Alternatives to Cement in Concrete – A Review

Atishay Lahri, Dr. Savita Dixit

Abstract— In the present world, concrete has become a vital part of our lives. With each passing day, the use of concrete is increasing at a very high rate. One of the main constituents of concrete is Portland cement. With the increase in use of concrete, the manufacturing and consumption of cement has increased drastically. Although cement has exceptional binding properties and is very suitable for use in concrete, the manufacturing of cement results in emission of large amounts of CO_2. Due to this, researchers have started finding alternatives to cement that are economical as well as environment friendly. Fly ash, Silica Fume, Metakaolin and Ground granulated blast furnace slag are industrial by-products which provide excellent binding properties to concrete and serve as a replacement of cement. These alternatives are generally termed as Supplementary cementitious materials (SCMs). The use of these materials not only helps in reducing the consumption of cement but also serves as an efficient method for their safe disposal. This paper reviews the effect of using the various alternatives that can be used in concrete as partial replacement of cement. The literature review of various researchers reveals that a single alternative cannot provide all the benefits that cement does. Rather, a suitable combination of these products can be incorporated in concrete to provide properties similar to or better than that of Portland cement concrete.

Index Terms—Cement, Concrete, Fly Ash, GGBS, Industrial by-products, Metakaolin, Silica Fume, Supplementary cementitious materials

1 Introduction

Concrete is a composite material formed by bonding together aggregates and fluid cement which hardens over time. The most commonly used concrete today is the Portland Cement Concrete. One of the main constituents of concrete is cement which is harming the environment at an alarming rate. It is estimated that about 0.9 tons of carbon dioxide is released in the environment for the production of 1 ton of cement. Carbon dioxide comes in the category of green house gas and is largely responsible for global warming [1]. This prompts us to study the various alternatives to cement to make the concrete environment friendly. The concept of using eco friendly materials in place of hazardous material in concrete is called green concrete. Green concrete makes use of various industrial by-products like fly ash, silica fume, metakaolin, GGBS etc. These by-products are harmful for the environment and hence their use in concrete not only helps in safe disposal of such waste products but also helps in reducing cement production which is yet another environmental concern. In this paper, a review of work done by various researchers on alternatives to cement is done. Finally, a comparative study of various materials used as a substitute or partial replacement of cement has been done.

2 Cement

Cement is a fine grey powdery substance made by burning a mixture of clay and lime that sets hard when it is mixed with water. It is used with water and sand to make mortar or mixed with sand, aggregate and water to form concrete. The manufacturing of cement involves crushing, milling and proportioning of lime, silica, alumina, iron and gypsum. Cement is a binder material, that is, a substance that helps in binding together different materials. This property makes it an excellent constituent of concrete. The most common type of cement used in the construction industry is the Portland cement. The chemical composition and physical properties of Portland cement are given in Table 1.

3 Literature Review

3.1 Fly Ash

Fly ash is one of the residues generated by coal combustion, and is composed of the fine particles that are driven out of the boiler with the flue gases. Fly ash is used in Portland cement concrete to improve the performance of the concrete. The Free state calcium oxide released during hydration of cement reacts with fly ash silicates to form strong and durable cementing compounds and helps in improving the properties of concrete [2].

Wankhede and Fulari [3] studied the effects of fly ash on the properties of concrete and concluded that with 10 % and 20% replacement of cement with fly ash, the compressive strength was increased whereas for 30 % replacement, the compressive strength was decreased. It was also observed that the slump loss of concrete kept on increasing with the increase of quantity of fly ash.

Patil et al [4] investigates the compressive strengths of concrete with partial replacement of cement with fly ash. The cement is replaced with fly ash from 5% to 25% by an increment of 5%. The rate of compressive strength development is maximum at 60 days for concrete with no replacement of cement with fly ash. Concrete with 5% fly ash has maximum rate of compressive strength development up to the age of 21 days and then the rate decreases. It is observed that 10% fly ash addition gives the maximum strength at 90 days. Thus, for concrete with partial replacement of cement with fly ash, the initial rate of strength development is less but ultimately the required maximum strength is achieved.

Sigrun Kjær Bremseth [5] discussed the various advantages and disadvantages of using fly ash in concrete. The most important advantage of fly ash concrete is the ability to resist alkali aggregate reaction whereas the greatest disadvantage of using Fly ash in concrete is Air entraining and lower rate of

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strength gain.

