CHAPTER 1
INTRODUCTION

1.1 GENERAL

Concrete is one of the major construction materials throughout the world owing to its design versatility, availability and cost efficiency. Ordinary Portland cement (OPC), which is a major constituent of concrete and act as a binder, is produced enormously. With continuously increasing demand of cement and concrete, a number of challenges are faced by the cement industry due to depleting fossil fuel reserves, scarcity of raw materials, growing environmental concerns linked to climate change. A large amount of CO$_2$ is released in the atmosphere in the production of cement, which is a major environmental concern. It is estimated that for each tone of cement being produced, an average of 0.87 tons of CO$_2$ is being emitted.

CO$_2$ emissions can be reduced or eliminated by either improving the production methods or utilizing supplementary cementitious materials (SCMs) in the cement manufacturing process. In order to counter the impacts on product cost of new regulations, green taxes and escalating fuel prices, emission reduction is high on the agenda. In that context, utilization of locally available minerals, recycled materials and industrial, agriculture or construction waste, may be appropriate for blending with OPC. Well established examples of cement replacing (partial) materials are metakaolin (MK), fly ash (FA), Blast furnace slag (GGBS), silica fume (SF), lime powder (LP), rice husk ash (RHA) that are in commercial use today. Through laboratory tests and practical experiences, Engineering, Environmental and Economical (EEEs) benefits of partial replacement of these materials with OPC have been acknowledged and validated. On priority basis, by-product of coal combustion comes first, the second is iron smelting and the third is electric arc furnace production of elemental silicon or Ferro silicon alloys.

As a construction material, Concrete will remain in high demand in the near future. The world without concrete is hard to imagine and thus its dominant precursor,
Ordinary Portland Cement (OPC). Although, there are different types of concrete that have been developed for use in different applications, their common qualities are familiarity, versatility, strength, durability, wide availability, fire resistance, resistance to elements and comparatively low cost. Cement is a vital construction material and also a strategic commodity [1]. The world is dependent on cement as nearly 3.6 billion metric tons of cement is produced every year [2]. It is also predicted that the production of cement is going to rise and it will touch the figure of 5 billion metric tons by 2030 [3, 4]. However, statistics differ worldwide as it can be seen from Figure 1.1

![Per Capita Cement Consumption (Kgs)](image)

**Figure 1.1: Per Capita Cement Consumption in All Over the World [3,4]**

Cement is not only used in concrete production but it is also used in other engineering applications, such as, soil stabilization, mortars for plastering & pointing, repair purposes, [5, 6].

Just like other industries, cement industry is also facing unprecedented challenges related to energy consumption and resources, CO₂ emissions and use of alternative materials to reduce cost and burden on environment. All over the world, the energy cost is increasing inexorably due to depletion of the fuel sources, which has clear impact on
the cost of cement production and its market price. Green taxes are supplementary cost that is incurred if emissions are not restricted, potentially leading to doubling of the price of cement by 2030 [7].

1.2 WORLD CEMENT PRODUCTION

The cement production differs greatly from country to country with the availability of raw materials. Naturally, if the production does not satisfy the demand, it is imported. Recent trends in the global production of cement demonstrate that out of total amount of cement manufactured all over the world, China dominates the market as shown in Fig. 1.2 [8]. Typical cement plant capacity is expected to remain in the range of 1.5 and 2.5 million tonnes per annum [9]. Fig. 1.3 shows global cement production trend which is expected to increase continuously and become the second most consumed product on the planet after water. The cement industry is growing quickly in developing countries like India as well. India has a high demand for infrastructure and housing as reported by World Business Council for Sustainable Development in 2009.
1.3 ENVIRONMENT CONCERNS IN CEMENT PRODUCTION

CO₂ emission is a major environmental concern of cement industries leading to depleting air quality and various other disasters due to global warming.

Fig. 1.4 demonstrates the projected CO₂ emissions from the cement industry if no changes are made to current production methods. It is projected that the emissions will increase 5 times by 2050 from the value in 1990 [10], which is a matter of serious concern in general and to the government and concerned industries in particular. The Sustainability Initiative of cement through OECD/IEA and World Business Council for Sustainable Development (in 2009) refers how the cement industry can bring changes on a global scale by promoting the best available efficient technologies for new and existing production plants that increases awareness of alternative fuels and encouraging clinker
replacement. These initiatives will not only reduce greenhouse gas taxes but also help in paving the way for a ‘greener’ cement industry.

Figure 1.4: Projected global cement industry reference CO₂, million metric tonnes [10]

To summarize, the annual world cement production has grown from 1.0 billion tons to approximately 1.7 billion tons, which is enough to produce 1 m³ of concrete per person [12]. It has been reported that the production of 1 ton of cement consumes about 4GJ of energy and requires about 1.7 tons of raw materials (limestone and shale) which leads to environmental degradation and pollution problems [13-15]. In addition, issues, such as, CO₂ emissions during the production of Portland cement, along with a significant amount of energy, water, aggregate and fillers used for the production of porous concrete, make this important construction material less compatible with the environmental requirements of a modern sustainable construction industry. Therefore, concrete technology has focused on other alternatives that can be used as cement replacement materials in concrete. Hence, use of supplementary cementitious materials as partial replacement to Portland cement in concrete is a better step towards sustainable development because of their technological, economic, and environmental benefits.
1.4 SUPPLEMENTARY CEMENTITIOUS MATERIALS (SCMs)

Concrete is a mixture of cement, fine aggregate, coarse aggregate and water in which cement is the most important. Cementitious material in concrete is a source of environment concern now-a-days. In recent years, most concrete mixtures also contain supplementary cementitious materials, which constitute a portion of the cementitious materials in concrete. As stated earlier, the most commonly used SCMs are fly ash (FA), ground granulated blast furnace slag (GGBS), silica fume (SF), metakaolin (MK), lime powder (LP), rice husk ash (RHA) etc. These, SCMs are either by products of different industries or sometimes natural materials. SCMs when used with Portland cement in concrete, contribute towards enhancement in the fresh, hardened as well as durability properties of the concrete through hydraulic or pozzolanic activity or both. Some of the SCMs are called pozzolana that do not have any cementitious properties but when used with Portland cement, react to form cementitious compounds. Partial replacement of Portland cement with SCMs ensures improvement in the environmental footprint of concrete as well as reduction in the Green House Gas emissions and air pollutants. Moreover, because SCMs are by-products of other industrial processes and are typically directed to landfills, recycling of these materials as raw materials for another process reduces waste. Overall, the use of SCMs contributes towards enhanced sustainability in the construction industry.

