CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

In this chapter, a critical review of literature on the chemical composition, reactivity of fly ash, mineralogical composition, morphology, activation of fly ash, activation of high calcium fly ash, ettringite based fly ash binder, use of waste materials in flowable slurry, use of waste materials in pavement application, fly ash in stabilized base, asphalt concrete and rigid pavement are presented.

2.2 FLY ASH - A POZZOLANA

Fly ash, also known as Pulverized Fuel Ash (PFA), is an industrial waste material produced from thermal power plants. Normally, it is disposed by the wet or by dry process. Of the above two processes, the dry method requires either an Electro Static Precipitator (ESP) or a circulator. Apart from the efficiency offered by the dry collection process, dry fly ash is sought more due to the ease with which it can be utilized and consistent chemical properties.

Fly ash consists of particles measuring between 1-150 micron in diameter. However, the collected fly ash from ESP is as fine as 50 micron in diameter. The main constituents present in most of the fly ashes are SiO$_2$ (25% - 60%), Al$_2$O$_3$ (10% - 30%), and Fe$_2$O$_3$ (5% - 25%). The quantity and their proportion depend mostly on the type of coal from which it is obtained.
Sub-bituminous coal or lignite yields high calcium fly ash (Class C fly ash) in which calcium in the form of CaO is expected to be present in significant proportion. However, the sum of silicon di-oxide, aluminium oxide and iron oxide must be more than 50%. The bituminous coal yields low calcium fly ash (Class F fly ash). The sum of the main constituent such as silicon di-oxide, aluminium oxide and iron oxide in Class F fly ash must be minimum of 70%.

Fly ash exhibits pozzolanic activity. A pozzolana is defined as “a siliceous or siliceous and aluminous material which by itself possess little or no cementitious value, but in a finely divided form and in the presence of water, chemically react with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties” [ASTM C595]. Such pozzolanic fly ash requires an activator to initiate the formation of cementitious compounds lime, cement, gypsum, alkalis, etc are commonly used activators. Class-C fly ash which contains higher calcium oxide may not require additional lime, whereas, Class-F fly ash requires additional lime as an activator.

2.3 REACTIVITY OF FLY ASH

An exhaustive research has been carried out to study the effect of chemical composition, physical properties, mineralogical composition and morphology of fly ash on its reactivity.

2.3.1 Chemical Composition

Richartz (1984) state that a pozzolanic reaction is to be expected only from substances whose SiO₂ dissolves with sufficient rapidity. The dissolved silica will be able to form C-S-H gel with calcium hydroxide for the strength development. Therefore, the percentage of soluble silica contained in
fly ash should be a characteristic criterion for ascertaining the potential reactivity of the fly ash. The soluble silica is particularly present in the amorphous form in the vitreous part of the fly ash.

Mehta (1985) has concluded that only the calcium content of fly ash has more effect on the reactivity than any other constituents. Superior reactivity of the high calcium fly ashes compared to low calcium ones, was probably due to the presence of reactive crystalline compounds, such as $C_3A$ and the more active calcium alumino silicate glass.

Also, Cabrera et al (1986) observed that only the reactive portion of silica and alumina is the significant factor rather than their percentages in fly ash. Only those portions of silica and alumina, which are soluble in alkaline environment, can take part in the pozzolanic reaction.

### 2.3.2 Physical Properties

Fineness is one of the important physical characteristics, which influences the activity of fly ash more than any other physical properties. There seems to be a general agreement among various researchers that finer the fly ash higher is the pozzolanic activity. Dan Ravina (1980) found a linear relation between specific surface and the pozzolanic reactivity of fly ash. But Chopra et al (1964), Garg et al (1988) and Luxan et al (1989) found no definite relationship between the pozzolanic activity and other physical characteristics of fly ash or its chemical or mineralogical composition.

Fineness of fly ash is expressed in terms of specific surface area. It has been adopted by almost all national standards as a criterion for assessment of quality of fly ash. However, it is found to be not a satisfactory criterion as it does not appear to bear any consistent relationship to any major property of fly ash concrete. Also, there is a lack of agreement between particle size
distribution and specific surface area of fly ash obtained by different methods. In view of these reasons, the specification for the specific surface area of fly ash was deleted from ASTM C 618 after 1977.

Sinha et al (1988) have carried out some laboratory studies on NTPC fly ashes and found that these ashes are useful for making Portland pozzolana cement. Lime reactivity of these ashes were in the range of 4.8 MPa to 7.4 MPa. Fineness was in the order of 3300-6400 cm$^2$/gm. Also it was observed that lime reactivity value increases with the increased fineness.

2.4 MINERALOGICAL COMPOSITION

Fly ash contains both amorphous and crystalline components in the range of about 10% to 50%. Carbon particles are also present. quartz, mullite, hematite and magnetite form the major portion of the crystalline matter. In addition, corundum, calcium hydroxide, calcium carbonate and anhydrite were also found in fly ash. Since, these are present in small quantities; they may not influence significantly the long-term pozzolanic activity. Amorphous portion consists of siliceous, aluminous and ferruginous glasses. It has been noticed that the glass content has the bearing on the pozzolanic reactivity of fly ash (Davis et al 1937, Diamond 1983).

Cabrera et al (1986) and Dhir et al (1986) found that it is the amorphous glass fraction of pulverized fuel ash which is active in the pozzolanic reaction. Bulk of the samples, tested by him exhibited amorphous glass, apart from mullite, hematite, magnetite, quartz and occasionally gypsum minerals. It has been reported that the difference in the chemical and mineralogical compositions and physical properties of pulverized fuel ash (PFA) does not influence the strength properties of cement concrete blended with fly ash.
The exhaustive study carried out by McCarthy et al (1984) revealed that the western fly ashes are characterized by the presence of higher oxide contents of CaO, MgO, SO₃ and lower quantity of Al₂O₃ and SiO₂, unlike eastern fly ashes from bituminous source. Also, western fly ashes contain more crystalline particles. Typical phases identified in them are quartz, lime, periclase, anhydrite, ferrite spinel, tri-calcium aluminate, merminite and malilite. Alkali sulfates, a sodalite structure phase and hematite also occurs in some fly ashes.

2.5 MORPHOLOGY

Diamond (1986) examined the internal as well as external morphological characteristics of fly ash particles using SEM analysis. The presence of mostly spherical particles cenospheres and plerospheres are noticed in fly ash samples. Also, the presence of inorganic spheres embedded in residual carbon and large platy carbon residue particle were observed.

2.6 ACTIVATION OF FLY ASH

Fan et al (1999) carried out studies on the activation of fly ash using Ca(OH)₂ and Na₂SiO₃. It is found that addition of calcium hydroxide corrode the protective glassy layer on the surface of the fly ash particle and thereby expose the reactive portion of the particle. Also, corrosive action of the Ca(OH)₂ is found to be more at the ratio of 1:3 of Ca(OH)₂ and fly ash. The addition of Na₂SiO₃ (3.91%) breaks the stubborn silica - alumina glassy chain. It increases pH value due to hydrolysis and also produces NaOH. This method of activation considerably increased the reactivity of the fly ash and reduced the setting time when mixed with ordinary Portland cement.

Shi Caijun (1998) examined the effect of CaCl₂ and Na₂SO₄ on the pozzolanic reaction in a blend of lime-pozzolana (80% of volcanic ash and
20% of hydrated lime). The amount of free Ca (OH)$_2$ present in the mortar was used to monitor the rate of reaction. It is observed that effect of both the activators on pozzolanic reaction depends on curing temperature. Also, it is stated that addition of Na$_2$SO$_4$ accelerated the rate of pozzolanic reaction significantly during the first day at a curing temperature of 23° C to 35° C. Introduction of CaCl$_2$ had a significant effect on the pozzolanic reaction, especially at elevated temperatures. The lime pozzolana activated with Na$_2$SO$_4$ and CaCl$_2$ exhibited higher strength than control at all ages and curing temperature.

Manjit Singh and Mridul Garg (1999) carried out investigations on the preparation of cementitious binder using fly ash and other industrial wastes. It has been noticed that high volume fly ash concrete (FA:75, OPC: 25) with CaCl$_2$ as an activator exhibited early strength gain but strength at 28 days was not affected appreciably contradicting the findings of Shi Caijun (1998).

2.7 ACTIVATION OF HIGH CALCIUM FLY ASH

Studies carried out by Bentur et al (1981, 1981a) shown that one of the products of the hydration of high calcium oil shale ash is calcium aluminium tri-sulphate (AFt), i.e. ettringite. AFt is stable in an aqueous solution up to 90°. Dehydration and carbonation processes reduce the amount of AFt into gypsum, calcium carbonate and alumina gel. This process caused decrease in strength as well as stability. Further, it has been indicated that formation of an additional amount of more stable binder phases in the initial stage of curing eliminates the break down of AFt.

Freidin (1998) suggested that blending of high calcium oil shale fly ash (HCOSFA) and low calcium coal fly ash (LCCFA) to produce more stable binder phases. The blending would give secondary high strength and
more stable C-S-H and improve the stability of the hardened system in atmospheric condition.

Further, Freidin (1999) carried out the durability studies on the above blend. Ettringite phase was more closely monitored since its stability under various conditions influences binder durability. It has been revealed that curing in water was more effective than in moist air. Air cured specimens gained compressive strength initially during the first month. Subsequently, strength loss was observed during 2-6 months depending on the percentage of HCOSFA.

Also, it is noticed that higher percentages of high calcium fly ash improved initial compressive strength. However, the loss in strength prolongs upto six months. It is due to continuous decay of Aft. Further, it has been noticed that the steam cured specimens showed less loss in strength. It is attributed to crystallization of Aft at higher temperature.

