EFFECT OF AIR COOLED BLAST FURNANCE SLAG AND METAKAOLIN ON COMPRESSIVE AND FLEXURAL STRENGHTH OF CONCRETE CONTAINING FLY ASH

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CERTIFICATE

I hereby certify that the Project Dissertation titled **" Effect of Air cooled Blast Furnance Slag and Metakaolin on Compressive and Flexural Strength of Concrete containing Fly Ash**. " which is submitted by Kartic Gupta, Roll No 2K16/STE/10, Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere

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Abstract

Concrete is the most commonly used construction material in the world. Concrete is extensively used in infrastructure projects. The concrete obtained by mixing cement, water and an inert matrix of sand and gravelundergoes a number of operations such as transportation, placing, compacting, finishing and curing.

Pozzolanic materials including flyash, metakaolin, slag, Rice Husk Ash and silica fume have been used in recent years as cement replacement material for developing HSC with improved workability, strength and durability with reduced permeability. Metakaolin, which is a relatively new material in the concrete industry is effective in increasing strength, reducing sulphate attack and improving air-void network. Pozzolanic reactions improve the microstructure of concrete and chemistry of hydration products by consuming the released calcium hydroxide (CH) and production of additional calcium silicate hydrate (C-S-H), resulting in an increased strength and reduced porosity and therefore improved durability.

Use of Metakaolin in construction industry as partial replacement of cement started in the 1960's and the interest in this material has considerably increased in recent years. Metakaolin has pozzolanic properties bringing positive effects on resulting properties concrete. Pozzolanic properties cause chemical reaction of active components with calcium hydroxide (portlandite), which is formed as a product of cement hydration. This reaction leads to formation of binding phases of following types: secondary C-S-H gel, C4AH13, C3AH6, and C2ASH8 thereby increasing strength.

The Air cooled blast furnance slag (ACBFS) has also been used as partial replacement of coarse aggregates in the recent past . In the previous studies it has been confirmed that the concrete made with natural aggregates and with ACBFS has comparable compressive.

Chapter 1
Introduction

1.1 General

Concrete is the most commonly used construction material in the world. Concrete is extensively used in infrastructure projects. The concrete obtained by mixing cement, water and an inert matrix of sand and gravelundergoes a number of operations such as transportation, placing, compacting, finishing and curing. The ingredients of the concrete consists of active materials like cement, water and inactive materials comprising of fine and coarse aggregates. Concrete is most widely used construction material due to good compressive strength and better durability characteristics.

A properly designed concrete mix should have minimum possible cement content without sacrificing the strength in order to make it an economical mix. In general, a fresh concrete must be workable and a hardened concrete must be durable and have the desired strength . Water-cement ratio is the most critical factor in concrete mix design which directly effectsthe strength of concrete. Other important factors are: aggregate to cement ratio, grading of aggregate, shape and texture of aggregate particle and amount of entrained air.

The properties like durability, workability etc. are vital performance parameters of concrete. This has led to the work which was initially limited to High Strength Concrete (HSC), then extended to High performance Concrete (HPC). HPC mix is designed with mineral and chemical admixtures along with other normal ingredients of concrete having low water-cement ratio.

Pozzolanic materials including flyash, metakaolin, slag, Rice Husk Ash and silica fume have been used in recent years as cement replacement material for developing HSC with improved workability, strength and durability with reduced permeability. Metakaolin, which is a relatively new material in the concrete industry is effective in increasing strength, reducing sulphate attack and improving air-void network. Pozzolanic reactions improve the microstructure of concrete and chemistry of hydration products by consuming the released calcium hydroxide (CH) and production of additional calcium silicate hydrate (C-S-H), resulting in an increased strength and reduced porosity and therefore improved durability.

Use of Metakaolin in construction industry as partial replacement of cement started in the 1960's and the interest in this material has considerably increased in recent years. Metakaolin has pozzolanic properties bringing positive effects on resulting properties of concrete. Pozzolanic properties cause chemical reaction of active components with calcium hydroxide (portlandite), which is formed as a product of cement hydration. This reaction leads to formation of binding phases of following types: secondary C-S-H gel, C4AH13, C3AH6, and C2ASH8 thereby increasing strength.

The Air cooled blast furnance slag (ACBFS) has also been used as partial replacement of coarse aggregates in the recent past . In the previous studies it has been confirmed that the concrete made with natural aggregates and with ACBFS has comparable compressive strength.