The economical and engineering benefits of SCMs are justified when the costs of these alternative materials are less than that of Portland cement while providing comparable performance.
1.4.1 FLY ASH

Fly ash, which is produced by coal thermal power plants, is spherical and glassy material collected in fine and powdery form [Figure 1.5]. The use of fly ash in concrete production, as supplementary cementitious materials, was started in the last century and its use in concrete has seen dramatically growth in the last 50 years, which is close to 15 million tons [11].

Figure 1.5: Fly ash and its SEM image [16]

Fly ash of pulverized coal is generally generated from its combustion and it is estimated that one ton of pulverized coal can produce 30-40% fly ash by using circulation fluidized bed combustion technology [16]. Usually, large amount of fly ash are discharged to waste dumps or stockpiled landfills, which lead to substantial land occupation and environment pollution [17]. In some countries, this waste is found in abundance which requires extra attention for handling and safe disposal. Figure 1.6 shows annual production of fly ash from different countries.
UTILIZATION OF FLY ASH IN CONSTRUCTION MATERIALS

Fly ash can be utilized as prime material in blocks, paving or bricks; however, one of the most paramount applications is PCC pavement. PCC pavements utilize a substantial amount of concrete and superseding fly ash provides paramount economic benefits. Fly ash has been utilized for paving roads and as embankment and mine fills, and its gaining acceptance Worldwide.

Fly ash concrete has a number of substantial, well-documented benefits that make it accumulation of choice for many countries, their transport departments and transport engineers. It is more durable, yet less extravagant than other traditional Portland cement blends.

The present utilization of fly ash in various sectors is shown in table 1.1 and figure 1.7. Ministry of science and Technology, India has reported nearly 100 million tons of fly ash being utilized out of 200 million tons by the end of 2012.
Table 1.1: Percentage Utilization of Fly Ash (DST Govt. of India, 2012)

<table>
<thead>
<tr>
<th>Sector</th>
<th>Million Tons</th>
<th>% Utilization of Fly Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>In Production of PPC</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Cement Replacement in RMC batching plant</td>
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<td>10</td>
</tr>
<tr>
<td>Filling in low lying areas</td>
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<td>17</td>
</tr>
<tr>
<td>Roads and Embankments</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
<td><strong>100</strong></td>
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</table>

Figure 1.7: Present Utilization of Fly ash in Different Segments
Figure 1.8: Utilization of Fly Ash in cement and concrete industry during 1998 to 2016

[DST Govt. of India, 2016]

From the above figure 1.8 it can be seen that approximately 8 million ton of fly ash was utilized by cement and concrete industry in 1998-1999. And by 2015-2016 it has been increased around 45 million ton.

Some of the environmental benefits of fly ash are listed below:

ENVIRONMENTAL BENEFITS OF FLY ASH

- Diverts material from waste stream
- Reduces the energy investment in processing virgin materials
- Conserves virgin materials
- Reduces pollution
- 131 million tons of fly ash is produced annually and approximately 56 million tons of that fly ash is recycled.
• Recycling this fly ash saves approximately 36,700 acre of landfill space which is equivalent to roughly 28,200 football fields one foot deep.

1.4.2 SILICA FUME

Silica Fume (SF) also known as microsilica or condensed silica fume, is a by-product of the manufacturing of silicon or ferrosilicon alloys. The first experience with SF in concrete dates back to 1952 in Scandinavia, and in 1971, the first documented use of SF in structural concrete is reported in Norway. Because of its highly amorphous silica content (at least 90% SiO\(_2\)), SF is an effective pozzolan. Such effectiveness is augmented by extremely fine, spherical particles with an average size of 0.1 µm (Fig 1.9). Standard specifications for silica fume used in cementitious mixtures are ASTM C1240, EN 13263.

![Figure 1.9: Silica Fume and its SEM image [18]](image)

The presence of silica fume in the Portland cement concrete mixes causes considerable reduction in the volume of large pores at all ages. It basically acts as filler due to its fineness and because of which it fits in spaces between grains in the same way that sand fills the pores in coarse aggregates and cement fills the pores between fine aggregates grains.

The advantages of using SF are increased pore refinement, improved strength at early age, stickiness, ASR resistance and enhanced sulfate resistance. Additional benefits are consumption of Ca(OH)\(_2\) in the chemical process and improved durability as well as
resistance to sulfate attacks. Often, SF is available in the form of black or grey color due to heavy content of carbon and iron inside. The particle size of SF is shown in fig. 1.9. SF has a high surface area (15-28 m²/g), which increases the amount of water required in the concrete mixture to ensure sufficient workability. Hence, it is recommended to use high-range water reducing admixture while using SF [19].

**USE OF SF IN CONSTRUCTION INDUSTRY**

The utilization of silica fume is varied and open to the designers. The earliest applications for high-strength silica fume concrete were in columns for High-rise structures. As concrete strength increases column size can be reduced and reinforcing steel designs in the columns can be simplified. Cast in place parking garages also stimulated rapidly to incorporate High Performance Concrete into the structures. Chloride penetration is very critical in Marine structures and direct salt-water contact as well as above ground sea salts effect structures like pilings for bridges, wharfs, piers, break walls, and bridge decks. This structure would have been better prepared to resist the aggressive salt environment with the use of silica fume in concrete construction.

Many chemical plants use silica fume in their concrete for the reduction in permeability and increased durability. They find that this concrete is much more resistant to attack by acids or other aggressive chemicals as it decreases the rate of deterioration or time between repairs in extremely aggressive chemical processing areas. Additional benefits also come from the higher strength and increased abrasion resistance.

Oil well grouting is another area where silica fume is used extensively. In both primary oil well grouting, when the grouting is used as a hydraulic seal in the well bore and secondary grouting such as leak repairs, sealing splits, and closing depleted zones. The addition of silica fume to the oil well grout produces a blocking effect that prevents gas migration. Silica fume’s ability to decrease the permeability of the grout, slows or stops gas leakage from the well. Increased strength of the cured slurry provides greater durability of the installation and the addition of silica fume to the slurry, improves its flow, so the installation is more effective. Shotcrete applications such as tunnels, mines,
tanks, repairs and domes use large quantities of silica fume. The increased cohesion from silica fume allows for greater application thickness, particularly overhead, significant reduction in rebound and increased flexural strength.