Manjit Singh and Mridul Garg (1995) investigated on blend - A (fly ash-40%, lime-20% and calcined phospho-gypsum) and blend - B (fly ash, gypsum, lime and portland cement) to study the effect of curing temperature.

It has been observed that ettringite is the main hydration product in both blends. Higher rate of reaction was observed at elevated temperature. The strength development in blend - B is higher than blend - A due to the formation of ettringite and tobermorite. The early strength is attributed to the setting of calcined gypsum and the later strength is due to the formation of ettringite and tobermorite.

Solem Tishmack et al (1995) studied the hydration behavior of high calcium fly ashes (23% to 28% CaO content) with and without OPC. XRD analysis showed that the principal phases developed are ettringite, mono sulfate and stranlingite (C$_2$ASH$_8$). The amount of the above phases depends
on the availability of aluminium and sulfur. Although, high calcium fly ashes have the capability of forming significant amounts of ettringite, fly ash activated with cement actually formed less ettringite than the corresponding cement pastes. Also, the cement/fly ash pastes produced more mono sulfate than the corresponding cement control paste.

Weiping Ma and Brown Paul (1997) studied the pore structure of the low lime fly ash activated by Ca (OH)$_2$ and CaSO$_4$.2H$_2$O under hydrothermal treatment. It is found that the surface area of fly ash treated with Ca (OH)$_2$ at 100° C was 33.4 m$^2$/g, while that of untreated fly ash was only 2.39 m$^2$/g. Also, pores of fly ash treated with Ca (OH)$_2$ having radii of 19 Å, increased with increasing temperature during thermal treatment. The formation of calcium silicate with a very large surface area controls the pore structures fly ash activated with Ca (OH)$_2$.

**Lime as an Activator**

Schlorholtz and Demirel (1984) investigated on the effect of activation of different types of fly ash using three types of lime such as reagent grade, commercial and a mixture of reagent grade lime and MgO, It is observed that class F fly ash satisfied the lime pozzolana activity test with all the three types of limes. The lime reactivity of Class C fly ash is also satisfactory with all types of lime except reagent grade lime. It has been concluded that the glass in a high- calcium Class C ash is calcium saturated and hence the addition of reagent grade lime with high calcium content has not improved the lime reactivity of fly ash. The magnesium is suspected to be the active component of the solution in promoting the pozzolanic reactions.

Tenoutasse and Marion (1986) carried out investigations to confirm the pozzolanic activity of fly ashes in lime saturated solution. The results showed low solubility of the alkali oxides from fly ashes. The calcium content
in the liquid phase decreased significantly between 8 hours and 28 days, indicating pozzolanic reaction.

Amitava roy et al (1992) studied alkali activation of Class C fly ashes using hydroxide solutions of Li, Na, and K. The pH of the activating solutions varied from 12.34 (0.02N) to 14.69 (5N). It has been concluded that the microstructure and phase assemblage depend on the pH value. Ettringite was absent beyond pH 14.3 (2N). Strantlingite, gehlenite hydrate, C$_2$ASH$_8$ and other compounds having a hexagonal plate like crystalline form becomes more abundant at higher pH. The microstructure at higher pH was characterized by high amounts of the plate like crystalline phase and a dense matrix, due to higher reactivity of the glassy phase in fly ash. The effect of setting time was insignificant compared to that of pH.

**OPC as an activator**

Tenoutasse and Marion (1986) investigated the influence of fly ash substitution on the microstructure of hydrated normal Portland cement. It is observed that fly ash particles seem to be intact, even after 60 days of hydration. The addition of fly ashes to OPC increased the total porosity, especially during the early hydration period. Also, the total porosity and pore size distribution of cement blended with 25% of fly ash are similar to those of OPC paste even after three months of hydration.

Studies carried out by Helmuth et al (1986) indicated considerable reduction in strength at 30% replacement of OPC with Class C and F fly ashes. However, the strength loss is considerably high in the blend with Class F fly ash than Class C fly ash. This is due to the self-cementitious as well as pozzolanic property exhibited by Class C fly ashes. Class F fly ash blend gave a low early strength but the strength improved with prolonged curing.
Douglas Hooton (1986) studied the permeability and pore-structure of cement pastes as well as cement pastes blended with mineral admixtures. It has been concluded that as Portland cement hydrates, large capillary pore spaces are filled in with hydration products, thus refining the size of these large pores. Supplementary cementing materials react with the calcium hydroxide liberated in the hydration of C₃S and C₂S in the Portland cement. This reaction process develops additional cementitious products (C-S-H) within the framework of the hardened cement paste, leading to further refinement of pore structure. Also, it is concluded that addition of Class F fly ash effectively reduces the ultimate permeability.

Giergiczczz and Werynska (1989) attempted to study the effect of physical, chemical properties of fly ashes (Class C & F) on mechanical properties of cement fly ash mortars. It is found that fly ash with smaller fraction (0-20 micron) brings about the lowest strength decrease in the mortars.

Halse et al (1984) and Plowman and Cabrera (1984) carried out investigation to establish relationship between Ca(OH)₂ content in fly ash blended cement (30% fly ash) and compressive strength. It is observed that Ca(OH)₂ content reached a maximum during 7-14 days and there after decreased due to pozzolanic reaction. The decrease in Ca(OH)₂ content followed by the dissolution of the fly ash augmented the strength. It is also observed that the pozzolanic reaction accelerated with increase in temperature in fly ash cement mortar. Both class C and F fly ashes not only retarded the C₃S hydration but also C₃A in the cement.

Tenoutasse and Marion (1986) examined the effect of addition of a typical Belgian fly ash on the heat evaluation of OPC during hydration. Increase in fly ash reduced the heat of hydration and acted as a ‘retarder’ in
the hydration of cement. However, the substitutions of up to 20% of cement by fly ash had no drastic effect on the rate of hydration of cement.

Sturrup et al (1983) stated that the use of fly ash to reduce the heat of hydration of cement concrete is well established. The pozzolanic reaction of the alumina-silicates of fly ash with calcium hydroxide (liberated by the C₃S and C₂S components of Portland cement) takes place more slowly than C₃S reactions and approximates the reaction rate of C₂S. This combined with the dilution of the Portland cement component of fly ash results in a reduced rate of heat evolution and also reduces the ultimate heat of hydration. Similar results were reported by Wei Fajun et al (1985) who carried out SEM and heat evolution studies on the retardation effect of fly ashes, class C and F fly ash.

He Jun-Yuan et al (1984) studied the hydration products of fly ash-Portland cements. It is noticed that the amount of calcium hydroxide crystals in the cement pastes has diminished due to the addition of fly ash to cement. Also, partial conversion of ettringite to mono-sulphate was observed within the first 7 days of hydration in the fly ash-Portland cement pastes. Further, it has been noticed that the pozzolanic reaction was incomplete even after 90 day of curing period.

Also, Feldman (1984) found the total porosity of blended cements, containing fly ash or slag, is higher compared to reference Portland cement. It is noticed that the finer pores were higher in blended cements.

Helmuth et al (1986) has reported that it is more difficult to correlate strength development with the degree of reaction in cement-fly ash mixtures, as it requires to determine the degree of reaction of each constituent. The degree of reaction of cement can be determined by XRD of the remaining alite but the amount of calcium hydroxide must be separately determined as
the calcium to silicate ratio of C-S-H, formed by the cement hydration which depends on the reactivity of fly ash.

2.8 ACTIVATION OF GYPSUM

Gregory et al (1984) analysed physical properties of phospho gypsum. A wide distribution in the specific gravity of solids and fineness (less than 75µ sieve) is noticed for various phospho gypsum in Florida. The particle size is in the range of 1.2 mm to 100 microns for phospho gypsum produced in Florida, Louisiana and Texas. The major constituents such as CaO, SO₄ and SiO₂ are present in phospho gypsum. Also, fluorides, P₂O₅, F₂O₃, Al₂O₃ and trace elements such as As, Ba, Cr, Pb, Hg, Se, etc are present as minor constituents. The particles present are generally radiating agglomerates of platelets. Some of the aged and weathered materials are rounded and denser. A few samples showed un-agglomerated platelets. The difference in morphology can be attributed to the place of collection from the stockpile. The morphological characteristics ultimately have bearing on behavioral properties of gypsum.

Taha and Seals (1992) carried out long-term reactivity test in order to find out the suitability of a given Portland cement for stabilizing phospho-gypsum. Cement (11% C₃A) stabilized phospho gypsum mortar specimens were cured for approximately three years showed higher expansion than the specimen with cement having low level of C₃A. It is concluded that increase in C₃A content cause increase in expansion but, the rate of expansion decreases with the curing period.

Manjit Singh (1992) investigated the effect of different salts, such as, sodium succinate, aluminium sulphate and sodium citrate (0.1% to 0.25 %) on the morphology and mechanical properties of α-plaster (CaSO₄½H₂O). It is noticed that complete dehydration takes place in α-plaster due to the addition
of above salt in the range of 0.1% to 0.25%. Microscopic analysis showed that the crystals are of prismatic needle and lath shaped in clusters. Also, an increase in bulk density and compressive strength are noticed in α-plaster with sodium succinate salt.

Wiresching (1978) studied the influence of lime on the hydration of β-hemi-hydrate (β-HH) of phospho gypsum. It is noticed that the addition of lime reduced initial setting time and the final setting time of phospho gypsum by three and more than twenty folds, respectively. Also, bending strength showed a loss of 50% with the increase in lime content. pH value shot up from 3 to 11 with the addition of 2.5% of lime. The loss of strength is due to incomplete hydration of β-HH to di-hydrate, as the di-hydrated cluster covers HH crystals.

