26]. The mixtures were prepared using the following materials:

1) Cement: Ordinary Portland Cement
2) Steel Slag: Ground granulated blast furnace slag, particle size <5mm provided by the company.
3) Silica Fume: Dark grey almost sand-type silica fume obtained from local plant
4) Fly Ash: Class F fly ash obtained from a local coal plant
5) Aggregate: Black stone, medium-sized sand, and gravel
6) Water: Tap water

The following figure 1 shows the materials used for work:

Fig. 1. Used materials for the preparation of the specimens (from left: cement, silica fume, fly ash, steel slag, sand, stone chips)

The following table 3 shows the amount of each material in a specimen.

Table 3. Proportions of materials in concrete mix

Specimen No.	CEM kg/m^3	Steel Slag kg/m^3	Fly Ash kg/m^3	Silica Fume kg/m^3	Sand kg/m^3	Stone Chips kg/m^3	Water kg/m^3	W/B Ratio
SP-1	317	-	-	-	698	1396	190	0.60
SP-2	269.45	139.6	31.7	15.85	698	1256.4	190	0.60
SP-3	253.6	279.2	47.55	15.85	698	1116.8	190	0.60
SP-4	237.75	418.8	63.4	15.85	698	977.2	190	0.60
SP-5	253.6	139.6	31.7	31.7	698	1256.4	190	0.60
SP-6	237.75	139.6	31.7	47.55	698	1256.4	190	0.60
SP-7	253.6	279.2	31.7	31.7	698	1116.8	190	0.60
SP-8	253.6	418.8	31.7	31.7	698	977.2	190	0.60
SP-9	253.6	139.6	47.55	15.85	698	1256.4	190	0.60
SP-10	237.75	279.2	63.4	15.85	698	1116.8	190	0.60
SP-11	237.75	279.2	31.7	47.55	698	1116.8	190	0.60
SP-12	237.75	418.8	31.7	47.55	698	977.2	190	0.60

150cm x 150cm x 150cm test specimens were prepared in an ambient setting with a relative humidity of 80% $\pm$ 5 and a room temperature of 24 $\pm$ 2 degrees Celsius. Prior to the compressive strength test, it was decided to adopt cube molding since it offers a noticeably higher strength than cylinder molding. However, the combination proportions and the aggregates utilized in this research were different from the proportions mentioned in the studies [12-14,25-27]. Aitcin advises beginning the shrinkage measurement as soon as possible because if not, the measurement could overestimate the actual shrinkage [28]. At first, all the materials were collected, completed some property tests, and classified by sieving. Then the mix proportions were calculated and the materials got mixed up with the designated proportions in the cube mold after the cube casting was done, the molds were laid aside. After the prescribed time the removal of molds took place after 24 hours after mixing. After the demolding process, the specimens were immersed in the water bath for the curing process. In every instance of testing, the cube was sundried first and then over-dried for releasing every last water content from the specimen. And then on the test day, the specimens were picked out from the water bath and laid down for the drying process, and weighed accordingly. After drying, the specimens were tested under point loading in UTM (Universal Testing Machine) at 35 kN/min under the code of ASTM C39.

3. Results and discussions

The following table 4 shows the compressive strength gained at various times over 7,14 & 28 days.

The following figure 2 shows the compressive strength achieved in 7 days, 14 days, and 28 days in the graph.

A compressive strength test of the specimens was performed by the Universal Testing Machine (UTM) at the loading of 35 kN/minute range. Table 4 shows the compressive strength of fly ash, silica fume, and steel slag replaced cement and coarse aggregate for 7, 14, and 28 days of curing respectively. From the table, it is found that the highest strength can be found for 25% of replaced cement. Beyond replacement, the compressive strength has declined from its peak value of 21.12 to 17.38 MPa in 28 days of curing. Fly ash was added, which caused a reduction in compressive strength. This was countered by the addition of silica fume, which continued the strength development in both the early and later phases of hydration. Both fly ash and silica fume served as fillers and increased the structure's strength over time.

Based on the above results obtained from the compressive strength test of the cube-sized specimens we’ve selected the best of three result-giving specimens for conducting the flexural strength test. Considering the standard specimen with no replacement of supplementary cementitious materials, the other three best results-giving specimens are listed in Table 5.