Bargaheiser and Butalia [6], reviewed the advantages of using high-volume fly ash concrete to resist corrosion damage in structures. Carbon dioxide and chloride penetrating the concrete are main reasons for corrosion of concrete. Use of Fly ash in concrete helps in reducing Carbon dioxide emission, provides sustainable design and longer service life of its infrastructure, slows down the ingress of moisture, oxygen, chlorides, Carbon Dioxide and aggressive chemicals in the concrete and prevents the deleterious effect of corrosion in reinforced concrete structures.

Soni and Saini [7] determined the compressive strength, split tensile strength and modulus of elasticity of fly ash concrete at 80˚C, 100˚C, and 120˚C. The percentage of fly ash was taken as 30, 40 and 50% by weight of cement. It was observed that for concrete having cement replacement up to 30%, the compressive strength, split tensile strength and modulus of elasticity was comparable to the concrete without fly ash where as for cement replacement of more than 30%, these values were lower than the concrete with no cement replacement. The compressive strength of fly ash concrete decreased at 120˚C as compare to room temperature.

Fig. 1 - Fly Ash

3.2 Silica Fume

Silica fume is an amorphous polymorph of silicon dioxide, silica. It is collected as a byproduct of producing silicon metal or ferrosilicon alloys. One of the unique properties of silica fume is its high surface area. It is a very good pozzolanic material and hence finds its use in high performance concrete. Concrete containing silica fume can have very high strength and can be very durable. Silica fume is often added to the concrete as admixtures or partial replacement of cement.

Ghutke and Bhandari [8] determined the optimum replacement percentages of cement with silica fume which can be suitably used under the Indian conditions. It is observed that the optimum replacement percentage varies between 10 to 15% because after 15%, the compressive strength decreases. Further investigation reveals that workability of concrete decreases with the increase in percentage of silica fume.

Roy and Sil [9] did a study on the nature of Silica Fume and observed how it affected the properties of fresh and hardened concrete. Properties like ultimate compressive strength, Flexural strength, splitting tensile strength are determined for various mix combinations of silica fume and then compared with the conventional concrete. It is concluded that silica fume helps in achieving lower water-cement ration and better hydration of cement particles. 10% replacement of cement with silica fume gave the maximum compressive strength and also gave significant increase in tensile and flexural strength. Silica Fume can also be used in construction places where chemical attack, frost action etc are common. High early strength is achieved in silica fume concrete.

Srivastava et al [10] reviewed the effects of silica fume in concrete and came to the conclusion that adding silica fume increases the compressive strength and bond strength of concrete. The tensile strength, flexural strength and modulus of elasticity of silica fume concrete are comparable to that of Portland cement concrete.

Amudhavalli and Mathew [11] performed a detailed experimental study on M35 grade concrete, partially replacing cement by silica fume by 0, 5, 10, 15 and 20%. The consistency of cement increases upon addition of silica fume to the concrete. The increase in flexural strength was observed upto 15% replacement of cement by silica fume. The gain in split tensile strength was significant upto 10 % silica fume. The optimum compressive and flexural strength was obtained in the range of 10-15% replacement of cement by silica.

Pradhan and Dutta [12] performed experiments to determine compressive strength, compacting factor and slump of concrete of concrete incorporating silica fume. The optimum compressive strength was observed when 20% of cement was replaced by silica fume. The compacting factor ranged from 0.82 to 0.88 and the slump value from 20 to 50 mm when silica fume was added in different proportion to the concrete. Improved pore structures at the transition zone of silica fume concrete is the reason behind improved performance of concrete.

Shanmugapriya and Uma [13] carried out experiments on concrete with mean strength of 60Mpa having a water binder ratio as 0.32 and using CONPLAST SP 430 super plasticizer. 7.5% silica fume by weight was inferred to be the optimum dosage for maximum performance of concrete. Compressive strength increased by 15%, tensile strength increased by 20% and flexural strength increased by 23%.

Fig. 2 – Silica Fume

3.3 Metakaolin

Metakaolin is a dehydroxylated form of the clay mineral kaolinite. It is an amorphous non crystallized material which consists of lamellar particles. Research on Metakaolin shows that it is an excellent pozzolanic material which can improve strength, durability and other mechanical properties of concrete.

Yogesh R. Suryawanshi et al [14] investigated the effects of Metakaolin and super plasticizer on concrete of grade M-35. Cement was replaced by Metakaolin by 4,8,12,16 and 20%. The water cement ratio was taken as 0.43 for all cases and compressive strength at 3, 7 and 28 days was determined. The compressive strength increased up to cement replacement of 12% after which a decrease in compressive strength was observed. The compressive strength increased by more than 10 % on replacing cement by metakaolin. Although, the use of metakaolin reduces the workability of concrete but suitable use of super plasticizers can compensate this reduction.