2.9 ETTRINGITE BASED FLY ASH BINDER

Ghorab and Kishar (1985) studied the effect of temperature on the stability of ettringite prepared by stirring anhydrous tri calcium aluminate with gypsum in the mole ratio of 1:3 in excess redistilled water for 10 days at room temperature. It is observed that ettringite phase is stable in water at 30°C with an equilibrium concentration of 168 mg SO$_3$/lit and 56.2 mg Al$_2$O$_3$/lit in a solution having pH value of 11. The ettringite decomposes to the mono sulphate hydrate phase after one hour boiling in water with the splitting of 2.25 moles sulphate. It seems that the grain size of the ettringite phase plays a decisive role for its decomposition to the low sulphate form in boiling water.

Further, Ghorab et al (1998) studied the effect of alite, lime and mono-carbo-aluminate hydrate at 30°C and 100°C on the stability of ettringite. The systems studied are ettringite –alite-water, ettringite-lime-water, and ettringite-mono carbo aluminate hydrate-water, with mole ratios 1:1 and 1:10 (expressed relative to the ettringite phase). It is noticed that the
Solubility product of ettringite is found to be more in pure water \((1.98 \times 10^{-37})\), than in the presence of alite \((1.11 \times 10^{-40})\). The XRD analysis showed that the pure ettringite phase was converted to the mono sulphate hydrate after one hour boiling in water and then decomposed to gypsum and hemi hydrate after 11 days. In the presence of alite, anhydrate and tobermorite are formed as end products after 14 days. However, it is observed that a lime solution of concentration 0.2 g to 1.2 g CaO/L is found to be ineffective on the morphology of ettringite phase.

Beretka et al (1996) studied the effect of the variation in \(C_A3\) \(\hat{S}\) (calcium sulpho aluminate) content on the ternary system. calcium sulpho aluminate-calcium sulpho silicate \((C_S2\) \(\hat{S}\))- calcium sulphate\((C\hat{S})\) \((C\hat{S}/ C_A3\) \(\hat{S}\) ratio of 0.5) and \(C_A3\) \(\hat{S}\) content was varied between 15% to 55%. Ratio of \(C_A3\) \(\hat{S}\)/ \(C_S2\) \(\hat{S}\), by weight was varied from 1:3 to 3:1. It is observed that higher mechanical strength developed at early ages and the maximum strength was reached at the age of 28 days for all compositions. Ettringite was formed rapidly with increase in \(C_A3\) \(\hat{S}\) content within one day and then continue to increase slowly up to age of 365 days. It is also noticed that water/solid ratio has a greater influence on the mechanical strength than their \(C_A3\) \(\hat{S}\) content and corresponding ettringite concentration. Further, it is concluded that the \(C_A3\) \(\hat{S}\) content and w/s ratio are critical in regulating the behaviour of calcium sulpho aluminate based cements.

Sarkar et al (1996) attempted to study on the activation of fly ash and lime mixture using phospho-gypsum. It is observed that hydrated lime was consumed to a large extent within the first week of hydration and ettringite and calcium silicate hydrate are the major reaction products at the age of 28 days. The mixture with higher or equal lime to gypsum yielded compressive strength of 10 MPa to 12.5 MPa at the age of 28 days. C-S-H is the principal phase in fly ash – lime - gypsum contributing the strength.
Bhanumathidas and Ayyanna (1989) reported to have used calcined gypsum to activate fly ash and lime mixture to produce mortar with a compressive strength up to 24 MPa, at the age of 28 days. Also, it has been concluded that 15% (by weight) is the optimum content of calcined gypsum to activate fly ash and lime mixture (Fa: L 5:1).

Murthy and Narasinga Rao (1992) and Siddique (1996) studied the flexural behaviour of reinforced concrete beams made of gypsum activated fly ash and lime as a binder in concrete. The above binder (1.5 parts in place of one part) in concrete showed a comparable behavior with that of OPC.

Bhanumathidas and Kalidas (1992) reported that the ettringite in the fly ash – lime - gypsum system converted to mono-sulphate at the age of 28 days. The addition of gypsum, converted relatively shorter; less cohesive and weak reactionary products of fly ash-lime system to stable products.

Further, Anne Roja (1996) carried out experimental studies on the activation of low- calcium (1.4%) class F fly ash and lime mixture using gypsum. It is suggested that 5% to 10 % of gypsum by weight can be used to activate fly ash. FL-G binder (in the ratio of 68:23:9) with sand in the ratio 3:2 yielded maximum compressive strength of 4.1 MPa at 30 days of curing. It was also observed that addition of gypsum contributed to the early strength up to 10 days. Further it was noticed that ettringite is converted to mono-sulphate faster in the specimens air cured than water cured. The aluminate hydrate and ettringite compounds are reported to be present at the end of 30 days.

Mridul Garg et al (1996) carried the durability studies on the blend of phospho-gypsum, fly ash and Portland cement. It is observed that ettringite and tobermorite are the compounds which impart stability to the matrix. Wetting and drying and heating and cooling cycles showed decrease in the
compressive strength. The maximum strength loss is observed during heating at 60°C. The fall in strength is attributed to the decomposition of ettringite.

Alunno Rossetti et al (1982) studied the expansive properties of the mixture of calcium sulpho aluminate and CaSO₄ at 20°C in different contact solutions consisting of ettringite, calcium hydroxide and calcium sulphate. In the presence of calcium hydroxide, the rate of reaction is high due to the catalytic action of the lime in the nucleation of ettringite. As a consequence, the crystal size has become smaller and thereby specific surface area of ettringite significantly increased. It is noticed that expansion is faster in the presence of calcium hydroxide due to higher reaction rates.

2.10 DURABILITY OF FLY ASH BINDER

One of the main causes of deterioration in concrete structures is the distress due to its exposure to aggressive environment such as contaminated groundwater, industrial effluents and sea water. Most aggressive chemicals that effect durability of concrete are chlorides and sulphates. (Wee et al 2000). Exhaustive research work has been carried out to unravel this complex phenomenon through immersion tests in the laboratory as well as in the field (Khatri and Sirivivatnanon 1997, Tamimi 1997).

In 1936, the U.S. Bureau of Reclamation classified potential of sulfate attack on concrete based on levels of soluble sulfates in soils and groundwater. Concentrations of soluble sulfates below 0.1% in soils and below 0.15 g/L in groundwater are considered too low to cause sulfate attack. Higher concentrations, between 0.1% to 0.2% in soils and 0.15 g/L to 1.5 g/L in groundwater are classified as having moderate potential for sulfate attack. More than 0.2% of soluble sulfates in soils and above 1.5 g/L in groundwater are categorized as high potential for sulfate attack (Mehta 1992).
Petry and Little (1992) reviewed a background on sulfate-induced heave in lime and cement-treated clay soils. The total reaction and favorable environment for formation of expansive minerals resulting from the interaction of lime and sulfate-bearing clay soils or Portland cement and sulfate-bearing soils are not completely understood. The most often found expandable mineral is ettringite. Therefore, the formation of ettringite is necessary for the sulfate heave phenomenon to occur, and curtailment or elimination of its formation would dramatically reduce the volume increase. The addition of lime or cement in sufficient quantities to clay increase the pH. Once the pH exceeds 10.5, dissolution of the clay surface occurs, and siliceous and aluminous elements are released. The sulfates present in sufficient quantity either in solid or groundwater form produce significant quantities of ettringite or monosulfate hydrate.

Fly ash provides the silica and alumina needed for cementitous reaction with lime to increase the strength, stiffness, and durability of the stabilized base layer (Butalia 2007). The superior resistance of the concrete mixture against sulphate attack can be brought in by the pore refinement process and densification of transition zone. It is due to reaction between excessive lime and reactive silica present in fly ash leading to the formation of additional binding material (Haque and Kayali 1998, Shannang and Hussein 2003).

Sherwood (1958) is one of the early investigators who first noticed the problem concerning sulfate attack on soil cement. Further, Sherwood (1962) studied the effect of the presence of sulfate ions in soils on the durability of cement and lime-stabilized soils. It is noticed that cement- or lime-stabilized clay mixtures containing calcium, magnesium, or sodium sulfates disintegrated within a few days, whereas, cement-stabilized sand mixtures containing the same proportions of sulfates were unaffected even
after being immersed for one year. It has been concluded that sulfate attack on cement-stabilized soils is principally due to the reaction involving clay minerals.

Subsequently, Cordon (1962) conducted a similar laboratory test to evaluate sulfate resistance of soil cement made of different kinds of cements (Type I, Type II and Type V) and coarse-grained soil as well as fine-grained soil. It is observed that sulfate attack on soil cement is same as that of cement concrete. However, the rate of deterioration in soil-cement is more rapid than in cement concrete. The soil cement specimens with Type II and Type V cements are more resistant to the sulfate attack than soil cement specimens with Type I cement. Also, it is noticed that soil cement specimens made with fine-grained soils deteriorate more rapidly than the soil cement made of coarse grained soil.

Dakshina Murthy et al (2007) carried out a detailed experimental study on the effect of incorporation of fly ash (10% to 40%) on sulphate resistance of M25, M45 and M60 grade concrete at 7 days and 28 days. The cubes were cured in separate tanks containing 5% $\text{H}_2\text{SO}_4$ solution and potable water for 28 days. The compressive strength and weight loss indicated that use of fly ash in concrete has improved performance against sulphate attack in all the three grades of concrete.