**SOME OF THE ADVANTAGES OF SILICA FUME ARE LISTED BELOW**

- High early compressive strength
- Very low permeability to chloride and water intrusion
- Enhanced durability
- Increased toughness
- Increased abrasion resistance on decks, floors, overlays and marine structures
- Superior resistance to chemical attack from chlorides, acids, nitrates and sulfates and life cycle cost efficiencies.
- Higher bond strength
- High electrical resistivity and low permeability

### 1.4.3 GROUND GRANULATED BLAST FURNACE SLAG

Ground granulated blast furnace slag (GGBS) is a byproduct from the blast furnaces used to produce iron. Blast furnaces are fed with controlled mixture of iron ore, coke and limestone, and operated at a temperature of about $1500^0\text{C}$.

Ground granulated blast furnace slag is a glassy material. The color of GGBS varies from beige to dark to off – white depending on moisture content, chemistry and efficiency of granulation. When it is ground it has usually white color [20].
Figure 1.10: Ground Granulated Blast Furnace Slag and Its SEM image [20]

The shape of GGBS processed by a vibro mill was predominantly spherical with a smooth surface, while that by a ball mill and an airflow mill appeared to have similar edges.

GGBS can be used as a direct replacement for ordinary Portland cement by weight. Generally, it is used up to 50% in most of the applications. In lean concrete, GGBS can be replaced up to 70%. The use of GGBS in concrete saves energy, reduces emission of carbon dioxide and conserves natural resources.

GGBS is an industrial by product of steel industries. It consists primarily of oxides of calcium, iron, silicon, aluminum, magnesium, and manganese in complexes of calcium silicates, aluminosilicates, and aluminoferrite. These compounds are generally similar to those found in the natural environment. Utilization of GGBS in construction industry has been used for the construction of roads and as filler material., Recently, GGBS has been included as a cement additive, landfill cover material, and for a number of agricultural and construction applications [21].
ADVANTAGES OF USING GGBS IN CEMENT AND CONCRETE

- Improved workability and compaction characteristics
- Increased pumpability
- Increased strength
- Enhanced durability
- Reduced permeability
- High resistance to chloride penetration
- High resistance to ASR
- Low heat of hydration
- Improved surface finish
- Enhanced architectural appearance
- Suppresses efflorescence
- Production of GGBS involves virtually zero CO₂ emissions, and no emissions of SO₂ and NOₓ

1.4.4 METAKAOLIN

Metakaolin (MK) is a pozzolanic material, which is a dehydroxylated form of the clay mineral kaolinite. It is obtained by calcinations of kaolinitic clay at a temperature ranging 500°C and 800°C. Kaolin is a fine, white, clay mineral that has been traditionally used in the manufacturing of porcelain. Kaolinite is a mineralogical term that is applicable to kaolin clays. Kaolinite is defined as a common mineral, hydrated aluminum disilicate, the most common constituent of kaolin. Metakaolin is produced from relatively pure kaolinite clay and it is used at 5% to 15% by mass of the cementitious materials.

In order to produce MK pozzolan, it requires complete dehydroxilization of kaolin into metakaolin, which is an endothermic process and requires large amount of energy to remove the chemically bonded hydroxyl ions. Metakaolin particles are extremely small with an average particles size of 3µm [22] and having off-white color.
METAKAOLIN IN CONSTRUCTION INDUSTRY FINDS ITS USAGE IN MANY ASPECTS:

Metakaolin reduces the porosity of concrete, a feature that can allow a reduction in the cover of concrete needed to protect reinforcing bars from corrosion. Road and marine structures exposed to corrosive salts are good examples where Metakaolin was used. Efflorescence is a common problem affecting concrete, caused by lime salts forming calcium carbonate on the surface of the concrete. Metakaolin reduced efflorescence by reducing the porosity of the concrete and reacting with the lime salts before they reach the concrete surface. With this metakaolin was used in many aspects of industries to achieve high performance, high strength and light weight concrete. Precast concrete for civil, industrial and structural purposes. Metakaolin was used for the purpose of mortars, repair material and pool plasters [22]
ADVANTAGES OF USING METAKAOLIN

- Enhanced workability
- Increased compressive strength
- Increased durability
- Reduced permeability
- Increased resistance to chemical attack
- Reduction in alkali-silica reactivity (ASR)
- Reduced shrinkage due to particle packing
- Reduced potential for efflorescence

1.4.5 LIME POWDER

Lime powder is a calcium-containing inorganic mineral in which carbonates, oxides, and hydroxides preponderate. In other sense lime is calcium oxide or calcium hydroxide. The rocks and minerals from which these materials are derived, typically limestone or chalk, are composed primarily of calcium carbonate. They may be cut, crushed, or pulverized and chemically altered. Burning (calcination) converts them into the highly caustic material quicklime (calcium oxide, CaO) and, through subsequent addition of water, into the less caustic (but still strongly alkaline) slaked lime or hydrated lime (calcium hydroxide, Ca(OH)$_2$), the process of which is called slaking of lime. Lime kilns are the kilns used for lime burning and slaking.
Figure 1.12: lime powder and its SEM image [22]

Lime has been used as a building material for thousands of years; the Egyptian Pyramids, the Coliseum in Rome, and the Great Wall of China all boost lime mortar cement. Yet, since the invention and widespread use of Portland cement from the mid-1800s, lime has faded into obscurity and few people know how to correctly use lime. This guide is a short introduction to this forgotten building material: how it is made, how to use it, and why lime is an attractive alternative to cement, modern plasters, and paints for both historic and contemporary buildings.

1.4.6 SCMs FINDS IT’S USAGE IN MANY ASPECTS OF CONCRETE

The utilization of SCMs conserves energy and has environmental benefits because of reduction in carbon dioxide emission as a result of reduction in manufacture of Portland cement. Strict air pollution controls and regulations have produced an abundance of industrial by products that can be used as supplementary cementitious materials. Supplementary cementitious materials are often used in concrete mixes to reduce cement contents, improve workability, increase strength and enhance durability through hydraulic/pozzolanic activity. Utilization of these by products in cement/concrete not only prevents them from being land filled but also enhances the properties of concrete in the fresh and hardened state.
1.5 BINARY BLENDED CONCRETE

FA is a by-product of thermal power stations and is solid materials remove 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 [23] Fly ash as supplementary cementing material used in concrete), from the last century but the first research in fly ash was conducted at the University of California by Davis et al. [24] and the first noteworthy operation of fly ash in concrete commenced with the construction of the Hungry Horse Dam in Montana in 1948. To reduce the gas emission other production of the material has been changed but though it has not affected the nature of fly ash.