1.2 Use of mineral admixtures in concrete

- The mineral admixtures like flyash, metakaolin and ACBFS have been used in production of concrete from sustainability viewpoint in the recent years. In the present study flyash, metakaolin and ACBFS have been used as additional materials and there effect on mechanical properties of concrete has been investigated.
- Metakaolin is white, amorphous, highly reactive aluminium silicate pozzolan forming stabile hydrates after mixing with lime stone in water and providing concrete with hydraulic properties.
- ACBFS is used as coarse aggregate in concrete is angular and roughly cubical , with texture ranging from rough and vesicular (porous) to glassy (smooth) with conchoidal fractures . Fine slag screenings are similar in density to natural sand , while the density of coarse aggregate particles is as much as 20% less than natural aggregates having the same gradation .
- Fly ash is used to achieve one or more of the following benefits:

- Reducing cement content to reduce costs
- Improving workability
- Reducing heat of hydration
- Improving durability
- Attaining required levels of strength

1.3Need and Objective of the Present Study

1.3.1 Need

The review of literature presented in the chapter 2 reflects that the various studies had been mainly confined to use of fly ash in concretes. A reviws of previous studies shows that the individual effect of addition of either ACBFS , fly ash or metakaoline on strength properties of concrete .Research has been done up to binary level however studies dealing with ternary mixes and quaternary mixes are scarce .Also the study dealing with combined effect of addition of ACBFS , fly ash and metakaolin on the flexural and compressive strength of concrete are scanty . Therefore a need was felt for carrying out the present study by using the above material at quaternary level .

1.3.2 Objectives

The objective of this investigation is to explore the feasibility and effect of replacement of coarse natural aggregates with blast furnace slag and partial replacement of cement by metakaoline and fly ash in different percentage proportions. This will help in conserving the natural resources and keeping ecological balance to fulfil present demand of construction material in infrastructure development sector which is increasing at alarming rate. Therefore it is required to reduce the use of natural aggregates and cement to meet the future demand which will enhance the utility of waste materials and at the same time minimize the demand for natural aggregates and cement.

The following specific objectives have been identified for the present study:

- To investigate the effect of partial replacement of cement by fly ash on compressive and flexural strength of concrete
- To investigate the effect of partial replacement of natural aggregates by air cooled blast furnace slag in different percentage on compressive and flexural strength of fly ash concrete
- To investigate the effect of partial replacement of cement by fly ash and metakaolin in different percentages as binary and ternary mix blends on compressive and flexural strength of concrete
- To compare the results of compressive strength and flexural strength of concrete containing fly ash , air cooled blast furnace slag and metakaoline

1.4Organisation of Thesis

The entire thesis has been presented in Fivechapters. The organization of thesis is as given below:

- **Chapter 1** deals with the introduction to concrete in general,metakaoline , air cooled blast furnace slag and fly ash as materials, environmental aspect of reducing cement content and strength characteristics (i.e. compressive strength and flexural strength). The need, objectives and the scope of work are also stated in this chapter. Finally, the organization of the thesis is presented.
- **Chapter 2** presents the literature reviews related to the present study. The available literature on concrete containing fly ash, metakaolin and ACBFS is presented in this chapter to establish the need for present study.
- **Chapter 3** presents the experimental program carried out to develop the mixture proportions, various laboratory tests conducted on the materials used in the investigation, Concrete mix design to select the reference mix, Proportioning methods of fly ash , air cooled blast furnace slag and metakaolin concrete mixes in the form of tables, the mixing procedure, and the curing of concrete cubes and beams and then the testing of hardened concrete are also discussed in this chapter.
- **Chapter 4** deals with the results obtained from the experiment which are presented and discussed in detail in the form of tables and graphs. Discussion on effects of fly ash , air cooled blast furnace slag and metakaolin on compressive strength and flexural strength is also mentioned.
- **Chapter 5** deals with the summary and the conclusions drawn from present study, followed by a set of recommendations for future work. The list of references has also been appended with.

Chapter 2
Literature Review

2.1 General

This chapter deals with the review of the published literature on concrete containing fly ash. Its hazards, disposal, environmental aspects and utilization are also discussed. Structural properties of fly ash concrete and quaternary concrete containing fly ash , air cooled blast furnace slag and metakaolin have been reviewed in brief and emphasis has been laid on Compressive strength and flexural strength of concrete containing fly ash , air cooled blast furnace slag and metakaolin.

Fly ash concrete is obtained by replacing a part of cement by an appropriate amount of fly ash in the concrete. In area of high performance concrete (HPC), major advancements have been largely observed with the incorporation of mineral admixture like fly ash. The use of metakaolin and air cooled blast furnace slag in addition with fly ash has proved effective in enhancing the mechanical properties of fresh and hardened concrete to a great extent. Addition of metakaolin improves the strength, durability and packing density of concrete, which leads to its improvement in resisting chemical attack, permeability etc.

2.2Review of previous studies on properties of flyash concrete

Davis (1937) investigated different properties of fly ash as Pozzolans and found that:

(i) Fly ash varies in detailed chemical composition the main difference, as far as effect on concrete is concerned being its carbon content. It was also found that particles of fly ash are spherical and finer than that of cement particles.

(ii) Fly ash exhibits Pozzolanic properties. Also fly ash of low carbon content and high fineness can be used as a 30% replacement of cement in concrete which is standard moist cured at a temperature of 27+ /- 2 degree Celsius and 60% relative humidity.