Bakharev (2005) investigated on the durability of geopolymer materials manufactured using class F fly ash and alkaline activators exposed to sulfate environment (5% sodium sulfate + 5% magnesium sulfate) over a period of 5 months. It has been observed that the specimens have not shown any significant changes in weight microstructure and compressive strength. The best performance in different sulfate solutions was observed in the geopolymer material prepared with sodium hydroxide and cured at elevated temperature. Also, it is concluded that specimens prepared with sodium
hydroxide were more stable in sulfate solutions than specimens prepared using sodium silicate or mixture of sodium and potassium hydroxide solutions.

Mari Paz Lorenzo et al (2002) studied the effect of fly ash in Portland cement paste exposed to sulfate environment. Mixtures with 0%, 15%, and 35% replacement of portland cement by Class F fly ash were immersed in Na₂SO₄ solution, of having 2880 ppm SO₄²⁻ concentration, for a period of 90 days. The results showed that all of the mixtures were sulfate resistant, despite the high Al₂O₃ content of the fly ash. The diffusion of SO₄²⁻ and Na⁺ ions through the pore solution activated the pozzolanic reactivity of the fly ashes resulting improved flexural strength.

Dhir and Jones (1999) described how low-lime fly ash can be used to develop chloride-resistant concrete by improving its physical resistance to the ingress of chloride ions. The concrete with fly ash (30% weight) made with optimum w/b ratio showed 2-4 fold improvement in performance than Portland cement concrete. It has also been stated that using ultra-fine fly ash, or in combination with silica fume/metakaolin improves the resistance to chloride ingress.

2.11 USE OF INDUSTRIAL BYPRODUCTS IN FLOWABLE SLURRY

Major environmental attraction of flowable slurry is its ability to utilize industrial by-products. There are two basic types of flowable slurry that contains high fly ash content and low fly ash content mixtures. High fly ash slurry normally consists of fly ash, small quantity of cement and enough quantity of water to produce the flowability required for particular application. Low fly ash mixtures normally consists of high percentage of
filler material/fine aggregate, a low percentage of fly ash and cement and enough water to obtain the desired flowability (FHWA 1998).

Extensive research work has been carried out by many researchers in the field of flowable slurry. A brief review of literature on flowable slurry is summarized and presented below.


2.12 HIGH FLY ASH SLURRY

In general, fly ash is principal component of flowable slurry and its use is widespread. Krell (1989), Naik et al (1990) attempted to study the characteristics of high volume fly ash slurry having class F fly ash, OPC (4% to 5%) and water to obtain the slump of 228 mm. It is observed that the slurry released bleed water prior to initial set and also shown shrinkage. However, no bleeding and segregation was noticed after initial setting. Further, high fly ash slurry mixtures released free water without segregation on adding additional water in the normal flow mixes. It is due to almost uniform particle size of fly ash and ordinary Portland cement. Flowable high fly ash slurry hardened sufficiently within 3 to 4 hours after placement. Subsidence/settlement of high fly ash slurry occurred in a matter of minutes.
Density of high fly ash is in the range of 1460 kg/m$^3$ to 1945 kg/m$^3$ (FHWA 1998). It is reported that density less than 800 kg/m$^3$ can be obtained with the use of foaming agent for flowable fly ash slurry (Charles et al 1997).

It has been observed that the compressive strength depends on the quantity of cement and water content. A cement content of about 90 kg/m$^3$ was required to produce compressive strength greater than 0.345 N/mm$^2$ at the age of 28 days. As the water content increased compressive strength will probably be reduced (FHWA 1998, Krell 1989 and 1989a, Naik et al 1990).

Permeability of high fly ash slurry was generally in the range of $1.9 \times 10^{-6}$ cm/sec to $3.3 \times 10^{-7}$ cm/sec. It is in the range of permeability of clay material. Flowable fly ash can resist erosion both in plastic and hardened state. This property can eliminate the need for silt curtains (containment by weirs) and other environmental concerns during usage under water (Krell 1989 and 1989a). Further, Ramme et al (1994) found that the corrosion potential of high fly ash slurry is significantly less than soil. Also, Krell (1989) noticed that the flowable fly ash can inhibit the rusting of iron and steel. Thermal conductivity of high fly ash slurry is lower than sand, silt and clay. High density, very low porosity flowable slurry is desired as backfilling material for underground power cables (Ramme et al 1994).

Flowable fly ash at 5% cement content performed well under freeze and thaw conditions in the field. Laboratory tests showed that 15% cement content is needed for lining in landfill applications (Charles et al 1997).

Naik et al (2006) investigated the use of high volume high carbon fly ash in manufacturing conductive flowable slurry. It is found that the high carbon fly ash showed very high electrical conductivity. This is especially useful for conducting electrical charge from lightning to the ground more safely.
Doven and Ayse Pekrioglu (2005) developed high volume fly ash mixture composite with various combinations of fly ash, cement, lime, silica fume and water reducing admixtures. It is reported that the density of the composite material in the range of 1190 kg/m$^3$ to 1650 kg/m$^3$. It will be beneficial in the design and construction of nonstructural / structural fills due to lower stress level exerted on the foundation. Hardening time can be adjusted for use in the construction of light to massive structural fills. The coefficient of hydraulic conductivity of composite material was in the range of $1.73 \times 10^{-4}$ cm/sec and $2.97 \times 10^{-8}$ cm/sec which is considered as impermeable layer. It provided certain advantages over conventional fill material with its lower unit weight, higher strength and high volume stability.

2.13 LOW FLY ASH SLURRY WITH RIVER SAND

Low fly ash mixtures contain an additional ingredient (sand or filler). There is a broad range of mix designs compared to high fly ash mixes. Quantity of sand is higher than the cementitious materials in flowable mortar or K.Krete mixes. In 1977, a company known as K.Krete formulated the mixtures with 1305 to 1661 kg sand, 166 kg to 297 kg of fly ash, 24 to 119 kg of cement and 0.35 m$^3$ to 0.40 m$^3$ of water per m$^3$ of product. Iowa Department of Transportation (IDOT) formulated the mixes consisting of 59 kg of cement, 178 kg of fly ash, 1543 kg of very fine sand with a specific gradation and 0.35 m$^3$ of water to produce one m$^3$ of IDOT mortar (Ronald 1990).

A flowability of 200 mm is considered to be optimum to ensure self leveling. Low fly ash mixtures with high calcium fly ash hardened within 1 to 2 hours after placement. Low fly ash mixtures exhibited less bleeding or shrinkage because of fine aggregate in higher proportion and ability to drain water more readily through the flowable fill. Density of low volume fly ash is in the range of 1785 kg/m$^3$ to 2190 kg/m$^3$. This is more than high fly ash
mixtures. The density of K.Krete mixes is reported to be between 2003 kg/m$^3$ to 2163 kg/m$^3$ (Ronald 1990). Addition of air entraining admixture reduced the density of the mixtures. K.Krete mixtures are frequently designed to achieve a compressive strength of 0.69 MPa, 3.448 MPa and 6.895 MPa by adjusting the quantity of sand (Ronald 1990). IOWA mixtures are designed for a compressive strength of 0.69 MPa to 3.448 MPa. In low fly ash mixtures, high calcium fly ash replaces completely Portland cement. Permeability of low fly ash mixtures is greater than that of high fly ash mixes. It is in the range of $10^{-4}$ cm/sec to $10^{-6}$ cm/sec.

Also, Zhang Zhongije and Tao Mingjiang (2006) demonstrated a mix design for trench backfilling in highway cross drains suitable for adjacent soil. A mixture with lower quantity of cement and fly ash was appropriate for trench backfill.

**2.14 LOW FLY ASH SLURRY WITH FOUNDRY SAND**


Bhat and Lovell (1997) reported that proper proportioning of cement, fly ash, foundry sand and water are necessary to obtain the desired flowability and compressive strength. Subsequently, a logical procedure for mix design was developed to reduce empirical design based on flow curve, a point of minimum water requirement, correlation between compressive strength and w/c ratio. Also, Naik et al (1998) proportioned the mixtures to
have a compressive strength of 0.3 MPa to 0.8 MPa with foundry sand as a partial replacement of fly ash.

Tikalsky et al (1998) developed different mixture proportions for flowable slurry having sufficient flowability with spent casting sand that has strengths between 0.3 MPa and 0.8 MPa at 7-days. It is reported that spent chemically bonded casting sand are excellent replacement for river sand.

Dingrando et al (2004) carried out an analysis to evaluate the factors affecting flow loss. Main factor is the presence of cementitious fly ash in the mix. It is found that mixtures with cementitious fly ash exhibited much greater rates of flow loss. This can be controlled by using foundry sand with at least 6% bentonite. Mixtures prepared without cementitious fly ash also required less retempering water to recover flow once it is dropped below an acceptable level. In order to give self leveling to the flowable fill in the field a spread of 230 mm was found adequate.

Bleed water increased with increase in foundry sand and water content (Naik and Singh 1997 and 1997a). Mixes with fly ash having higher fineness and less water are free from bleed water even at one hour age. Flowable slurry with foundry sand showed absence of shrinkage cracks (Naik et al 1998). Settlement decreased with decrease in water content (Naik and Singh 1997 and 1997a). However, settlement was noticed up to 3 days in flowable slurry and thereafter it is free from settlement. In order to have settlement less than or equal to 3 mm, the water content of the mixes should be maintained to have a flow of 275 mm or less (Naik et al 1998). Penetration resistance is found to be influenced by cement content, type of fly ash and drainage conditions. Introduction of a geo textile drainage layer increased the penetration resistance (Bhat and Lovell (1996). Density of flowable slurry containing foundry sand is lower than mixtures containing natural sand.
Tikalsky et al (2000), Naik et al (1998) reported that density varied from 1570 kg/m$^3$ to 2115 kg/m$^3$.