Density of fresh concrete reduced with the increase percentage level of fly ash with Portland cement and workability is increased Joseph and Ramamurthy [25]. Fly ash in concrete increases the fine volume and decreases the water content and so reduces the bleeding of concrete [26]. Kayali and Ahmed [27] prepared binary concrete by replacing OPC with fly ash at 0%, 25%, 50% and 75% percentage with water/binder ratio of 0.38. The compressive strength was measured at 7 and 28 days and it was found that with the increasing level of fly ash strength was decreased. Similar observations were obtained for modulus of elasticity also.
Solanki and Pitroda [28] observed flexural strength at 0%, 10%, 20% and 30% replacement level of fly ash with OPC. At the age of 28 days the flexural strength was increased at 20% replacement level of fly ash. From durability point of view fly ash has become beneficial and Sear in 2010, [29] reported that fly ash improve the sulfate resistance and chloride penetration. 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. ScotAsh [30], suggested that each ton of FA utilized in cement products saves an average 900 kg of CO$_2$ emission. Also, addition of fly ash in concrete as binary binder lowers the water demand which in turn saves energy. Moreover use of fly ash in concrete, decreasing the cost of concrete [30].

Study by Jones [31] revealed that GGBS affect the properties of Concrete both in fresh and hardened states. Hooton [32] found that the slump of GGBS concrete is unaffected as compared to OPC 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, setting times can be extended up to one or two hours. Hooton[32] 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.

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 [33].

According to Norchem [34], 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.

According to Wolsiefer [35], 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 manufacturing 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.

In recent years, metakaolin has been studied because of its high pozzolanic properties [36, 37]. It is well known that MK is a reactive aluminosilicate that is formed by the dehydroxylation of the kaolin precursor upon heating in the temperature range of 700–800°C [38, 39]. The effects of MK on the durability and mechanical properties of mortar or concrete have been widely reported [40, 41 & 42]. The performance of concrete incorporating MK at appropriate replacement levels is similar to that of concrete containing silica fume [43]. Recent works have shown that MK is effective as a supplementary cementitious material for improving the durability of concrete, for example, the alkali-silica reaction [44] and resistance to chloride ingress [45].
1.6 TERNARY AND QUATERNARY BLENDED CONCRETE

Concrete mix combination with one, two or three supplementary cementitious materials provides significant advantages over mixtures having only Portland cement. Utilization of supplementary cementitious materials at specific percentage level with Portland cement positively develops not only strength but also develops the overall durability of the concrete is still a focal point for research studies. According to the studies of Isaia (1997)[46], when a less reactive pozzolan is employed in ternary mixtures together with another more reactive mixture such as silica fume/RHA/MK, there is an interaction between these pozzolana, and the obtained result is higher than the respective binary mixtures. Therefore mixing more than one SCM is likely to improve the mechanical and structural properties of the concrete. Now-a-days, production of new generation concrete like geopolymer concrete, self-compacting concrete, high strength concrete, and high performance concrete is increasing throughout the world. For better performance and improved engineering properties, SCMs such as, fly ash (FA), silica fume (SF), ground granulated blast furnace slag (GGBS), metakaolin (MK) and rice husk ash (RHA) are added as partial (binary/ternary/quaternary) replacement to ordinary Portland cement.

Ezgi Yurdakul et al. [47] obtained compressive strength and chloride permeability of ternary blended concrete containing OPC, FA and GGBS. Author has concluded that ternary mixtures overall performed better than control mixtures as they increased the strength and decreased the permeability. Although they increased the shrinkage and setting time compared to control mixtures, they did not perform dramatically different than binary mixtures. Therefore ternary mixtures can be preferred due to their effect on decreasing the cost and being sustainable as it allows achieving similar performance with a lower cost while being sustainable.

M. Sharfuddin Ahmed et al. [48] also observed strength and durability of ternary concrete mixtures containing mixes (65%OPC+25%FA+10%SF) and (65%OPC+25%GGBS+10%SF). The ternary blend comprising 25% GGBS and 10% silica fume showed a significant increase in compressive strength and decreased in
permeability. Incorporation of MK and FA with OPC in ternary blended concrete provides lower permeability due to very high surface area of metakaolin [49].

Wongkeo et al. [50] observed the drying shrinkage of ternary and quaternary concrete containing OPC+FA+SF and OPC+FA+BA+SF. It was reported that drying shrinkage were higher than control concrete and it increases with increased percentage of SF.

Quaternary blended cements produced mortars and concrete that performed well in terms of better strength and durability [51]. Binary, ternary, and quaternary blends of Portland cement, fly ash (FA), ground granulated blast furnace slag (GGBFS), silica fume (SF), and metakaolin (MK) also reduced the drying shrinkage [52]. Additions of supplementary cementitious materials in concrete with OPC can reduce the total porosity of mortar and concrete and modifies the pore structure of the cement binder, mortar and concrete that significantly reduces the permeability and do not allow the transfer of harmful ions leading to deterioration of the concrete matrix [53].