Table 4. Compressive strength values

Specimen No.	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)
SP-1	12.03	17.39	19.63
SP-2	12.06	18.25	20.89
SP-3	10.32	15.37	18.45
SP-4	11.44	14.74	17.66
SP-5	10.83	14.36	17.59
SP-6	12.58	17.58	19.97
SP-7	11.19	15.24	17.38
SP-8	12.09	16.22	19.05
SP-9	11.56	16.94	18.86
SP-10	11.88	16.07	19.27
SP-11	12.19	18.39	20.76
SP-12	12.73	17.62	21.12

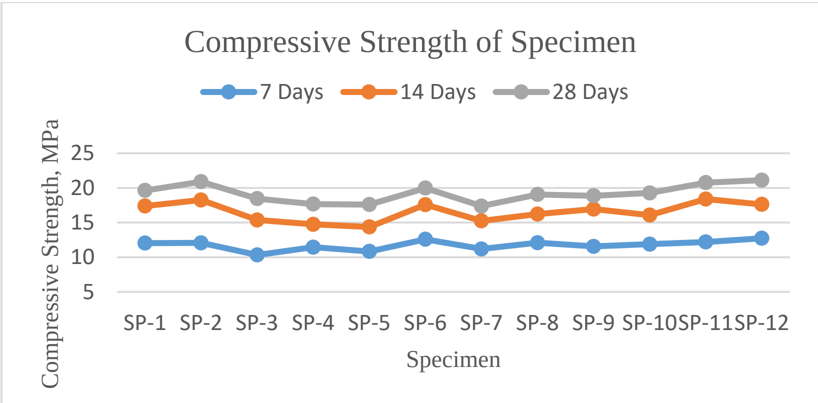

Fig. 2. Compressive Strength of the Specimens

Table 5. Percentage of materials in concrete mix for flexural strength test

Specimen No.	Binder (100%)			Fine Aggregate (100%)	Coarse Aggregate (100%)	
	Cement (%)	Silica Fume (%)	Fly Ash (%)	Sand (%)	Stone Chips (%)	Steel Slag (%)
SP-1	100	-	-	100	100	-
SP-2	85	5	10	100	90	10
SP-11	75	15	10	100	80	20
SP-12	75	15	10	100	70	30

Table 6. Flexural strength values

Specimen No.	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)
SP-1	1.37	2.53	2.86
SP-2	1.63	2.97	3.07
SP-11	1.21	2.59	2.74
SP-12	1.28	1.91	2.18

Figure 3 shows the flexural strength of the specimen achieved after 7 days, 14 days, and 28 days in the graph.

The Automatic Flexure Testing Machine (UTM) tested the specimens' flexural strength at loading rates between 35 kN/minute. Table 6 demonstrates the flexural strength of fly ash, silica fume, and steel slag replacement concretes for 7, 14, and 28 days of curing accordingly. The maximum strength may be obtained for cement with 15% replacement, and 10% replacement of coarse aggregate according to the table. In 28 days of curing, the flexural strength decreased beyond replacement, from a high of 3.07 MPa to 2.18 MPa. The strength fluctuation relative to compressive strength is within a conventional range of 7–16%.

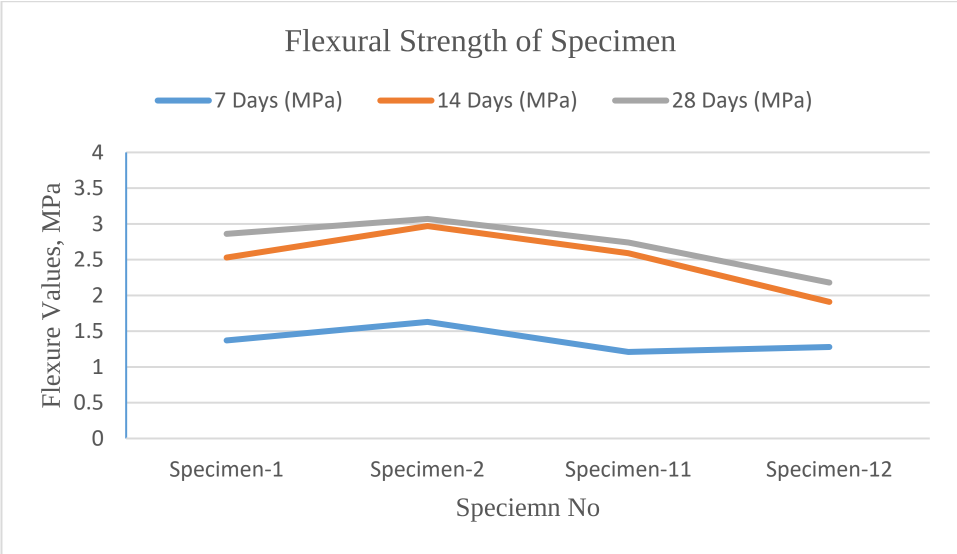

Fig. 3. Flexural strengths of the specimens

According to the experimental findings, employing fly ash merely reduces, and silica fume only marginally improves 28-day flexural strength. However, combining silica fume with fly ash results in a considerably greater increase in strength. Among all those tested, maximum 28 days flexural strength of 4.53 MPa is obtained for the mix proportions of 85 percent OPC + 10 percent fly ash and 5 percent silica fume. Compared to the data from the literature it is evident that the data we gained from our laboratory experiment is satisfying.