Higher water/cementitious (w/c) lower quantities of foundry sand and increased fly ash content are required to maintain a low compressive strength. Compressive strength of flowable slurry containing foundry sand was generally lower than flowable slurry containing river sand. Greater quantities of fly ash and foundry sand with lower w/cm was used to control bleeding and fluidity. Compressive strength mainly depends on w/c ratio and absence of chlorides in waste foundry sand. Excavable slurry can be developed with desirable properties using foundry sand as a replacement for fly ash up to 85% (Naik et al 1998).

Flowable slurry incorporating fly ash and foundry sand are environmentally friendly material as there was reduction in concentration of certain contaminants (Naik et al 1998).

High pH within flowable slurry and the absence of chlorides in the waste foundry sand indicated that the flowable fill is non-corrosive in nature (Naik et al 1998). Permeability was affected by inclusion of either clean or used foundry sand to fly ash up to 70% (Naik and Singh 1997 and 1997a, Naik and Kraus 1999). The lower foundry sand mixes with higher fly ash mixtures decrease permeability due to the densification of the microstructure (Naik et al 1998). Permeability is comparable to or lower than compacted granular fills ranging from $10^{-4}$ cm/sec to $10^{-5}$ cm/sec (Dingrando et al 2004).

Turkel (2006 and 2007) produced flowable slurry mixtures with a low pozzolanic cement content and high Class C fly ash and limestone filler content. This combination produced excellent flowability and low compressive strength in the range of 0.85 MPa to 1.15 MPa at 28 days. Shear strength, cohesion intercept and angle of shearing resistance values of flowable slurry
mixtures exceed the most conventional soil materials. These properties are especially favourable to use flowable slurry mixtures behind the retaining walls besides other filling jobs.

2.15 POND ASH FLOWABLE SLURRY

Weathered fly ash as a result of outdoor storage for extended periods of time is called as pond ash/ basin ash. Pond ash can be substituted for commercially available fly ash. Use of pond ash can reduce the long term environmental liability associated with disposal sites.

Langton et al (1998) investigated the use of three sources of pond ash in flowable slurry along with cement, sand and water. A cement content of 1% to 12% by weight of fly ash was used in order to develop 0.2 MPa to 1 MPa compressive strength at 28-days.

Further, Naik et al (2002) developed flowable slurry using pond ash, fine crushed sand, cement and water. Mixtures were developed with different combinations of pond ash and fine crushed sand, (0% coal ash and 100% fine sand, 100% coal ash and 0% fine sand). It is found that water requirement of the mixes decreased with increased fine crushed sand content.

Density of the flowable slurry increased as the amount of fine crushed sand increased. Mixes containing pond ash set in 26 hours to 30 hours. Shrinkage/settlement was only 5% after 28 days (Langton et al 1998). However, increasing fine crushed sand content with reduced fly ash content generally increased the settlement of the mixtures because of the higher specific gravity of the sand (Naik et al 2002). Flowable slurry mixtures produced at very high flows, would achieve satisfactory compressive strength to support construction loading.
Permeability of compacted sand is in the range of $1 \times 10^{-3}$ cm/sec. to $2 \times 10^{-4}$ cm/sec (Langton et al 1998). CLSM mix prepared with crusher sand and pond ash water exhibited permeability in the range of $2.9 \times 10^{-6}$ cm/sec and $43 \times 10^{-7}$ cm/sec (Naik et al 2002). Pond ash which is not uniform in colour, size and texture is recommended for common backfill only. Material which is fine grained, more homogeneous is recommended for both structural backfill and common backfill.

2.16 PHOSPHO-GYPSUM IN FLOWABLE SLURRY

Phospho gypsum is a by-product in the production of phosphoric acid during the manufacture of fertilizers. Gandham et al (1996) developed slurry mixtures with phospho gypsum, class C fly ash and water.

Class C fly ash was used in the mixture in order to provide flowability, strength and stability characteristics. Flowability mainly depends on fly ash and water content in the mixes and Phospho gypsum alone does not contribute to a satisfactory flowability. Setting time decreased with increase with fly ash content and increased with water content. Shrinkage and expansion were generally within acceptable limits. Compressive strength depends on the fly ash content. Variation of fly ash content between 20% to 40% yields no significant variation in compressive strength. Mixes produced with more than 40% fly ash showed higher strength. Flexural strength also did not vary significantly with fly ash content. Permeability of phospho gypsum and fly ash mixtures are in the range of $10^{-5}$ cm/sec to $10^{-6}$ cm/sec. Field trails is recommended before using in full scale applications.
2.17 RICE HUSK ASH AND QUARRY DUST IN FLOWABLE SLURRY

Nataraja and Nalanda (2008) evaluated the potential of rice husk ash and quarry dust in flowable slurry. Mixture proportions were made with different combinations of fly ash, rice husk ash, sand, quarry dust, cement and water. Low fly ash slurry was proportioned with sand as well as with quarry dust. High fly ash slurry was proportioned with fly ash as well as with rice husk ash.

It has been observed that flowability increased with increase in w/c ratio regardless of the type of mixture. Mixture containing fly ash achieved desired flowability with a lower w/c ratio compared to mixture containing rice husk ash. Mixture containing quarry dust achieved desired flowability with lower w/c ratio compared to mix containing sand. Dry density of the mixtures containing quarry dust was greater than those of mixtures containing sand. Mixtures containing rice husk ash have a lower density than mixtures with fly ash. Density of mixtures was greater than 800 kg/m$^3$. Compressive strength of the mixtures containing fly ash was greater than mixtures containing rice husk ash. Compressive strength of mixtures containing quarry dust was greater than mixtures containing sand. But the compressive strength of the mixtures containing cement, rice husk ash, sand was greater than mixtures containing cement, rice husk ash and quarry dust. Water absorption of mixture containing cement and rice husk ash was greater due its high porosity. Water absorption of mix containing quarry dust was less when compared to the mixtures containing sand.

2.18 BOTTOM ASH BASED FLOWABLE SLURRY

Bottom ash is a by-product material of coal combustion. Won et al (2004) determined the feasibility of utilizing bottom ash as a controlled low
strength material. Flowable slurry was developed by using cement, fly ash, bottom ash, sand and water. Long term compressive strength, permeability tests, repeated wetting and drying and repeated freezing and thawing were conducted. It has been observed that compressive strength of slurry made of bottom ash increased up to 28 days and thereafter rate of increase has substantially reduced. As the particles of bottom ash are porous, the permeability co-efficient of mixture is varying between $10^{-6}$ to $10^{-7}$ cm/sec. Also, it is found that change in the strength of the mixture with bottom ash even after 25 cycles of alternate wet and dry cycles is insignificant. However, the resistance to freezing and thawing is low due to low strength.

2.19 ASSESSMENT OF STRENGTH DEVELOPMENT IN FLOWABLE SLURRY

Pradeep et al (2005) made an effort on the possibility of employing Abram’s law and Lyse’s rule for assessing the strength development of flowable slurry. The phenomenological model has been developed using data obtained from experiment carried on various combinations of fly ash, cement and rock dust. It is noticed that the developed model is reasonable for 0.3 to 0.7 water-cement ratios for assessing strength at different ages. The generalized Abram’s law equation is also applicable to the mixture with water-cement ratio beyond 0.7, but the constants are different. Also, it is concluded that the phenomenological approach has to be further strengthened to make it more practical as the range of strength of flowable slurry is far lower than normal concrete.

2.20 CURING EFFECT ON STRENGTH DEVELOPMENT

Compressive strength of flowable slurry with Class C fly ash was more than Class F fly ash for all curing regimes. Flowable slurry mixes exhibited significant strength gain at 38°C compared with lower temperatures.
Increasing the cement content with a parallel reduction in fly ash content led to an increase in strength at all curing temperature for mixtures containing Class F fly ash. Ratio of tensile to compressive strength is varied from 5 to 17% for various curing temperature. Tensile strength was reduced considerably upon exposed to drying conditions (Folliard et al 2003).

2.21 EFFECT OF PROLONGED MIXING TIME AND RETEMPERING ON FLOWABILITY

The prolonged mixing time may be experienced during construction delays as well as excess water added by truck operators prior to discharge. Increasing mixing time from 30 min to 90 min produced an increased flowability from 203 mm to 254 mm. However, extending the mixing time from 90 min to 279 min reduced the flowability to 197 mm which is just below the minimum required for good flowability. Prolonged mixing time had no effect on the volume of bleed water released but time of setting was increased. Retempering with 20% extra water increased flowability. Once the material has reached the initial set, no shrinkage or long term settlement of low fly ash slurry occurs. Time of setting was increased with increasing mixing time up to 150 minutes (Gassman et al 2001).

The prolonged mixing time experienced during construction delays as well as excess water added by truck operators prior to discharge decreased the compressive strength. Retempering with 20% extra water reduced measured strength at 28 days and 90 days. Delaying water had no measurable effect on 28 days compressive strength (Gassman et al 2001).

Proper control of strength development in flowable slurry application is necessary to allow future excavation. Prolonged mixing time reduces both short term (up to 90 days) and long term compressive strength (beyond 600 days). Retempering by delaying water did not impact short term
performance but it has inhibited the long term strength development (Pierce et al 2002).

2.22 ADMIXTURES IN FLOWABLE SLURRY

In general chemical admixtures are not included in the backfilling application due to its high cost, lack of awareness about their proper use and lack of knowledge about their features and benefits. However, it is routinely and extensively used in concrete mixes to improve their plastic and hardened properties such as workability, pumpability, transportability, durability and strength. In flowable slurry foaming agents are used to produce low density flowable slurry. Low density flowable slurry mixtures typically have air contents up to 70% volume (Hamid Farzam et al 1998).