The use of SCMs can significantly reduced the embodied energy of precast concrete produced by substituting pozzolanic materials (FA, SF, GGBS, MK, LP etc.) for relatively high energy hydraulic cement. SCMs, such as, fly ash (FA), silica flume (SF), ground granulated blast furnace slag (GGBS), metakaolin (MK) and lime powder (LP) are often available as industrial by products from various industrial processes. Their judicious use in concrete production is desirable both for environmental and energy conservation as well as for achieving civil engineering design and construction benefits.
1.7 SCOPE OF THE STUDY

The consumption of Supplementary cementitious materials has increased enormously in the construction industry. There is a lot of potential with the utilization of fly ash, GGBS, silica fume, metakaolin in concrete. However, the characterization of quaternary blended cement is not much established. The quaternary concrete performed well in strength as well as shown good durability also. With the addition of different types of fibers the tensile properties of quaternary concrete can also be improved. Further analysis can be carried out to measure creep and shrinkage of quaternary concrete. The utilization of supplementary cementitious materials can be used for the construction of bridge structures due to very low permeability. Thus the Quaternary concrete could be the best substitute of OPC concretes. It’s utilization in construction may help in reducing the burden on natural raw materials used in OPC and promote the utilization of waste materials in construction.
1.8 TEST METHODS AND CODES

In the present study the detail analysis of the materials and their physical, chemical, mechanical properties along with durability properties was determined as prescribed in IS codes. The detail about the IS codes referred for various tests are described in table 1.2.
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<tr>
<th>Properties</th>
<th>Details of Experiments</th>
<th>Prescribed Standard</th>
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<tbody>
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<tr>
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<td>Bond Strength of Concrete</td>
<td>IS:2770-1 (1967)</td>
</tr>
<tr>
<td>Durability Properties</td>
<td>Ultrasonic Pulse Velocity</td>
<td>IS: 13311 (Part 1) – 1992</td>
</tr>
<tr>
<td></td>
<td>Rapid Chloride Permeability Test</td>
<td>ASTM-C-1202</td>
</tr>
<tr>
<td></td>
<td>Sulfate Expansion</td>
<td>ASTM-C-1012</td>
</tr>
<tr>
<td>Mineralogy</td>
<td>X-ray diffraction analysis</td>
<td>X-ray diffraction analysis [ASTM D 934-80 Practice B]</td>
</tr>
<tr>
<td>Morphology</td>
<td>Scanning electron microscopy</td>
<td>SEM</td>
</tr>
</tbody>
</table>
1.8.1 PHYSICAL PROPERTIES OF CEMENT & BINDERS
1.8.1.1 FINENESS TEST

Fineness of cement is the property of cement which indicates the particle size and total specific surface area of cement.

Blaine air permeability apparatus was used to determine the fineness of OPC, FA, SF, GGBS, MK and LP. The methodology was adopted as per IS: 4031:1999 (part-2) [54] and the fineness of OPC, FA, SF, GGBS, MK and LP was represented by specific surface expressed as total surface area in cm$^2$/g.

The sample was agitated by shaking it for 2 minute. Stir a resulting powder gently using a clean dry rod in order to distribute the fineness of cement. The density was measured using a pyknometer. The mass was correctly compacted, which produced a bed of porosity 0.500. Placed the perforated disc on the ledge at the bottom of the cell and place on it a new filter paper disc. Ensure that the filter paper disc fully covers the perforated disc and is flat by pressing with a clean dry rod. Place the weighed quantity of cement, ml, in the cell taking care to avoid loss. The specific surface, $S$, is given in 5.6.1 but is conveniently expressed as:

$$S = \frac{K}{p} \times \sqrt{e^3} \times (1-e) \times \sqrt{t / (1-0.1n)} \text{ (cm}^2/\text{gm})$$

Where,
$K$ is the apparatus constant
$e$ is the porosity of the bed,
$t$ is the measured time(s),
$p$ is the density of cement (g/cm3) and
$n$ is the viscosity of air at the test temperature
1.8.1.2 EXPANSION TEST

It is very important that the cement/binder after setting should not go through any appreciable change of volume. Certain cements or binders if found to undergo a large expansion after setting causing trouble of the set and hardened mass. This will cause serious difficulties for the durability of structures when such kinds of materials are used. Therefore testing of soundness of cement and binders, to make sure that these materials do not show any appreciable consequent expansion is essential. A material can be unsound due to the presence of MgO, which reacts with water in a manner similar to CaO. The unsoundness of material is not apparent until after a period of months or years, therefore it is necessary to test the soundness of cement in an accelerated manner. This test was carried out as per the given instructions in IS 4031 part 3 [55].

This test was measured to check the expansion of hardened cement and binder paste volume. Le Chatelier apparatus was used to measure volume expansion of cement and binder paste. It consists of a brass mold with 30 mm height and 30 mm diameter. Cement/binder paste was filled gently in oiled mould on a lightly oiled glass sheet with 0.78 times the water required to give a paste of standard consistency [ as per IS : 4031 (Part 4)-1988 ]. The paste was gauged in the manner and under the conditions prescribed in IS: 4031 (Part 4). The mould was covered with another piece of lightly oiled glass sheet and a small weight was placed on this covering glass sheet and immediately submerged in water at a temperature of 27 ± 2°C and kept there for 24 hours. The distance separating the indicator points to the nearest 0.5 was measured. The mould was again submerge in the water at the temperature prescribed above. The water was allowed to boil with the mould for next 3 hours and then the mould was removed from the water and allowed to cool. Once the mould was cooled the distance between the two indicator points was measured. The difference between these two measurements indicated the expansion of the cement.
1.8.1.3 CONSISTENCY

Vicat apparatus was used to determine standard consistency of the cement and quaternary binders and placed in a mold as per IS 4031(1988) part 4 [56]. The standard consistency of the paste was determined by adding water at different percentage levels till the paste has a given resistance to penetration. Vicat apparatus mold has been used to determine the standard consistency of different pastes. Consistency was recorded when the plunger of the Vicat apparatus penetrated into the paste 5 mm to 7 mm above the bottom of the mold. Consistency test helps to determine the water content required to produce cohesive paste. Consistency refers to the relative mobility of a freshly mixed cement/binder paste.

1.8.1.4 SETTING TIME

The cement or binder should neither set too rapidly nor too slowly as fresh concrete need sufficient time for transportation and placing before it becomes rigid. Also, too long setting time slows down the work unduly, and it may delay the actual use of the structure because of inadequate strength at the desired age. Two periods of times are used to assess the setting behavior. These are called “initial setting time” and “final setting time”.

The initial setting time was recorded as per IS: 4031part-5 [57]. The test block was placed on one non porous plate, under the rod bearing the needle. A needle of 1 mm square is used to penetrate into the paste at every 10 min intervals till the index scale shows 5 mm to 7 mm from the bottom of the mold called as initial setting time.