Patil and Kumbhar [15] studied the properties like workability, compressive strength and durability of M60 grade high performance concrete consisting of Metakaolin. Different percentages of metakaolin were added to the concrete along with a suitable super plasticizer. It was observed that incorporating metakaolin up to 7.5% by weight of cement gave the optimum workability and compressive strength. When 7.5% metakaolin was added, the compressive strength at 28 days was improved by 7.73%. The concrete was subjected to chloride and sulphate attack and it was inferred that addition of metakaolin enhances the chemical resistance of concrete.

E. Badogiannis et al [16] used a produced metakaolin and a high purity commercial metakaolin to replace certain amount of cement in the concrete. Concrete properties such as strength development, durability, chloride permeability, air permeability, sorptivity and porosity are studied and compared for both types of metakaolin. It is observed that the produced metakaolin and the commercial metakaolin gave similar results of strength development and durability of concrete. In both the cases, metakaolin exhibited higher 28 days and 90 days strength and reduced chloride permeability, gas permeability, sorptivity and pore size when compared to ordinary Portland cement concrete.

Devi [17] used metakaolin as a partial replacement of cement to study the compressive, tensile and flexural strength and durability of concrete having quarry dust as fine aggregate. Various percentages of metakaolin in concrete ranging from 5-20% have been used to replace cement. The incorporation of metakaolin in quarry dust concrete improved the rheological properties of concrete like workability, compactability, bleeding and segregation. The optimum replacement of cement by metakaolin was found to be 15% which enhanced the strengths and corrosion resistance at all ages of concrete. Metakaolin is also found to react with calcium hydroxide which improves the pore structure of the concrete.

Fig. 3 – Silica Fume

3.4 Ground Granulated Blast Furnace Slag

Ground-granulated blast-furnace slag also known as GGBS is obtained from molten iron slag which is a by-product of iron and steel-making. The process involves quenching of iron slag from a blast furnace in water or steam, to produce a glassy, granular product that is then dried and ground into a fine powder. This fine powder is then called as Ground-granulated blast-furnace slag.

Awasare and Nagendra [18] analyzed the strength characteristics of a M20 grade concrete with 20%, 30%, 40% and 50% replacement of cement with GGBS. Comparison of results for natural sand and crushed sand is also done. The optimum strength of concrete with both natural and crushed sand is achieved at 30% replacement of cement with GGBS. It is also inferred that flexural and tensile strengths are also improved by incorporating GGBS in the concrete.

S. Arivalagan [19] evaluated the strength efficiency factor of hardened concrete of grade M35 with partial replacement of cement with GGBS. Slump, compressive strength, flexural strength and split tensile strength values of concrete are experimentally determined for various ratios of GGBS replacement of cement. It is observed that the strength at 28days of the concrete increases for 20% replacement of cement with GGBS. Addition of GGBS up to 40% cement by weight gave normal workability of concrete as compare to OPC concrete.

Ramezanianpour et al [20] studied the effects of replacing cement with GGBS on compressive strength and sulphate resistance of concrete. Cement replacement levels of 35%, 42.5% and 50% were taken into consideration. The concrete was immersed in 5% sodium sulphate solution and compressive strengths at 180 and 270 days were determined. Concrete with 50% replacement of cement by GGBS showed an increase in resistance to sodium sulphate solution after 270 days where as concrete with 35% replacement levels show a decrease in resistance after 270 days of exposure. It is also observed that a lower w/c ratio indicates a higher compressive resistance.

V.S.Tamilarasan et al [21] studied the workability of M20 and M25 grade concrete with partial replacement of cement by GGBS. Replacement levels were taken in the range of 0 to 100% in steps of 5%. The properties of concrete were analyzed by performing various tests like Slump test, compaction factor test, Vee Bee consistometer test and Flow test. It is concluded that the workability of concrete improved for up to 45% replacement level in the case of M20 grade and up to 50% replacement levels in the case of M25 grade concrete. Also, the workability of M25 grade was found to be better than that of M20 grade concrete.

Pavia and Condren [22] examined the durability of GGBS concrete when exposed to silage effluent solution and magnesium sulfate solution. Properties like permeability, porosity, water absorption, capillary suction, compressive strength and mass loss were evaluated for different amounts of GGBS incorporated in the concrete. It was observed that the durability of concrete when subjected to silage effluent cycles and salt crystallization increases with the increase in GGBS content. There was a decrease in permeability, water absorption, capillary suction, mass loss and compressive strength loss in GGBS concrete exposed to silage effluent and salt cycling as compared to OPC concrete. Therefore, concrete mix with partial replacement of cement with GGBS can be efficiently used for agricultural use in silos.