From table 4 we can see the maximum value we get from specimen 12 in the 28 days course of time. The 25% binder replacement with 30% coarse aggregate replacement proved the most efficient proportion to get our primary motive. From table 6 it is also seen that specimen-2 for flexural strength purposes gives the best results from the 15% binder replacement along with 10% coarse aggregate replacement. Fly ash was added, which caused a reduction in compressive strength. This was countered by the addition of silica fume, which continued the strength development in both the early and later phases of hydration. Silica fume and fly ash were both used as fillers and led to the development of strength during the course of its presence [12]. Strength is increased as a result of the presence of silica fume brought on by the pozzolanic reaction between calcium hydroxide in the cement paste and the formation of calcium silicate hydroxide gel. Concrete's microstructure and mechanical strength can both be enhanced by silica fume. By filling up gaps in the cement paste and reacting with the calcium hydrates, ultrafine silica fume particles enhance the concrete's physical and chemical qualities and its ability to compress [27,29-31]. Because the particle size of the silica fume is smaller than that of cement, increasing the pozzolanic interaction between the SiO_2 in the cement results in an increase in compressive strength with increasing silica fume concentration up to 10% $Ca(OH)_2$ produced during the hydration process and silica fume [15]. To support this statement the materials were tested by scanning electron microscope for a better understanding of the interlocking bond between the supplementary cementitious materials used in the concrete.

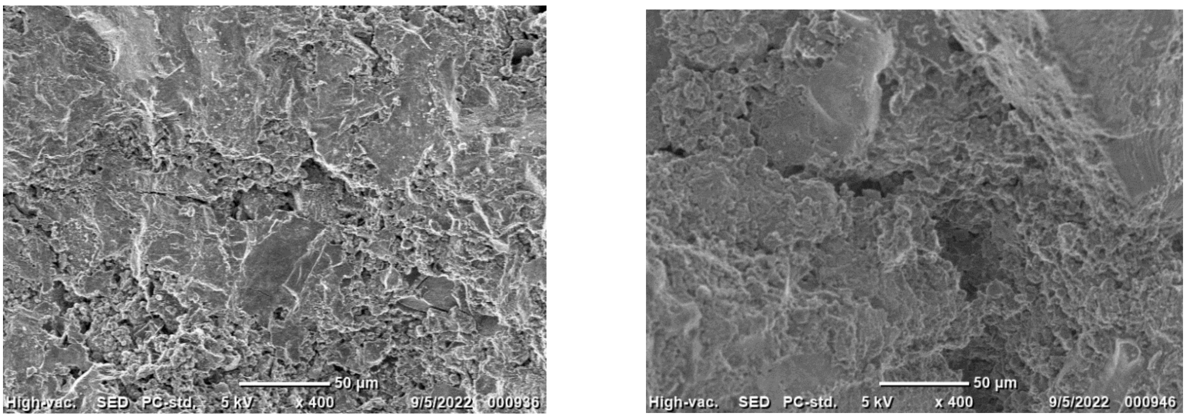

Fig. 4. SEM Analysis of Specimen-11 & Specimen-1

From the above figure, it is evident that the interlocking bond between the supplementary cementitious materials and cement-aggregate mixture develops significantly in specimen-11 with respect to reference normal concrete specimen-1. The increase in strength comes from this bondage which tends to rigidity and helps to solidify the concrete in terms of more compressive strength. The voids shown in the concrete mixture in Figure 4 specimen-1 were filled up with supplementary cementitious materials which are also shown in Figure 4 specimen-11. And thus, this rigid kind of formation of the concrete withstands more strength in lieu of reference specimen with no usage of supplementary cementitious materials.

4. Conclusion

The work presented is dedicated to the evaluation of the influence of silica fume, fly ash, and steel slag type on the behavior of concrete in due course of time. For comparison purposes, a reference specimen of normal cement concrete along with other specimens containing partial replacement of cement with silica fume and fly ash and coarse aggregate replacement with GGBFS were prepared. The results show that the early stage curing process has significantly raised the compressive strength in the normal cement concrete specimen but in the later stage for example at 14 & 28 days result the designated specimen-12 which contains 25% binder replacement additives and 30% coarse aggregate replacement additive, shows around 10% increase in compressive strength compared to the specimen-1 which is normal cement concrete. It is noted that the increasing pattern of compressive strength in the later stage of curing occurred due to the additives mixed with the cement concrete but the long-term serviceability characteristics could be a matter of question to future researchers in this field. Later the best-giving compressive strength test results were selected for flexural strength test results and the obtained results showed that significant increase in flexural strength of specimen 2 with 15% cement replacement condition along with 10% coarse aggregate replacement. Though the concrete behavior of higher attainment in compressive strength resulted in the microstructure bonding between the silica fume and fly ash particles. The scanning electron microscope also deduced the interconnecting bonding between the concrete materials and thus gives more rigidity and stability. When mixing cement, fly ash and silica fume can produce pozzolanic activity. This capability opens the door for the cement industry to utilize waste materials like fly ash and silica fume. This method for replacing cement might be a tremendous step toward a sustainable response to the issues of air pollution.

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