For determining the final setting time, the needle was replaced with an annular attachment. Released needle at every 30 min intervals till the needle makes an impression on the test block. The cement was finally considered set when needle made an impression on the test block. The period elapsing between the time when water was added to the cement and the time at which the needle makes an impression on the surface of test block called final setting time.
1.8.1.5 SPECIFIC GRAVITY

Specific gravity of the OPC, FA, SF, GGBS, MK and LP was determined as per IS 4031 (part 11) [58] procedure equivalent of which is ASTM D792 by using pycnometer bottle and kerosene. Specific Gravity is a comparison between the weights of a volume of a particular material to the weight of the same volume of water at a specified temperature. Sometimes materials are exposed to extreme moisture condition and therefore, the specific gravity of cement or binders will differ because of the moisture content present in the pores. The value will change over the time if the materials are exposed to different climate conditions. So it is necessary to determine the specific gravity of the materials before using it.

1.9 CHEMICAL PROPERTIES OF CEMENT AND BINDERS

The procedure used in the chemical analysis of OPC, FA, SF, GGBS, MK and LP was the X-Ray Fluorescence Spectrometer (XRF) and Atomic Absorption Spectrophotometer (AAS) method. The chemical analysis procedure was done as per the Indian Standard [59]. Chemical properties of supplementary cementitious materials used in this research were presented in table 2.
Table-1.3: Chemical Properties of OPC, FA, SF, GGBS, MK and LP

<table>
<thead>
<tr>
<th>Description</th>
<th>OPC</th>
<th>FA</th>
<th>GGBS</th>
<th>SF</th>
<th>MK</th>
<th>LP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Characteristics</td>
<td>(% By Mass)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calcium oxide, CaO, %</td>
<td>66.72</td>
<td>1.31</td>
<td>35.90</td>
<td>1.45</td>
<td>1.47</td>
<td>56.53</td>
</tr>
<tr>
<td>Silicon dioxide, SiO₂, %</td>
<td>17.53</td>
<td>61.21</td>
<td>40.65</td>
<td>87.28</td>
<td>50.62</td>
<td>0.04</td>
</tr>
<tr>
<td>Aluminum oxide, Al₂O₃, %</td>
<td>9.82</td>
<td>24.98</td>
<td>17.07</td>
<td>0.9</td>
<td>46.91</td>
<td>0.06</td>
</tr>
<tr>
<td>Ferric oxide, Fe₂O₃, %</td>
<td>2.19</td>
<td>3.3</td>
<td>0.68</td>
<td>1.52</td>
<td>0.38</td>
<td>0.05</td>
</tr>
<tr>
<td>Manganese oxide, MnO, %</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Magnesium oxide, MgO, %</td>
<td>1.24</td>
<td>2.60</td>
<td>3.75</td>
<td>0.13</td>
<td>0.09</td>
<td>0.10</td>
</tr>
<tr>
<td>Potassium oxide, K₂O, %</td>
<td>0.48</td>
<td>0.98</td>
<td>0.56</td>
<td>2.01</td>
<td>0.18</td>
<td>0.04</td>
</tr>
<tr>
<td>Sodium oxide, Na₂O, %</td>
<td>0.22</td>
<td>0.05</td>
<td>0.19</td>
<td>0.39</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>Loss of ignition, %</td>
<td>0.9</td>
<td>3.30</td>
<td>1.08</td>
<td>2</td>
<td>0.56</td>
<td>5.62</td>
</tr>
</tbody>
</table>
1.10 PROPERTIES OF FINE AND COARSE AGGREGATES

1.10.1 AGGREGATES PROPERTIES

Aggregate properties greatly influence the behavior of concrete, since they occupy about 80% of the total volume of concrete. Aggregates are most commonly known to be inert filler in concrete; the different properties of aggregate have a large impact on the strength, durability, workability, and economy of concrete. These different properties of aggregate provide designers and contractors some flexibility to meet their design and construction requirements. The aggregate are classified as (i) Fine aggregate and (ii) Coarse aggregate. Fine aggregate are material passing through an IS sieve that is less than 4.75mm gauge beyond which they are known as coarse aggregate. The grading size of fine aggregate is in between 150 µm to 4.75 mm and coarse aggregate size is up to 63 mm. for the production of high strength concrete it is necessary that aggregate size and shape should be perfect. In this study coarse aggregate size is used 10 mm and 20 mm.

The specific gravity, shape and size of the aggregates are the most important characteristics to measure the strength and workability of concrete. As per IS; 456-2000 [60] and IS:2386-1990 (reaffirmed) [61], the range of specific gravity of aggregates should be within 2.5 to 3.

Aggregate size and shape influence the properties of freshly mixed concrete more than the properties of hardened concrete. Flaky and elongated particles require more water to produce workable concrete than smooth, rounded aggregate. Therefore it is necessary to determine the fineness modulus test of aggregate before utilizing it in concrete as per IS:2386-1963 (reaffirmed 1997) (part-I) [62].

The fine aggregate was used as river sand, passing through 4.75 mm sieve size confirming to IS;456-2000 [60]. Coarse aggregate was collected from local supplier with angular shape and 10mm-20 mm size. Specific gravity of aggregates was determined as per IS: 2386-1990 [60] (reaffirmed) part-III. The fineness modulus of aggregates was determined as per IS: 383-1970 [63].
1.11 PROPERTIES OF FRESH AND HARDENED CONCRETE

1.11.1 FRESH CONCRETE PROPERTIES

The concrete mix proportions should be chosen carefully and it must have the desired adequate workability for proper placement and compaction in the formwork. Workability of unitary, binary and quaternary concrete was determined as per IS 456-2000[60]. Slump test was used to determine the workability of unitary, binary and quaternary concrete. This test is used extensively in site works all over the world. Slump test is prescribed by IS: 456-2000, which is similar to ASTM C 143-90a and BS 1881: part 102:1983. As per IS: 456-2000 and according to IS 1199, the slump value for pumpable concrete should be from 100 mm to 150 mm.

The spherical shape and glassy surface of most of the fly ash particles, usually finer than cement, permits greater workability for equal water – cement ratios. A study [64] reported that the use of fly ash as partial replacement of cement usually reduces the water content for a given consistency. Study also [65] revealed that the fly ash containing large fraction of particles, usually coarser than 45 µm or fly ash with higher amount of unburned carbon, exhibiting loss on ignition more than 1%, require higher amount of water to obtained a good workability. The same as ACI [66], the better solid volume and the higher fineness of slag permits more coarse collectives to be used in concrete without loss of workability. Wan et al. [67] stated that workability enhances with the increase of GGBS, while the study by Batis et al. [68] revealed that with increase in the proportions of Metakaolin content in concrete, the water demand increases. With the addition of silica fume at varying percentage with Portland cement and fly ash, the workability of slump decreases due to the higher specific surface area of silica fume [69].
1.11.2 COMPRESSION STRENGTH OF BINDERS AND MORTARS

The compressive strength of concrete should resist to failure under the action of any compressive forces because it is an important factor, which determines the performance of the material during service condition.