(iii) Fly ash under moist curing conditions may be in as high as 50% replacement.

(iv) The results obtained are most favorable, if fly ash with cement of normal or high fineness or high lime content is used.

(v) If fly ash is intergraded with cement, very good results are obtained and higher early strength concrete is obtained.

(vi) Fly ash retard the setting time, but this remains within specified limits & water reducing agents are more effective in concrete with fly ash than without it.

(vii) Fly ash can be used in excess of amount of cement replaced and as such, excess can then be considered as replacing the sand, thus permitting a reduction in the amount of sand.

Davis further found that the properties of concrete containing fly ash with relatively low carbon content and high fineness as compared to concrete containing no fly ash are affected as follows:

(i) With the decrease in carbon content and increase of fineness of fly ash, the water demanddecreases.

(ii) Improved workability and reduced tendency to segregation and bleeding.

(iii) For a 30% replacements and standard curing, the early strength is lower than that of control concrete but becomes higher after 3 months.

(iv) Under moist curing conditions. The strength of fly ash concrete is higher than that of plain concrete even at the age of 28 days.

(v) Increased ultimate compressive strength is not affected by increase in cement content of mix. Also modulus of elasticity is not affected much. It is lower at lower ages and higher at later ages.

(vi) Shrinkage and autoclave expansion is reduced.

(vii) Resistance to sulphate and also to freezing thawing is increased.

(viii) Heat of hydration is reduced.

(ix) Permeability and leaching arc reduced.

(x) Plastic flow at early ages is more and is less at later.

Haque et al.(1984) reported that compressive strength of high volume fly ash content increased. In case of super plasticized concrete, there was almost negligible strength loss between the mixes 0.40 and 0.50 (w/c). The rate of strength variation seemed to be dependent on the consistency and presence of different admixtures. They also reported that high volume fly ash concrete (HVFC) all appeared to more workable than indicated by the results of the slump test. A slump loss of 25 mm to 30 mm (1 to 1.2 inches) was measured for all mixes that recorded slumps within 40 minutes of the initial test No slump concrete also appeared to be much stiffer toward the end of the casting period. This apparent loss in workability seemed to a characteristic of HVFC. They also reported that the compressive strength of HVFC with a given aggregate cement ratio decreased as the fly ash content increased. As an average, a slump loss of 25 mm (1 inch) took place after 40 minutes under laboratory conditions. In field applications, the loss in workability could be greater.

Berry et al. (1986) reported that the fly ash concrete showed reduced bleeding and segregation and to be more satisfactory when placed by pumping than plain concrete placed under similar circumstances. According to Singh, et al." the dispersion obtained by fly ash was stable. As the water content was low in HVFC the bleeding was very low and often negligible.

Ravina & Mehta (1986) investigated the effect of replacing 35 to 50 % of cement by fly ash, on the compressive strength of lean concrete mixes using two ASTM class F and two ASTM class c fly ash .tests results showed that, compared concrete with 35 to 50% replacement with fly ash reached the required strength at 35 to 170 days, depending on the replacement percentage and properties of fly ash.

Berry et al. (1986) reported that both the strength at a given age and the rate of strength gain of fly ash concrete were affected by the characteristics of the fly ash (properties, chemical composition, particle size, reactivity), the cement with which it was used, the proportions of each used in the concrete, the temperature and other curing conditions, as well as the presence of other additives.

Parrott (1987) reported the rate at which concrete carbonates was a function of the following factors: level of compaction, carbon dioxide concentration/level, period of moist curing, permeability, ambient temperature and humidity conditions, mix proportions, degree of saturation (moisture content), and the mass of calcium hydroxide available for reaction The main factor that could be used to limit the rate of carbonation is W/CM. In general a reduction in W/CM greatly reduced the measured depth of carbonation. Slow reacting systems such as those with fly ash benefit more from prolonged moist curing because the cement in the surface layers of drying concrete will virtually stop hydrating if the internal relative humidity drops to about 80%. This resulted in a high porosity and a high permeability in the surface layers and increased the rate of carbon dioxide diffusion.

Lame (1989) investigated the effect of replacing cement (0 to 55%) by the fly ash, he took three series of concrete mixes with water- cementitious material ratio of 0.3, 0.4, 0.5 respectively and concluded that fly ash contributed little strength at early ages. At 3 days, compared to portland cement concrete, the compressive strength reduced by 16% in average for a 15% fly ash replacement, and 66% for 55% fly ash replacement. At 28 days, the strength of fly ashes mixes was slightly lower (4% in average) than portland cement mixes, although 55% fly ash replacement still resulted in a 44% strength reduction. At the later ages, the contribution of fly ash to compressive strength development became significant.

Sivasundereram et al. (1990) reported that excessive dosage of the naphthalane — based superplasticizer used in HVFC to obtain the required workability resulted in delayed setting of certain concretes especially, in those with high cementitious material content.
Rao, et al. reported that workability of fly ash concrete was more than that of controlled concrete even at 60% fly ash content.