3.5 Combination of Fly Ash and Silica Fume

Heba A. Mohamed [23] experimented on self-compacting concrete incorporated with different percentages of fly ash, silica fume and a combination of fly ash and silica fume. Cylinder specimens were used for slump and V-funnel test. The experiment involved different curing conditions for different specimens. Concrete having 15 % fly ash and cured in water for 28 days achieved the maximum compressive strength. When fly ash and silica fume were added to concrete as a combination, 10 % fly ash and 10% silica fume were found to be the optimum percentages.

Fig. 4 – Ground Granulated Blast Furnace Slag

Nochaiya et al [24] examined the effects of adding silica fume in Portland cement concrete incorporated with fly ash. Different combinations of Portland cement, fly ash and silica fume were used to make specimens for testing. The percentages of fly ash used were 5%, 10%, 20% and 30% and percentages of silica fume used were 2.5%, 5%, and 10%. The tests for normal consistency, setting time, workability and compressive strength were carried out and it was found that on increasing the silica fume content in concrete, the water requirement for normal consistency increases, initial setting time decreases. An overall increase in compressive strength was observed in concrete on utilization of silica fume in concrete incorporated with fly ash. The workability reduced on adding silica fume to fly ash concrete but remained higher than that of Portland cement concrete.

Wongkeo et al [25] evaluates the influence of high-calcium fly ash and silica fume on self-compacting concrete (SCC). Different specimens of SCC with cement replacement at 50, 60 and 70% by wt were used. The percentages of fly ash used ranges from 40 to 70% where as that of silica fume ranges from 0 to 10%. Various tests were conducted to determine the density, water absorption, volume of permeable pore space, compressive strength and chloride resistance of SCC. It was observed that there was no significant change in apparent densities on adding fly ash and silica fume to SCC. Fly ash tends to increase the volume of permeable pore space and water absorption where as Silica fume decreased the voids and water absorption of SCC. Higher compressive strength was achieved for ternary blend of concrete with fly ash and silica fume as compared to binary blend of concrete with fly ash. The optimum percentage of fly ash was found to be 40% when used with 10% silica fume at water-cement ration of 0.3.

3.6 Combination of Fly Ash and Metakaolin

Nazeer and Kumar [26] experimented on high-volume fly ash concrete blended with metakaolin. Fly ash used as partial replacement of cement in Portland Cement concrete was 50% by weight. Metakaolin was used to replace the remaining cement by 5%, 10%, 15% and 20%. The concrete mix was formed for grade M30 with water binder ratio as 0.44 and two curing conditions i.e. boiling and normal curing were used. Test for

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determining workability, compressive strength, split tensile strength, modulus of elasticity and impact strength of concrete were carried out. It was observed that the impact resistance of concrete blended with fly ash and metakaolin was higher but the workability was lower than that of controlled Portland cement concrete. On adding metakaolin, compressive strength, tensile strength and modulus of elasticity reduced.

Patil et al [27] evaluated the strength and durability of a high performance self compacting concrete incorporated with a combination of fly ash and metakaolin. Cement is partially replaced by fly ash and metakaolin. The fly ash is used in proportions of 5%, 15% and 25% and Metakaolin is used in proportions of 3%,6% and 9%. It was found that use of metakaolin and fly ash resulted in changes in the chemical composition of the pore solution phase of the hydrated material and increased the chloride resistance of concerte. Fly ash is responsible for increasing the workability of concrete. The optimum percentages of metakaolin and fly ash for strength and durability of concrete are 9% and 15% respectively.

Muthupriya et al [28] studied the behavior of high performance reinforced concrete column made with metakaolin and fly ash as a partial replacement of ordinary Portland cement. Concrete mixes were formed by using 10% fly ash and different percentages of metakaolin for long and short columns. Higher strength development, more cohesion, less segregation, more durability, less rate of water absorption and increased ductility parameters were observed in concrete containing fly ash and metakaolin as compared to normal concrete mix. Metakaolin when used as 7.5 % by weight of concrete gave the maximum strength which was 12% higher than normal concrete. The brittleness of concrete was observed to be increased which causes sudden failure of columns with explosive sound.

3.7 Combination of Fly Ash and GGBS

Li and Zhao [29] investigated the effect of combination of fly ash and granulated blast furnace slag in high strength concrete partially replacing the cement in it. It was observed that this combination can be used to improve early compressive strength as well as long term properties of the concrete.