To prepare homogeneous mixture of binder and mortar, first of all dry materials were mixed properly and then water was added in pre-determined quantity to obtain the desired water – binder ratio and again mixed properly. The mould specimens for compressive strength test were prepared and the size of cement binder and mortar cubes were 70.6 mm X 70.6 mm X 70.6 mm. The mixing of binders and mortars was carried out at room temperature (27 ± 2 C). The mortar cubes were casted for 1:3, 1:4, 1:5 and 1:6 proportions at a water cement ratio of 0.5 and the mixtures were stirred for 3–5 min. After 24 h of curing at 95% humidity, the samples were demolded and immersed in tap water and cured up to 28 days. Compressive strength tests were conducted as per IS 516-1959 [70] in a Compression Testing Machine (CTM). All the strength values reported are the average values of three specimens. The flow of mortar was kept constant at a value of 115 by utilizing super-plasticizer.

1.11.3 COMPRESSION STRENGTH OF CONCRETE

Strength of concrete is commonly considered its most valuable property. Strength of concrete usually provides an overall representation of the quality of concrete because strength is directly related to the structure of the hydrated cement paste. The compressive strength of concrete is approximately invariably important element of structural design and is specified for compliance purposes.

Compressive strength was measured as per the instructions given in I.S. 516-1959 (Reaffirmed 2004) using a 200 T capacity Universal Testing Machine (UTM). The cubes were casted in the standard 150mm X 150mm X 150 mm size mold. On the hardened concrete after 7, 28, 56, 90, 180, and 365 days of curing, Compressive strength tests were performed. The load was applied on the cubes at the rate of approximately 14 N/mm²/minute. The average of three specimens was taken as the representative value of compressive strength of each batch of concrete.
1.11.4 SPLIT TENSILE STRENGTH

The split tensile strength is a vital property of concrete because the structures of concrete are extremely susceptible to tensile cracking because of various kinds of effects and applied loading itself. Though, tensile strength of concrete is very low in comparison of its compressive strength. The method to determine the tensile strength of concrete is splitting tensile strength test on concrete cylinder. Because of its fragile nature the concrete is very weak in tension and it is not expected to resist the direct tension.

As per IS: 5816-1999 [71] split tensile test was performed. Concrete cylinders are very important for casting, they have the size of 150 mm diameters and 300 mm height, they were casted. At the time of casting, the cylinders were mechanically vibrated using a vibrator table. The specimens were removed from the mould after 24 hours. They were subjected to water remedial for 28 days. Once the specified remedial period was over, by using Universal Testing Machine (UTM) the concrete cylinders were subjected to split tensile test. Tests were carried out on triplicate specimens and the average split tensile strength values were recorded.

1.11.5 FLEXURAL STRENGTH

Flexure strength was estimated by using standard beam specimens 100mm X 100mm X 500 mm. It just supported on an effective span of 400 mm and loaded at the third points after 90 days of remedial. As per IS: 516-1959 (Reaffirmed 2004) [70] the test was carried out for given specifications. Flexural strength is one measure of the tensile strength of concrete. It is also a measure of an unreinforced concrete beam or slab to resist failure in bending. That is measured by loading either 6 x 6 inch or 150 x 150 mm concrete beams with a span length at least three times the depth.

The flexural strength of concrete is determined by flexural Modulus of Rupture, which is almost 10 to 20 % of compressive strength which relies on the type, size and volume of coarse aggregate utilized. Though, the best correlation for specific materials is gained by laboratory tests for given materials and mix design.
1.11.6 BOND STRENGTH

The bond stress between steel and concrete is the essential condition to the good behavior of reinforced concrete structures.

Bond strength was measured using standard 150mm X 150mm X 150 mm cube specimens. The test was carried out as per IS: 2770-1967 (part 1) [72]. The bar diameter was 16 mm and length of bar was 40 mm. The bar placed approximately 10 mm down from the bottom face of the cube. Top surface of the cube, which is the bearing surface of the pull-out test, was capped with a thin layer of cement paste. The load was applied to the reinforcing bar at a rate was 2250 kg/minute.

1.12 DURABILITY PROPERTIES OF CONCRETE

It is necessary that every concrete structure should continue to perform its proposed functions. That maintains its acquired strength and serviceability during its specified service life. It follows that concrete have to be able to endure the processes of deterioration to which it could be expected to be exposed. Such concrete is known as durable.

1.12.1 ULTRASONIC PULSE VELOCITY

To check the quality of concrete and natural rocks, the ultrasonic pulse velocity test is an in-situ, nondestructive test. The strength and quality of concrete or rock is assessed through this test, by measuring the velocity of an ultrasonic pulse which passes through a concrete structure or natural rock formation. In this test a pulse of ultrasonic wave is passed through concrete sample which is to be tested and the time taken by pulse to get through the concrete sample is measured. Superior quality and stability of the material is designated by higher velocities, while slower velocities might show concrete with many breaks or voids.

Ultrasonic pulse velocity measurement is typically performed using a pair of transducers in contact with the specimen through a coupling medium as per IS 13311 (Part 1) – 1992 [73]. It can be used for several applications including pulse velocity measurement, path length measurement, uniformity assessment, surface velocity
measurement, crack depth measurement etc. Direct transducer arrangement method was adopted to ensure the maximum signal transmission between the transducers. For measuring the pulse velocity, it is essential to evaluate the path length between the two transducers. The distance that is travelled by the signal which means path length, between the transducers should be measured as precisely as possible. To ensure adequate acoustic coupling of the transducers to the surface under test, a thin layer of couplant should be applied to the transducer and the test surface. In some cases it may be necessary to prepare the surface by smoothing it. By using the calibration rod the ultrasonic instrument should be zeroed every day. It should be done mainly when the transducer frequency is changed or when the cables are changed.