Reddy et al. (1994) investigated the effects of fly ash, obtained from Nellore Thermal Power Station, on six lean concrete mixes replacement levels of 10,20,30,40 and 50% and observed that though the rate of gain of compressive strength of fly ash concrete was less than that of reference concrete during the initial period of 28 days, it was more during the subsequent period reaching 90% of the reference mix at the age of 90 days.

Naik et al. (1994) investigated the effects of source and amount of fly ash on strength and durability properties of concrete. Mechanical properties considered were compressive strength, tensile strength, flexural strength, and modulus of elasticity.. They concluded that in general strength and durability properties of concrete were considerably affected by both of the fly ash source and amount of fly ash. In addition, the strength and durability properties for the 40% fly ash mixture were either comparable or superior to the no fly ash concrete. The salt scaling resistance of fly ash concrete was either comparable to or better than no —fly ash concrete; except for one source of fly ash at 60% cement replacement level. All the mixtures, with and without fly ash, tested in this investigation confirmed to the strength and durability requirements for excellent quality structural grade concretes. They also investigated the compressive strength and abrasion resistance of concrete by replacing cement with fly ash upto 70%. They reported that compressive strength as well as the abrasion resistance of the concrete decreased with increase inproportion of fly ash.

Malhotra et al. (1994) reported that the water required for workability of mortar and concretes, depends on the carbon content of fly ashes; the higher the carbon content, higher the water needed to produce a paste of normal consistency and that higher carbon content (2- 10%) was quite common in low –calcium fly ashes. They have explained that the properties of fly ash were affected by the quality of coal fired in the furnace and the combustion process. They found that the un-burnt carbon in fly ash (determined by loss on ignition), was one of the important parameters of the assessment of the quality of fly ash.
Langley and Leaman, (1998) elaborated Plastic shrinkage was a potential problem of HFVA concrete. The amount of bleed water available for evaporation of HVFA concrete was very low because of its low unit water content, and therefore it was recommended that moist curing of HVFA concrete be started as soon as the concrete was poured to limit the amount of evaporable water and reduce plastic shrinkage.

Mehta (1998) investigated that in order to understand the benefits of using fly ash in concrete, the physical manifestations of the chemical reactions should be looked at. The properties of concrete are influenced by many factors. One of the factors that was particularly very important was the strength properties of the interfacial bond was called the transition zone in the Portland cement was very weak because of the presence of very large crystals of $Ca(0H)_2$, which find space here due to the wall effect next to the coarse particles.

Rangaswamy (1999) investigated in India National mission on fly ash utilization and disposal had been initiated under the aegis of department of science and technology. The Andhra Pradesh government had directed all thermal power plants in the state to supply fly ash free of cost to cement and building material manufacturers. Reclamation of abandoned ash ponds undertaken by several countries to convert them as parking lots, grazing fields, playgrounds etc

Rao et al. (1999) reported that workability of fly ash concrete was more than that of controlled concrete even at 60% fly ash content. However the workability increased up to

40% fly ash and then showed slight decrease for fly ash contents onwards. They had further reported that the compressive strength of HVFC for a given aggregates cement ratio decreased as the fly ash increased.

Gopalakrishanan et al.(2001) studied the strength characteristics and durability of fly ash concrete with different fly ash replacement levels and reported that fly ash concrete up to 25% replacement level would render the concrete more durable and corrosion resistant, beside the strength requirements.

Krishna et al. (2002) reported that constructive efforts were being made all over the global to utilize fly ash in spite of several avenues identified for potential use of fly ash and attractive incentives offered by the government, only less than 5% of ash was put to use in India , leaving large volume of flyash in lagoons leading to air water and land pollution. 10% of current concrete produced worldwide utilizes flyash . Inchina rate of utilization of flyash in hongkong and some European countries like Netherlands and Denmark was very high. Thus there was huge potential for the increased use of flyash in concrete in the world (Malhotrav.m. . several research institutions like CBRI –Roorkee, CBRI- New Delhi , CPWD, IIT’s etc. are launching demonstrative projects on flyash utilization to create confidence in the perspective users to promote its bulk utilization. It was felt that bulk utilization of fly ash was possible by using it in the construction of roads and embankments. Wide spread reluctance in use of flyash in civil engineering. Applications may be due to the fact that thermal power plants in India have not yet accorded recognition to bottom ash and fly ash as two distinctly different resource materials for other industries.

Singh et al. (2003) reported that due to low cement content there was less heat of hydration, therefore very efficient in reducing temperature rise and eliminating thermal cracks. He has further reported that fly ash, since 30% lighter and finer than cement, it made concrete more workable. Ordinary Portland cement grains were prone to exhibit some coagulation or flocculation fresh concrete resulting non-uniform non-homogeneous structure. Addition of fly ash dispersed these cement flocs thus making more paste and improving the workability.