Pratap et al [30] observed that a concrete mix of M60 grade incorporated with fly ash and GGBS had a higher compressive strength, flexural strength and split tensile strength as compared to normal mix concrete. The compressive strength was found to be increased by 11.13%, flexural strength by 11.74% and split tensile strength by 23.01% at 28 days.

Ali and Abdullah [31] partially replaced cement in concrete by Fly ash and GGBS. Fly ash was added in percentages of 20%, 40% and 60% and GGBS was added in percentages ranging from 5 – 10%. The compressive strength, split tensile strength and flexural strength increased up to 40% of fly ash and 9 % of GGBS.

3.8 Combination of Silica fume and Metakaolin

Srivastava et al [32] used a combination of silica fume and metakaolin in Portland cement concrete to study its effect on 7 and 28 day compressive strength. The optimum dose of silica fume and metakaolin for maximum compressive strength was 6% and 15% respectively. It was observed that increasing metakaolin content increased the 28 day compressive strength but decreased the 7 day compressive strength. Addition of metakaolin also reduced the slump in concrete.

Anbarasan and Venkatesan [33] carried out compressive strength test, split tensile test and sorptivity test on concrete made by silica fume and metakaolin as partial replacement of cement. The optimum percentage replacement of cement with silica fume and metakaolin is 35 % and 15 % respectively. At this percentage, the strength and durability was observed to be higher than the conventional concrete.

Shirke et al [34] studied the performance of concrete on incorporating metakaolin, silica fume and a combination of them. Replacing cement by 5 % Silica fume and 15% metakaolin by weight gave the highest strength. Concrete which was ternary blended with metakaolin and silica fume showed the least mass loss on exposure to HCl solution.

TABLE 1. Comparison of physical and chemical properties of cement and its alternatives

Constituent/ Property	Portland cement	Fly ash	Silica Fume	Metakaolin	GGBS
CaO %	62	1 - 40	0.1	0.05	30 - 45
SiO_2 %	21	20 - 60	85 - 97	51.2	17 - 38
Al_2O_3 %	5	5 - 35	0.1	45.3	15 - 25
Fe_2O_3 %	3	4 - 40	0.6	0.60	0.5 - 2.0
SO_3 %	2.86	0 - 10	-	-	2.49
MgO %	0.88	0 - 10	0.2	-	4.0 - 17.0
Surface area, m^2/kg	300 - 500	300 - 500	15000 - 30000	10000 - 25000	420 - 650
Specific gravity	3.15	2.38-2.65	2.22	2.50	2.85
Color	Dark Grey	Dark grey	Light to Dark Grey	White	Off white

4 Conclusion

The present study aimed at reviewing the literature on different alternatives to cement in concrete. These include fly ash, silica fume, metakaolin and Ground granulated blast furnace slag. Cement can be partially replaced by one of these alternatives or by a combination of these alternatives. The literature review revealed the following conclusions –

- Fly ash increases the compressive strength, tensile strength and flexural strength of concrete. It also increases resistance to alkali aggregate reactions, slows down ingress of moisture, oxygen, chloride, carbon dioxide and aggressive chemicals and prevents corrosion. The main disadvantages of using fly ash are lower rate of strength gain, increased air entraining and increased slump loss.
- Addition of silica fume helps in increasing the strength of concrete by 10–15 % and also gives high early strength. Other advantages of adding silica fume are lower water-cement ratio, resistance to frost action and chemical effect. However, silica fume reduces workability of concrete and increases the consistency.
- Metakaolin increases the compressive strength up to 12 %, gives higher resistance to chemical effect, reduces chloride permeability, sorptivity and pore size and enhances corrosion resistance of concrete. The main disadvantage of using metakaolin as partial replacement of cement in concrete is that it reduces workability of concrete.
- Ground granulated blast furnace slag helps in increasing compressive strength, flexural strength and tensile strength up to 30%. Incorporation of GGBS in concrete increases workability, enhances sodium sulphate resistance, provides better durability against silage effluent cycles and salt crystallization, and decreases permeability, water absorption and capillary suction. However, GGBS slows down the setting time of concrete, which can cause delay in the construction process.

5 Future Scope

After reviewing the various works done by different researchers, it can be inferred that there is a vast scope in improving the characteristics of concrete as well as reducing the content of cement used. It is clear that all the four alternatives to cement presented in this paper affect the properties of concrete in a unique way. Thus, future work lies in replacing all of the cement from concrete by using a suitable combination of cement alternatives to increase the strength, workability and durability of concrete. Also, new alternatives should be found which can overcome the drawbacks of the above mentioned alternatives.

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