1.12.2 CHLORIDE ION PENETRATION TEST

Inadequate durability manifests itself by deterioration which can be either due to external factors or internal causes within the concrete structure itself. Mechanical damage is caused by impact, abrasion, erosion and cavitation. The chemical causes of deterioration include the alkali – silica and alkali – carbonate reactions. External chemical attack occurs mainly through the action of aggressive ions, like chlorides, sulfates and carbon dioxide as well as many natural or industrial liquids and gases.

Capillary absorption, hydrostatic pressure, diffusion, and evaporative transport are a variety of mechanisms for chloride penetration crack-free concrete and amongst them diffusion is main. When the concentration of chloride ions at the surface of concrete mass is greater than inner concentration, then diffusion occurs. This leads to chloride ions penetration in concrete to the level of the rebar. When it occurs in combination with wetting and drying cycles in the presence of oxygen, it causes corrosion. Chloride ion penetration rate in concrete mass depends on the interior pore structure. The pore structure depends on factors like degree of hydration, mix design, curing conditions, use of supplementary cementitious materials, and construction practices. The concrete should be examined for chloride permeability where there is a possible risk of chloride-induced corrosion.
Rapid chloride permeability test (RCPT) was performed following the instructions given in AASHTO T 277 or ASTM C 1202 [74] by monitoring the amount of electrical current passes through a sample 50 mm thick and 100 mm in diameter for 6 h. The test results were obtained at 28 and 90 day of sample curing. A voltage of 60 V DC was maintained across the two ends of the sample throughout the test. One lead was immersed in a 3.0% salt (NaCl) solution and the other in a 0.3 M sodium hydroxide (NaOH) solution.

1.12.3 SULFATE ATTACK

Concrete are attacked by solutions containing sodium or magnesium sulfate. This attack can lead to expansion, cracking, strength loss and disintegration. Utilization of supplementary cementitious materials in concrete increases its resistance to sulfate attack. Sulfate attack is a chemical breakdown mechanism where sulfate ions attack components of the cement paste. It decreases the durability of concrete by changing the chemical nature of the cement paste, and of the mechanical properties of the concrete.

Most investigations have considered weight loss as acceptable indicator for evaluating the resistance of concrete to sulfate attack [75]. Percentage of sulfate expansion was determined as per ASTM C 1012 – 2004 [76]. All the mix combinations were cured in 5% Na$_2$SO$_4$ + 3% MgSO$_4$ solutions for 56, 90, 180 and 365 days.

The use of mineral admixtures, such as, silica fume and fly ash in concrete has improved the sulfate resistance attack [77]. Some of the studies indicated that fly ash improves the sulfate resistance of any concrete mix. Fly ash at replacement level of 50% has significantly improved the sulfate resistance compare to 30% replacement with OPC. Sulfate resistance of concrete with fly ash is strongly controlled by the gypsum content of the mix [78–80]. It was also identified that the use of binary and ternary concrete mix gives better performance in resistance to sulfate attack [81-83]. Quaternary concrete along with OPC, FA, SF and GGBS/MK performed good resistance to sulfate attack. Makhloufi et al. [84] reported that the use of GGBS, natural pozzolans and limestone powder improved the resistance of sulfuric acid attack because of the reduced presence of calcium hydroxide.
1.13 RESEARCH OBJECTIVES

Major research objectives of this study are as follows:

1. To study the influence of SCMs on the properties of cement binder matrices with different percentages of OPC, FA, SF, GGBS, MK and LP and establish the best mix proportion of quaternary binders in mortars. The mechanical properties studies are compressive strength and durability at 1/3/7/28/56/90/ days age. Additional properties for the investigations were Porosity, water absorption and density of quaternary mortars of 1:3, 1:4, 1:5 and 1:6 proportions.

2. To identify suitable percentages of FA, GGBS, MK and SF for the production of quaternary concrete mixtures for M20 and M40 grades satisfying the requirements of plasticity of fresh concrete, compressive strength, tensile strength and flexural strength, as well as durability of hardened concrete as per IS specifications.

3. To study the microstructure of the M20 & M40 grade concrete matrices to validate the strength and durability results. These studies would justify the utilization of quaternary binders in construction industry through a cost-analysis study.
1.14 RESEARCH METHODOLOGY

The research methodology adapted to for achieving the research objectives of the research work is shown in figure 1.12. The details of the materials used and the methods adopted to achieve the properties of quaternary concrete are discussed in above sections.

Figure 1.13 Adopted Research Methodology
1.15 ORGANIZATION OF THE THESIS

Entire thesis is covered in six chapters. Chapter 1 includes an introduction which describes the production and utilization of cement, fly ash, silica fume, ground granulated blast furnace slag, metakaolin and lime powder in cement and construction industry. Properties of binary, ternary and quaternary blended concrete are discussed. Also, physical, chemical, mechanical and durability properties of binders and aggregates are discussed. The objective of the research work and methodology adopted for this research work is covered in chapter 1. Chapter 2 covers the overall literature review of the properties of unitary, binary, ternary and quaternary concrete. Literature about individual properties of SCMs, mechanical and durability properties also has been included in this chapter. Chapter 3 provides the detailed experimental discussion about the quaternary binders and mortars. This chapter covers the experimental discussion about the physical, chemical, mechanical and durability properties of quaternary binders and mortars. Chapter 4 discusses the results of mechanical properties of M20 and M40 grade of quaternary concrete. Results of compressive strength, flexural strength, split tensile strength and bond strength have been discussed. Chapter 5 covers the results of durability and micro-structural studies of M20 and M40 grade quaternary concrete. Durability studies cover result and discussion part related with the rapid chloride permeability test, ultra sonic pulse velocity test and sulfate expansion tests. The summary of work done and significance of the present research work has been discussed in chapter 6.
1.16 CHAPTER CONCLUSION

- Sustainable development and Sustainable construction can only be achieved by conservation of resource in the construction and design for creating sustainable built environment.

- The demand of major construction material i.e. concrete would continue to increase; therefore in future extraction of natural resource will be more for concrete production unless more environment friendly and sustainable means for concrete production are explored.

- The utilization of SCMs in pre-determined proportions can help in reducing the demand of cement for concrete production. It requires proper research work on percentage of various SCMs in binder, standardization of their specifications, impact of SCMs on workability, strength and durability of binary and quaternary concrete using standard methods prescribed in IS codes.

- The quaternary binders incorporating SCMs would continue to make Concrete more sustainable and environment friendly.