Siddique (2003) reported the results of an experimental investigation to study the effects of replacement of clement (by mass) with throe percentages of fly ash and the effects of addition of natural san fibers on the slump. Vee Bee time, compressive strengths,Splittensile strength, flexural strength and impact strength of fly ash fiberous concrete San fibers belong to category of 'natural bast fibers" It was mostly grown in the Indian subcontinent, Brazil,Eastern & Southern Africa and some parts of the United states (Hawaii and Florida). A control mixture of proportions 1:1.4.2.19 with W/C of 0.47 and super plasticizer,cementitious ratio of 0.015 was designed Cement was replaced with three percentages (35%, 45% and 55%) of class F fly ash. Three percentages of san fibers (0.25%. 0 50%, 0.75%) having 250mm length were used. The test result indicated that the replacement of cement with fly ash increased the workability (slump and Vee-Bee time), decreased compressive strength, splitting tensile strength and flexural strength and had no significant effect on the impact strength of plain (control) concrete. Addition of san fibers reduced the workability, did not significantly affect the compressive strength, and increased the split tensile and flexural strength and tremendously large-impact on strength of fly ash concrete as the percentage of fiber was increased.

Siddique (2004) reported the results of an experimental investigation that were performed for fresh concrete properties; slump, air content, unit weight and replaced with three percentages (40%, 45% and 50%) of class F fly ash Tests were performed for fresh concrete properties; slump, air content, unit weight and temperature. Portland cement modulus of t incorporating with concrete replacement of cement in concrete decreased its 28 days compressive Test result indicated that the use of high volume of class F fly ash as a partial elasticity and abrasion resistance were determined up to 365 days temperature, Compressive strengths, splitting tensile and flexural strengths, modulus of elasticity and abrasion resistance of concrete. However all these strength properties and abrasion resistance showed results continuous and significant improvement at the ages of 91 and 365 days, concrete which was most probably due to the pozzolanic reaction of fly ash., Based on the tests, it was concluded that class F fly ash could be suitably used upto 50% level of cement replacement in concrete for use in precast elements and reinforced cement concrete construction.

Bremner et al.(2004) investigated that although concrete mixtures containing fly ash tend to gain strength at a slower rate than concrete without fly ash, the long-term strength was usually higher. After the rate of strength gain of hydraulic cement slows, the continued pozzolanic activity of fly ash provides strength gain at later ages if the concrete was kept moist; therefore, concrete containing fly ash with equivalent or lower strength at early ages may have equivalent or higher strength at later ages than concrete without fly ash as long as the concrete was moist cured or exposed to sufficient quantities of moisture during service. The strength gained continues with time and resulted in higher later-age strength than could be achieved by using additional cement. However, by using accelerators, activators, water reducers, or by changing the mixture proportions, equivalent 3 or 7-day strength may be achieved as per (ACI Committee 232, 2003). High calcium fly ashes (Class C) showed a more rapid strength gain at early ages than concrete made with a lower calcium fly ash (Class F) because Class C ashes often exhibited a higher rate of reaction at early ages than Class F ashes.

Mohommed et al.(2011) reported that consumption of Ordinary Portland Cement (OPC) caused pollution to the environment due to the emission of CO_2. As such, alternative material had been introduced to replace OPC in the concrete. Fly ash was a by-product from the coal industry, which was widely available in the world. Moreover, the use of fly ash was more environmental friendly and saved cost compared to OPC. Fly ash was rich in silicate and alumina, hence it reacted with alkaline solution to produce aluminosilicate gel that bind the aggregate to produce a good concrete. The compressive strength increased with the increasing of fly ash fineness and thus the reduction in porosity could be obtained. Fly ash based geopolymer also provided better resistance against aggressive environment and elevated temperature compared to normal concrete. As a conclusion, the properties of fly ash-based geopolymer were enhanced with few factors that influenced its performance in many aspects such as compressive strength, exposure to aggressive environment, workability and exposure to high temperature.

Gunavant et al. (2013) investigated and reported that High Strength Concrete was made by partial replacement of cement by fly ash. The shrinkage of High Strength Concrete had been studied using the different mixes from a minimum of 10% to maximum of 70 %.. The rate of increase in shrinkage with time was uniform for low fly ash content, whereas it generally increases after 28 days for high volume of fly ash and the high volume fly ash concrete yielded slow strength development at an early age.