Air entraining admixture used in flowable slurry can increase flowability, lower density but at the same time increase undesirable subsidence. Therefore, maximum amount of air entraining admixture adopted in the mix design should be determined with caution. It can also be added in flowable slurry to inhibit strength development. In general, the flowable slurry mixes without an accelerator agent generally hardened about 8 hours to 10 hours. Accelerator can be used to speed up the hardening time in 2.5 hours to 6 hours (Zhang Zhongije. and Tao Mingjiang 2006).

2.23 CORROSION RESISTIVITY OF FLOWABLE SLURRY

Corrosion is the one of the most important factor for deterioration of underground metallic pipe lines. Major effect of corrosion is the material loss in cross section and thereby, reducing the pipe carrying capacity and safety. Flowable slurry is being used as bedding and backfill for pipelines. Flowable slurry is less corrosive around metallic pipes compared to

Trejo et al (2005) investigated on the corrosion of ductile iron coupons embedded in 30 different flowable slurry mixtures exposed to a chloride solution for 18 months. It is noticed that the corrosion of ductile iron coupons embedded in CLSM and exposed to a corrosive chloride solution environment was lower than the corrosion of ductile iron coupons embedded in sand backfill material. Also, it is indicated that type of fine aggregate and fly ash type used in the flowable slurry mixture are statistically significant factors affecting the percent loss of mass coupons.

Halmen et al (2005) studied the corrosion of ductile iron and galvanized steel in 13 flowable slurry mixtures containing different types and proportions of materials exposed to aggressive environments. It is shown that ductile iron pipe and galvanized steel embedded entirely in flowable slurry exhibited lower corrosion activity than in sand.

In the field, conditions can occur where the pipe is not completely embedded in the flowable slurry, forming galvanic corrosion cells. Halmen et al (2006) investigated the corrosion performance of ductile iron and galvanized pipes exposed to sand, a combination of sand and flowable slurry, and a combination of clay and flowable slurry environments. It has been revealed that samples embedded in the sand-flowable slurry and clay-flowable slurry environments experienced higher mass loss than samples embedded entirely in sand.

2.24 FLOWABLE SLURRY IN PAVEMENT APPLICATIONS

Flowable fly ash slurry can be used effectively for embankments, base and sub base course for highways, railroads and bridge abutments
(Doven and Ayse Pekrioglu 2005, Krell 1989). Modulus of sub grade reaction (k) is used for the design of rigid pavement. It is usually in the range of 8.2 N/cm$^3$ to 49.2 N/cm$^3$ for most of soils. k-value of high fly ash slurry is usually 820 N/cm$^3$ or higher. Hence, it is superior to any other backfill material (Krell 1989).

The soil-based rubberized flowable slurry with 40% sand can be used for the bridge approach repair. The optimal design ratios are 0.7 cement to water ratio and 0.35 water to solid ratio. This mixture offered an acceptable flowability and a reasonable strength. The hardened CLSM behaved as a heavily over consolidated soil due to the cementation of binder and leading to a sound bearing capacity, negligible compressibility and hydro collapse (Pierce and Blackwell 2003).

Flowable fill is generally used for backfill and is placed underneath pavement. Lovencin et al (2006) evaluated the effect of moisture on the long term strength of flowable fill. Studies have been carried out on both excavatable and on-excavatable flowable fill mixtures. Drained samples were designed to allow seepage of bleed water from the mix and undrained samples were designed to not allow seepage of bleed water from the mix after placement.

Wisconsin Department of Transportation experimented with flowable fill using foundry sand, fly ash, cement and water for backfilling two bridge structures. One end of the structures was constructed with flowable fill while the other end was constructed with conventional granular fill. Base course and pavements were then placed to complete the project. The profile of the pavement was evaluated periodically by taking levels. Pavements distress was also monitored for rutting and cracking. The concrete bridge deck was in excellent condition and free from cracks. It has been observed that the use of
flowable fill as backfill performed slightly better than conventional granular fill. However the difference is not significant.

Jason and Mufan (2009) evaluated the bearing capacity of the soil-based rubberized hardened CLSM using California bearing ratio (CBR) method. It is found that CBR value is as high as 48, which is equivalent to that of a standard compacted aggregate sub base and base course. Therefore, the soil-based rubberized flowable slurry developed is suitable for pavement.

2.24.1 Rapid Setting Flowable Slurry for Pavement Applications

Street cut/repairs and re-opens them to traffic within 24 hours is quite common in cities. Regular CLSM requires 2 to 3 weeks to support traffic loads. In such circumstances, rapid set CLSM is found to be an ideal one. Rapid set CLSM initially attain considerable compressive strength (0.14 MPa) for withstanding traffic loads without undue settling within 4 hours, so as to permit overlaying a wearing course of pavement.

Du Lianxiang et al (2006) investigated the suitability of rapid setting controlled low strength material without cement for bridge approach applications. Ingredients used include Class - C fly ash, river sand and water. Rapid setting flowable slurry mixtures are designed using sand-to-ash ratio between 5 to 7. An excellent bonding has been observed between rapid setting flowable slurry backfill and hot-mix. Also, lower water-to-ash ratio achieves faster setting and hardening.

Regular flowable slurry contained more cementitious material such as cement and fly ash than quick set flowable slurry. Quick set flowable slurry consisted of cement, sand, accelerator and water. Landwermeyer and Rice Edward (1997) carried out both laboratory and field investigations on quick set and regular flowable slurry to study bearing strength, digablity and
subsidence. Also, cost analysis was made by considering the factors such as excavation, waste disposal, in-place backfill material costs, pavement demolition, construction costs, traffic control and quality assurance testing and inspection costs for utility cut/repair application. It has been noticed that regular flowable slurry attained good pavement support after 45 days. The bearing strength and sub grade reaction of quick set flowable slurry was comparable with sandy soil and gravelly soil. Also, the quick set flowable slurry is more cost effective than regular flowable slurry.

2.25 USE OF WASTE MATERIALS IN PAVEMENT

Use of waste materials in pavement would result in significant energy savings by reducing expensive transportation charges usually incorporated in the cost of conventional construction materials (Gregory et al 1984).

Extensive studies have been carried out using waste materials in pavement. It includes different kinds of industrial, domestic, and mining/metallurgical wastes. They are fused incinerator residue (Ormsby and Fohs 1990), colliery shale (Sherwood 1974 and 1975), calcined bauxite (Hosking and Tubey 1973), fly ash (Bofinger and Duffell 1972, Seung and Fishman 1993, Takuda et al 1995, and Sarkar and Little 1998) blast furnace slag (Mathur et al 1999), electric furnace slag aggregate (Rohde et al 2003), stone dust (Praveen Kumar et al 2006), recycled concrete (Molenaar and Van Niekerk 2002), recycled aggregate (Seung and Fishman 1993 and Taesoon Park 2003), recycled asphalt pavement aggregate (Bennert et al 2000), waste plastic strips (Sobhan and Mashnad 2002), cement kiln dust (Miller Gerald and Zaman Musharraf 2000, Taha 2003, Si Zhiming and Caroline 2007), bottom ash (Forteza et al 2004), incineration of municipal refuse (Lauer 1979), recycled roofing shingles (Watson et al 1988), zinc clinker and road milling material (Lawton et al 1999), quarry waste (Lilian Ribeiro
de Rezende et al. 2003), foundry sand (Aydalek and Guney 2007), phosphogypsum (Gregory et al. 1984), phosphogypsum slag (Foxworthy et al. 1996), blended calcium sulfate treated with slag (Mohammad Louay et al. 2006).

### 2.26 FLY ASH IN STABILIZED SUB BASE / BASE COURSE

Fly ash stabilized base courses are proportioned mixtures of fly ash, aggregate and an activator (cement or lime). This produces a strong and durable pavement base course with proper placement and compaction. Fly ash stabilized base courses are cost effective substitutes for properly engineered full-depth asphalt, cement-treated and crushed stone base courses. Fly ash stabilized base course is suitable for both flexible and rigid pavements (AASHTO, 1986).

Kaniraj and Gayathri (2003) investigated the factors influencing the strength of cement fly ash base courses. It has been stated that by appropriate selection of dry unit weight and degree of saturation of the mixes, it may be possible to achieve the required strength. The unconfined compressive strength increased up to a certain curing period and then tended to decrease.

Subsequently, Cho Yoon-Ho et al. (2006) proposed an approach to minimize the amount of shrinkage cracking in a cement-treated base (CTB). CTB is a stiff base that features higher rutting resistance and reduced fatigue cracking because of its ability to distribute traffic loads. It has been suggested that 25% fly ash and 10% expansive additive is the optimal mixing alternative to a cement-treated base to reduce shrinkage cracks.

Further, Hilmilav et al. (2006) attempted to study the effect of Class -F fly ash on the characteristics of pavement base course. It has been concluded that calcium silicate hydrate (C-S-H) gel along with calcium hydroxide maintained a bond between particles. Also, ettringite rods jointed
together resulting in an increased strength. Further, poisson’s ratio and dynamic elasticity modulus indicated that the strength of free stabilized fly ash with out aggregate is lower than the mixtures with aggregate. Mixtures having cement content less than 8 % may be used as sub base materials instead of being used in pavement base.

Also, Naji Khoury and Musharraf Zaman (2006) evaluated the effect of freeze-thaw on flexural strength of fly ash (10% Class C) stabilized limestone aggregate base. It is found that modulus of rupture decreased as freeze-thaw cycles increased up to 16. Subsequently, Guthrie et al (2008) assessed the durability of aggregate base materials stabilized with Class C fly ash, lime-fly ash, and portland cement. It is observed that Class C fly ash-treated specimens were significantly durable than the other specimens due to prolonged pozzolanic reactivity.