2.3 Previous studies on the properties of metakaolin based concrete

Wild et al. (1996) investigated the workability of metakaolin concretes. Replacement levels ofordinary Portland cement (OPC) by metakaolin (MK) were 0, 5, 10, 15, 20, 25, and 30% and water-binder ratio (w/b) was 0.45. OPC concrete mixture proportion was1:2.3:3.4.Workability results (slump, compacting factor and vebe time are given in Table 2.1

Table 2.1 Workability of metakaolin concretes

Metakaolin (%)	Superplasticizer (%)	Slump (mm)	Compacting Factor	Vebe time (sec)
0	0	5	0.81	26
5	0.6	10	0.84	15
10	1.2	15	0.88	10
15	1.8	25	0.89	9
20	2.4	75	0.89	7
25	3.0	75	0.89	4
30	3.6	90	0.90	5

Wild et al. (1996) investigated the effect of varying percentages of metakaolin on the compressive strength of concrete mixtures. Replacement levels of ordinary Portland cement (OPC) by metakaolin (MK) were 0, 5, 10, 15, 20, 25, and 30% and water-binder ratio (w/b) was 0.45. OPC concrete mixture proportion was 1:2.3:3.4. Compressive strength tests were conducted up to the age of 90 days, and results are presented in Table 2.2. They concluded that inclusion of MK as partial replacement of cement enhanced the compressive strength of concrete at all ages, but the optimum replacement level of OPC by MK to give maximum long term strength enhancement was about 20%.

Table 2.2 Compressive strengths and densities of metakaolin concretes

MK (%)	Density (kg/	Compressive strength (MPa)				
		1 day	7 days	14 days	28 days	90 days
0	2490	19.07	50.23	57.10	62.60	72.43
5	2440	21.50	53.80	58.97	63.50	71.63
10	2460	22.43	62.30	69.23	71.00	80.07
15	2470	20.23	64.80	74.67	76.00	83.70
20	2480	19.33	66.47	75.73	82.47	85.13
25	2470	15.73	62.50	69.77	73.93	82.23
30	2480	14.53	60.53	72.33	76.73	81.80

Brooks et al.(2001) investigated the compressive strength of concretes containing 0, 5, 10, and 15% metakaolin (MK). Mixture proportion of OPC concrete was 1:1.5:2.5 with a water-to-cement ratio of 0.28. 28-day Compressive strength results of MK concretes are given in Table 2.3 It is evident from the table that compressive strength increased with the increase in the metakaolin content.

Table 2.3 Compressive strengths of MK concrete mixes

Concrete mixes	Compressive strength (MPa)
OPC	87.0
MK5	91.5
MK10	104.0
MK15	103.5

Brooks et al. (2001) reported the slump and setting times of concretes containing 0, 5, 10, and 15% metakaolin (MK). Control concrete mixture proportion was 1:1.5:2.5 with water-binder ratio of 0.28. Slump and setting times results are given in Table 2.4. It can be seen that slump decreased and setting times increased with the increase in MK content.

Table 2.4 Workability, setting times of MK concretes

Concrete mixes	Slump (mm)	Initial setting time (hours)	Final setting time (hours)
OPC	100	5	7.7
MK5	30	6.42	8.82
MK10	20	6.98	9.42
MK15	5	6.45	9.31

Sabir et al. (2001) investigated the utilization of Metakaolin as pozzolanic material for mortar and concrete and mentioned about the wide range application of Metakaolin in construction industry .They reported that the usage of Metakaolin as a pozzolana will help in the development of early strength and some improvement in long term strength. They mentioned that Metakaolin alters the pore structure in cement paste mortar and concrete and greatly improves its resistance to transportation of water and diffusion of harmful ions which lead to the degradation of the matrix.

Poon et al.(2001) investigated that the cement pastes containing 5% – 20% MK had higher compressive strengths than the control at all ages from 3 to 90 days, with the paste containing 10% MK performing the best. The cement pastes containing SF or FA had lower compressive strength than the control at early ages. The SF replacements resulted in higher compressive strengths than the control at 28 and 90 days, while the FA replacement resulted in a higher compressive strength than the control only at 90 days. The above results indicated that at early ages, the MK contributed better to the compressive strength development of high-performance cement pastes than the SF.

Bai et al. (2001) reported the influence of the composition of Portland cement– pulverized fuel ash–metakaolin binders on strength development of PC–PFA–MK concrete cured both in air and water. Concrete mixtures were made with four different total cement replacement levels (10, 20, 30 and 40%) for PC–PFA–MK concrete with various MK/PFA proportions and cured in water and air up to 18 months.In water-cured concrete made with PC–PFA–MK binder, the MK enhanced early (28 days) strength, and PFA retarded early strength. Air-cured concrete showed a loss in strength relative to equivalent concrete that was water cured and the strength difference increased with curing period. The difference was enhanced in concrete made with PC–PFA binder at high replacement levels, which showed a much reduced strength gain with time when air cured, whereas for PC–PFA–MK concrete, this difference was reduced as the MK content increases.

Muthupriya et al. (2011) investigated an experimental investigation on the behavior of High Performance Reinforced Concrete column (HPRC) to assess the suitability of HPRC columns for the structural applications. High performance concrete was prepared by partial replacement of Ordinary Portland cement with Metakaolin and Fly ash. The test results showed improvements in strength, brittleness and durability. The optimum replacement level for Metakaolin and Fly ash was reported as 7.5%.they reported that the compressive strength of high performance concrete containing 7.5% of Metakaolin was 12% higher than the normal concrete.

Dojkov et al.(2013) investigated the reaction between Metakaolin-Ca(OH)2-water and Fly ash- Ca(OH)2-water. It was clear that during the initial period of curing (up to 7 days), Metakaolin combined lime with a very high rate. This indicated that the overall rate of the reaction taking place in early age of Portland cement -Metakaolin concretes and cement mortars was limited by the hydration of the cement phases. The reaction between Fly ash-Ca(OH)2-water was taking place at a moderate rate in the initial age as compared with Metakaolin-Ca(OH)2-water. The experimental results justified the possible combined use of Metakaolin-Fly ash-Portland cement in concrete industry.

John (2013) investigated the Strength properties of metakaolin admixed Concrete. The results of a study carried out to investigate the effects of Metakaolin on strength of concrete were presented. The referral concrete M30 was made using 53grade OPC and the other mixes were prepared by replacing part of OPC with Metakaolin. The replacement levels were 5%, 10%, 15% up to 20 %(by weight) for Metakaolin. The various results which indicate the effect of replacement of cement by metakaolin on concrete are presented in this paper to draw useful conclusions. The results were compared with reference mix. Test results indicate that use of replacement cement by metakalion in concrete has improved performance of concrete up to 15%.

2.4 Previous research on properties of concrete containing ACBFS

Timms (1963) investigated the properties of air cooled blast furnace slag which make ACBFS as option against natural aggregates . Research indicated that the concretes which were made with aggregate from different sources and concretes which were made with slag were nearly uniform in compressive strength when compared . The same was true for flexural strength of concrete .

Lewis (1982) investigated the properties and uses of iron and steel slag . The major chemical constituents in blast furnace includes lime (32% to 35%) , Magnesia (5% to 15%) , Silica (32% to 42%) , Alumina (7% to 16%) , Sulphur (1% to 2%) , Iron oxide (0.1% to 1.5%) , Manganese Oxide (0.2% to 1%) . The chemical composition of the slag is dependent upon the composition of the available iron ores , flux stones , fuels and on the proportions required for efficient furnace operations . The blast furnace must be charged with uniform raw materials if the iron produced is to be consistent in quality . This procedure also ensures uniformity in the composition of slag and as a result the composition of slag from a given source varies within relatively narrow limits . Greater variations were found between sources where different raw materials are being used .

Ghailan (2005) investigated the use of ACBFS as coarse aggregates in concrete as against the traditional concrete . The experimental setup consists of two types of concrete mixes , concrete mixes made with natural aggregates as a coarse aggregate (mixes of type A) and concrete mixes made with slag as a coarse aggregate (mixes of type B) . The parameters investigated includes modulus of rigidity , rebound test and chemical resistance namely . From the test results obtained in this study , it is approved that the mixes with slag aggregate compromise higher modulus of rigidity , higher rebound number and higher durability compared with those made of gravel . The results confirmed that the cheap industrial slag adds more modified properties in the concrete mixes and this candidate the use of this material as coarse aggregate for high strength concrete.

Morian et al. (2012) investigated that individual particles of ACBFS aggregates are highly variable due to their vesicular nature and mineralogy , which are largely a function of how the material is cooled during processing . In general , slowly cooled slag will have fewer entrapped pores , resulting in increased density . Slow cooling will also result in the formation of crystalline phases , resulting in increased chemical stability .It is recognized that denser , more crystalline ACBFS aggregates are more desirable . Bulk physical properties of ACBFS are relatively uniform over time , having similar variability to that observed in naturally derived materials . Although absorption is expected to be higher than that of natural aggregate , it is known that the highest quality ACBFS aggregates will have less than 4 percent absorption . In addition , the higher the density , the higher the suitability of the ACBFS for use as an aggregate in paving concrete . The Japanese standards set a minimum oven-dry density of 2.4 g/cm^3 (0.0867 lb/in^3) for ACBFS aggregates to be used in normal concrete applications (JIS 2003). Chemical properties of ACBFS that pose a risk to concrete performance are unsoundness of iron and dicalcium silicate . Both are considered rare in modern ACBFS and can be addressed through control of the chemical composition .The chemical property of greatest concern regarding the use of ACBFS aggregate in concrete pavement is CaS . It is known that the solubility of CaS increases with increasing alkalinity of the concrete pore solution , which is a function of the cement alkalinity , cement content and the presence of other sources of internal soluble alkalis including those that might exist in SCMs (e.g., certain Class C fly ashes).