Hilmi Lav and Maysen Lav (2000) examined the microstructural, chemical, and mineralogical characteristics of stabilized fly ash as pavement base material. It has been observed that only calcite \([\text{CaCO}_3]\), calcium hydroxide \([\text{Ca(OH)}_2]\), quartz and mullite were present in the stabilized fly ash. The thermal analysis indicated that the lime in fly ash reacted immediately with water and carbon-di-oxide present in air. The studies on micro structural development indicated that fly ash particles served as nucleation sites for hydration and pozzolanic reaction products (C-S-H, CH and ettringite) at the early stage. Further, it has been concluded that cement stabilized fly ash gained higher strength than lime stabilized fly ash.

Kaniraj and Gayathri (2004) carried out investigation on consolidation and permeability characteristics of compacted fly ash. It is noticed that properly compacted fly ash embankments and fills resting on firm strata would not suffer large settlements and also co-efficient of consolidation
is similar to non-plastic silts. Fly ash exerts lesser lateral thrust on retaining walls than silt.

Samrat Mohanty and Yoginder Chugh (2006) carried out post construction environmental monitoring studies to assess the impact of unstabilized Class F fly ash sub base on flow direction of ground water and its quality. It has been concluded that the large volume fly ash sub base had no adverse effect on ground water flow direction as well as quality of ground water. Also, an attempt has been made to evaluate long term post construction structural performance of fly ash based road base. Falling weight deflectometer studies proved the excellent structural performance of fly ash based road base.

Jain et al (2004) carried out studies on fly ash stabilized with 10% to 50% of sand. It is found that optimum moisture content for stabilized fly ash decreases with increase in the proportion of sand. Also, addition of sand increased its CBR value substantially. Further, it is concluded that fly ash mixed with 40% to 50% sand can be effectively used in road construction on the poor soil sub grade.

Aykut Senol et al (2006) evaluated the effect of stabilization of four different types of soft sub grade using 10% to 20% fly ash. It is noticed that stabilization of sub grade using fly ash increased both the unconfined compressive strength and CBR value. Also, stabilizing soft sub grade minimizes delay in compaction in the field.

Wen Haifang et al (2007) investigated on stabilisation of recycled asphalt pavement material using cementitious high carbon fly ash to bring out a new pavement base material. It has been reported that using cementitious high carbon fly ash to stabilize recycled asphalt pavement as a base course has the potential to be a cost-effective and environment-friendly technology.
Shirazi (1999) evaluated the performance of lime (2% to 4%) and fly ash (3% to 6% Class C fly ash) stabilized base for flexible pavement systems on reconstructed highways in Louisiana and compared with soil-cement base (8% by volume). It is reported that unconfined compressive strength of lime and fly ash showed 30% lower than that of soil cement.

Ambarish Ghosh and Chillara Subbarao (2001) indicated that the addition of lime to fly ash produces a compact matrix and prolonged curing is necessary to achieve more compact structures. Formation of a densified interlocking network of reaction products is prominent in the mixes containing gypsum and cured for 10 months at 30°C. It has been stated that pozzolanic reaction produced compact matrix in the specimens stabilized with high lime (10%) and gypsum (1%) leading to strength and durability. Subsequently, Ambarish Ghosh and Chillara Subbarao (2006) investigated the effects of lime (4%, 6%, and 10%) and gypsum content (0.5% and 1.0%) on the tensile strength, bearing ratio, and durability characteristics of the stabilized fly ash. It is concluded that addition of small percentages of gypsum (0.5% to 1.0%) to fly ash lime mixes increased the tensile strength even at the age of 28 days. Further, it is observed that addition of gypsum to fly ash (1.4% CaO) is very much effective in enhancing the durability of the stabilized fly ash.

Sunil Arora and Aydilek Ahmet (2005) investigated on application of activated Class F fly ash with cement/lime mixtures for base layers in highways. It is noticed that unconfined compressive strength, CBR and resilient modulus test depend on the curing period, compactive energy, cement content and water content. Also, it is stated that lime treatment does not provide sufficient strength for designing the mixtures as highway bases.

Mike Jackson et al (2009) demonstrated to recycle the blend of bottom ash and fly ash new circulating fluidized bed (CFB) boilers as
stabilizer for pavement base course material. The plate bearing, automated
dynamic cone penetrometer (ADCP) and falling weight deflectometer (FWD)
test result revealed that the CFB ash exhibited modulus or strength equal to or
greater than the conventional lime rock material in both subgrade stabilization
and base course applications.

2.27 FLY ASH IN FLEXIBLE PAVEMENT (ASPHALT
CONCRETE)

In addition to the growing truck traffic volume, tire pressure and
traffic loading, daily and seasonal temperature variations also increase
stresses on asphalt pavements. This has increased the demand to modify
asphalt mixtures. Different methods are in practice to upgrade the properties
of asphalt mixtures. One of the most commonly used procedures is
modification by additives. AASHTO (1986) recommended fly ash as mineral
filler in HMA paving applications. Mineral fillers increase the stiffness of the
asphalt mortar matrix, improving the rutting resistance and durability of
pavements.

Ibrahim Asi and Abdullah Assáad (2005) attempted to find out the
optimum replacement percentage of the mineral filler with the fly ash. It has
been observed that asphalt concrete mixes with fly ash as a replacement of the
mineral filler showed better resistance to water damages and it is proportional
to the fly ash content. However, 10% of the mineral filler is the optimum
percentage to be replaced by fly ash to improve the mechanical properties.

Al-Suhaibani and Tons (1991) investigated the effect of size of fly
ash on the resilient modulus, rutting potential and water resistance of asphalt
concrete mixtures. It is found that the medium-size fly ash is the best size for
an asphalt extender.
Berthelot and Gerbrandt (2002) explored the use of cold in-place recycling and full-depth cementitious stabilization to strengthen thin pavements. Industrial waste co-products such as coal fly ash, bottom ash, and kiln dusts are used as cementitious waste material for the construction of road as base course. It has been stated that cold in-place recycling and full-depth cementitious stabilization is technically and economically feasible solution for thin paved roads built on clay-till sub-grades.

Barenberg and Thompson (1982) evaluated the performance of a pavement in power plant consisting of a 10-in (250 mm) thick lime and fly ash aggregate base and a 3-in (75 mm) thick asphalt concrete surface. It has been observed that the structural capacity of the pavement has not decreased over a period of five years. However, some transverse and longitudinal cracks are noticed over the pavement. The fatigue cracking is found to be insignificant.

2.28 FLY ASH IN RIGID PAVEMENT (CEMENT CONCRETE WEARING COURSE)

Sudip Basak et al (2004) reported that in rigid pavement fly ash can be used to replace a part of cement or sand or both. It is suggested that approximately 25% of volume of cement can be saved which indirectly save 15% of the cost of construction.

Franklin (1981) assessed the effects on the strength of pavement quality of air entrained concrete (4.5 ± 1.5%) using pulverished fuel ash to partially replace cement. It is found that air entrained mixtures containing hydrocarboxylic acid showed much greater reduction in water demand. Also, it is observed that mixes with 20% fly ash equalled the strength of pavement quality concrete by three months, whereas, mixtures with 40% fly ash equalled the strength of pavement quality concrete between 3 to 12 months.
Radlinski Mateusz et al (2007) evaluated the scaling resistance of ternary concrete prepared using varying quantities of Class C fly ash and silica fume. It has been concluded that the ternary mixtures containing 20% FA are much less prone to scaling than the mixtures with 30% FA.

Hazaree Chetan (2007) carried out laboratory study on fly ash concrete mixtures incorporating marginal aggregates. Cement replacements of 30%, 40% and 50% with fly ash was employed to prepare mixtures. Marginal aggregates found to be suitable in making pavement concretes with proper evaluation of aggregate grading and optimization of mixtures.

Ali Abolmaali et al (2006) evaluated the performance of fly ash concrete designed for highway pavements containing three different types of aggregate gradations such as gap-graded, dense-graded, and optimum-graded aggregates. Portland cement was replaced with 30% of fly ash for concrete mixtures. The durability of concrete with dense-graded aggregates is found to much better than other types of concrete.

Sukhvarash Jerath and Nicholus Hanson (2007) studied the effect of fly ash content and aggregate gradation on the durability of concrete pavements. It is stated that concrete mixtures containing dense graded aggregates and higher percentage of fly ash require less water content. Fly ash content increased from 30% to 45% in the concrete mixtures, decrease permeability, specific gravity, water absorption, and voids in hardened concrete. Also, the presence of fly ash improves durability of concrete without the loss of flexural strength and compressive strength.

Sutton (1965) experimented on concrete road constructed during the year 1950 and 1951. Fly ash was incorporated as replacement for some amount of cement on certain sections of road. It is found that concrete containing fly-ash had slightly lower strength at early ages than concrete
without fly-ash but at later ages the fly ash concrete gained higher strength. Also, it is observed that the fly ash increased the freezing and thawing resistance and alkali-aggregate reaction of concrete.

Stingley and Peyton (1965) monitored concrete road containing fly ash for a period of fourteen years in Kansas. It is noticed that presence of fly ash in concrete increased flexural strength. Substitution of fly ash by 25\% of the cement reduced surface cracking and also eliminated the map-cracking.

Carpenter and Cramer (1999) investigated the use of low-level replacements of mineral admixtures in reducing expansion of mortar bars due to alkali-silica reaction (ASR). Silica fume, powdered bottle glass, fly ash, and slag cement were tried for their potential to mitigate ASR in Portland cement concrete. All the mineral admixtures reduced alkali silicate reactivity in mortar and thereby expansion. It has been concluded that incorporation of 20\% of silica fume or 20\% specific fly ash or 40\% of powdered glass is very effective in reducing expansion in mortar below 0.2\%. Mixture incorporating 20\% silica fume was found to be the most satisfactory for a planned pavement patch application.

2.29 HIGH VOLUME FLY ASH CONCRETE FOR RIGID PAVEMENT

Srinivasan et al (2004) indicated that concrete pavements using 40 to 60\% of fly ash can be characterised as high-volume-fly ash (HVFA) concrete pavements. In order to achieve desired strength and durability of high volume fly ash concrete, it is essential to maintain low water-to-cement ratio with the help of superplasticiser. Pore filling effect and pozzolanic properties of fly ash improve the properties of fresh and hardened concrete. Economy in construction can be achieved through utilisation of fly ash and reduction in pavement thickness.
Binod Kumar et al (2007) carried out laboratory study on superplasticized high-volume fly-ash (HVFA) concrete consisting of 20%, 30%, 40%, 50%, and 60% of fly ash. It is found that 50% to 60% fly ash can be incorporated to fulfill the requirement of strength and workability of concrete for pavement construction. Among all the concrete mixtures, the mixture with w-c ratio of 0.30 and containing 60% fly ash exhibited least shrinkage.

Naik et al (1995) proportioned fly ash concrete mixtures replacing 20% to 50% cement with a Class C and 40% with a Class F fly ash. High volume Class F fly ash mixture performed better than 50% Class F fly ash mixtures. Class F fly ash in concrete was more effective than Class C fly ash in reducing chloride penetration. High volume fly ash mixtures (40% Class F and 50% Class C) showed better results in terms of mechanical and durability properties which could be an alternative to conventional paving material.

Golden Anthony and Digioia (2003) attempted to use Class C fly ash to replace 70% of the cement in the concrete pavement. It is observed that high-cement replacement concrete had good working characteristics and no significant problems were encountered while placing and finishing the pavement. Also, it has exhibited good resistance against sulfate attack. However, slight shrinkage is noticed in concrete pavement made of high volume fly ash concrete.

Naik et al (2001) made an attempt to evaluate salt-scaling resistance of concrete incorporating large amounts of Class C fly ash as well as Class F fly ash obtained from different sources. It is reported that laboratory mixtures incorporated with Class C fly ash up to 60% (by mass) exhibited very slight to moderate scaling. But, the pilot mixtures indicated that it is possible to produce structural-grade, salt-scaling resistant concrete using Class C fly ash up to 56%. However, it is noticed that specimens from
field construction mixture, even with 50% Class C fly ash showed moderate to severe scaling. But in the case of the field concrete with class F fly ash, slight to moderate scaling is observed at 40% of fly ash.

Roller-compacted concrete (RCC) is typically used in the construction of dams and road pavements as it provides substantial benefits over conventional concrete such as faster construction, lower costs of construction and materials, etc. Incorporating fly ash into RCC can further reduce cost of materials and enhance the concrete performances. Tangtermsirikul et al (2004) formulated a model to predict compressive strength of mixtures of roller-compacted concrete with fly ash based on quantities of concrete ingredients, chemical composition and physical properties of cement and fly ash. It is found that the proposed model could be used to predict compressive strength of roller-compacted concrete with fly ash at the ages between 3 days to 91 days with satisfactory accuracy.

Cengiz Duran Atis (2005) carried out a laboratory investigation to evaluate the strength properties of high-volume fly ash (HVFA) roller compacted and superplasticised workable concrete cured at moist and dry curing conditions. Concrete mixtures were made with 0%, 50% and 70% Class F fly ash with w/b ratio in the range of 0.28 to 0.43. It has been stated that producing high-strength concrete is possible with high-volume fly ash content. HVFA concrete was found to be more vulnerable to dry curing conditions than OPC concrete. The HVFA concrete is an adequate material for both structural and pavement applications.

Naik et al (2001) studied the performance of conventional roller-compacted high-volume fly ash (HVFA) concrete pavement no-fines permeable base course containing fly ash and also, roller-compacted concrete pavement (RCCP) containing 30% ASTM Class C fly ash. It has been concluded that mechanical behavior of RCCP is similar to that of
conventional paving concrete. However, non air-entrained RCC is susceptible to freezing and thawing (F and T) effect under critical saturation. But the specimen derived from conventional HVFA pavement exhibited excellent performance. The specimen from RCCP pavement showed satisfactory performance except freezing and thawing resistance.

Naik et al (2003 and 2004) evaluated the long-term performance of concrete pavements made with high volume of Class F and Class C fly ash replacing cement up to 67% and 70% respectively. It has been reported that Class F fly ash contributed higher strength and greater resistance to chloride ion penetration to concrete than class C fly ash. Also, it is found that that the concrete pavement sections containing high-volumes of Class F fly ash (35% to 67%) performed well in the field with only minor surface scaling. Concrete pavement sections containing up to 70% Class C fly ash have experienced surface damage to some extent due to abrasion and scaling, especially in an area where truck traffic makes a 90° turn.

2.30 LIME FLY ASH WBM BASE COURSE

IRC 60 – 1976 specified that lime fly ash concrete is a semi rigid material having superior load dispersion characteristics than conventional WBM. As a base course in flexible pavement, the thickness of the base course should not be less than 10 cm. IRC 15 – 2002 recommends the provision of 10 cm thick of lime pozzolana concrete sub base in place of 15 cm thick WBM. Lime fly ash concrete should be designed to give a compressive strength of 4 MPa to 6 MPa at 28 days to act as semi rigid material. IRC 74 – 1979 also recommends small thickness of lean cement fly ash concrete as a pavement base or sub base course. Addition of fly ash in cement paste improves the plasticity and adhesiveness of the mixture and reducing the tendency of segregation.
2.31 CONVENTIONAL BASE COURSE OF PAVEMENT

Natural sources of soil or gravel are scarce and expensive to be used as a binding material in Water Bound Macadam (WBM) in developed and urban areas. Also, in most of the cases, conventional binders do not satisfy the specified criteria of liquid limit and plasticity index. Further, binders are very sensitive to water and are prone to erosion. Erosion is very severe in WBM with conventional binder without an overlay of bituminous topping. Binder used in WBM becomes dusty leading to raveling and pot holes. Hence, there is a need to look for a binder which is economically viable, environment friendly and perform better under moving vehicles.

Bhavanna Rao (2005) highlighted the adverse effects of using natural gravel in sub base, base and WBM. It has been reported that gravelly soils are not suitable for use in sub base or base for all major district roads (MDR), state highways (SH) and national highways (NH). The material such as gravel and sand or stone dust or fly ash in 1:2 proportions have been suggested as binding material in WBM for low traffic roads and for roads with immediate black topping. Also, gravel and sand or stone dust or fly ash in 1:1 proportion may be permitted in sub base for low traffic roads. In case of berms, gravel and sand or stone dust or fly ash in 2:1 proportion gives best results.

In India, mostly, wet mix macadam (WMM) is preferred as a base course for flexible pavement. As WBM construction is labour intensive and time consuming method, it is phased out. WMM should be well graded with enough fines to avoid any segregation during placement. If the care is not taken during discharge to avoid segregation, it will enhance the porosity leading to impregnation of dust and dirt. The degree of compaction is also difficult to achieve in such cases. At the same time, it will affect the adhesion of the flexible dense bituminous macadam laid over WMM. Dry lean cement
(DLC) base course is used to support the rigid pavements. Use of fly ash in DLC reduces the tendency of plastic cracking due to better water retentivity. It is possible to achieve finishability and compatibility (Ernest Kingley 2005).

Ravishankar and Nagabhushan Das (2004) studied the load settlement behaviour of WBM pavement with reinforcement. It is found that settlement was reduced for reinforced sub grade for heavy and light compaction at soaked condition. The load carrying capacity of pavement with geogrid interface was more than the pavement with geogrid in the sub grade.

2.32 SUMMARY

Approximately 110 million tonnes of fly ash are produced in India annually from the combustion of coal and it is increasing rapidly due to the growth in demand for energy. Presently as per the Ministry of Environment and Forest Figures, only 30 % of ash is being used. As per MoEF notification, 100% utilization of fly ash by all thermal power stations within four years for existing stations and three years for new stations has to be realized. Therefore, a much more aggressive fly ash utilization strategy has to be developed and executed. The concept of flowable slurry will boost the large-scale utilization of fly ash and other industrial wastes.

It is evident from the review of literature that the exhaustive and comprehensive studies were carried on the characteristics of high volume fly ash flowable slurry (using fly ash as principal component along with cement, lime, silica fume, water reducing admixtures etc) such as flowability, density, plastics properties and compressive strength to utilize as structural fill, embankment fill, utility cut fills, etc. pavement sub-base and base courses. Also, the characteristics of low volume fly ash flowable slurry with industrial waste materials as filler and their applications have been extensively investigated and reported in the literature. Further, substantial work has been
done regarding utilization of fly ash as a pozzolana or binder in asphalt concrete and rigid pavement and its effect on the performance of pavement, besides stabilization of soils in sub-grade.

However, not much attention has been focused so far on the characteristics of fly ash gypsum slurry with quarry waste as filler and its suitability as a binder to bind the aggregates together in base course of pavement to replace the conventional water bound macadam and wet bound macadam having some of the inherent demerits.

Hence, in the present work, an attempt has been made to study the characteristics of fly ash gypsum slurry with quarry waste as filler. Also, the concept of slurry bound macadam has been proposed for the pavement, wherein the flowable fly ash-gypsum slurry is used as filler to fill the voids in pre-packed aggregates as well as a binder to bind the aggregates together and evaluated its properties such as compressive strength and modulus of elasticity to assess its suitability as a base course in pavement.