Smith et al. (2012) investigated the production , physical and chemical properties of ACBFs aggregate , highlighting how this material differs from natural aggregates . The properties of concrete produced with ACBFS coarse aggregates and specific production issues and quality control practices applicable to ACBFS concrete were discussed . The document further provided the design and construction recommendations for improving the quality of concrete pavement made using this material . Results from field inspections and laboratory evaluations of concrete pavements made with ACBFS coarse aggregate are discussed . Finally, the life cycle and maintenance costs associated with concrete pavements incorporating ACBFS aggregate in the concrete are also discussed in the report.

Chapter 3
Materials and Methods

3.1 General

In the present study an experimental study was undertaken to investigate the effect of partial replacement of cement by fly ash and metakaolin, coarse aggregates by ACBFS on compressive and flexural strength of concrete. The basic properties of various constituents of concrete such as cement, fly ash, metakaolin , ACBFS, has been presented in this chapter. Concrete mixes detail along with method of casting, curing and testing has also been reported.

3.2 Test programme

The prime objective of this study was to evaluate the performance of binary , ternary and quaternary mix concrete in terms of above parameters and to compare them with results of plain cement concrete.The test program consisted of following activities

- To determine the properties of constituent materials of concrete like cement, fine aggregate, coarse aggregate as per relevant Indian Standard Codes of Practice, wherever applicable used in this investigation.
- To design concrete mix (M30) for selecting reference mix as per IS 10262-2009.
- To proportion binary ,ternary and quaternary concrete mixes incorporating varying percentages of fly ash , air cooled blast furnace slag and metakaolin.
- To cast and cure the specimens.
- To conduct compressive strength test on reference mix, binary mix containing fly ash, ternary concrete mix containing both fly ash and metakaolin and quaternary mix containing fly ash , metakaolin and air cooled blast furnace slag .
- To conduct flexural strength test on reference mix, binary mix containing fly ash , ternary concrete mix containing both fly ash and metakaolin and quaternary mix containing fly ash , metakaolin and air cooled blast furnace slag .

3.3Physical Properties of Materials

The properties of materials used for making concrete are determined in laboratory as per relevant codes of practice. The different materials used in the present study were cement, fine aggregate, coarse aggregate, water, fly ash, air cooled blastfurnace slag ,superplasticizer and metakaolin . Laboratory tests were conducted on these materials and their properties have been reported in the following sections:

3.3.1 Cement

Ordinary Portland cement (OPC) of 43 Grade (Ultratech) from a single batch was used for all the concrete mixes. Cement taken was fresh and without any lumps with uniformity in its color. The cement was tested as per IS: 8112-2013 for its normal consistency, Initial and Finals setting time, Specific gravity and compressive strength for 3, 7 and 28 days, the results of various tests conducted are reported in the table 3.1.

Table 3.1 Physical Properties of Cement

Sr. No.	Properties	Experimental value	Specified Value as per IS: 8112-2013
1	Consistency of Cement	30%	-
2	Specific gravity	3.12	3.15
3	Initial setting time	110 minutes	>30 minutes
4	Final setting time	265 minutes	< 600 minutes
5	Compressive Strength (N/mm^2) 3 days 7days 28 days	 30.4 41.16 48.82	 >23 >33 >43

3.3.2 Aggregates

Aggregates are the important constituents in concrete. They give body to the concrete, reduce shrinkage and affects economy. The aggregate consist of inert and course materials. Fine aggregate in concrete assists in producing workability and uniformity in mixture. The fine aggregate also assists the cement paste to hold the coarse aggregate particles in suspension. This action promotes plasticity in the mixture and prevents the segregation of the paste and coarse aggregates. The coarse aggregates are used primarily for the purpose of providing bulk to the concrete. IS: 383-2011 defines that the fine aggregate are aggregates most of which pass through 4.75 mm IS sieve. The coarse aggregates are defined as aggregates most of which are retained on 4.75 mm IS sieve.

3.3.2.1 Fine Aggregates

Sand obtained from a local quarry at Burj kotian near chandimandir was used as fine aggregate. The sand was thoroughly washed to remove dust and the dried for use .The sieve analysis and other tests were performed in the laboratory . The results of sieve analysis are listed in table 3.2, The physical properties of sand are presented in table 3.3.

Table 3.2 Sieve Analysis of Fine Aggregates

IS Sieve Designation	Wt. Retained on Sieve (g)	Cumulative Wt. Retained (g)	Cumulative Percentage Wt. Retained	%age Passing	IS 383-2011 requirement for Zone II
10mm	-	-	0	100	100
4.75 mm	0	0	0	100	90-100
2.36 mm	30	30	3	97	75-100
1.18 mm	100	130	13	87	55-90
600 μ	280	410	41	59	35-59
300 μ	290	700	70	30	8-30
150 μ	210	910	91	09	0-10
Pan	90	1000	-	-	-

Cumulative percentage weight retained =218

Fineness Modulus (F.M.) = $\frac{218}{100}$ = 2.18

Table 3.3 Physical Properties of Fine Aggregates

Characteristics	Results Obtained
Grading	Grading Zone II (IS: 383-2011)
Fineness Modulus	2.18
Specific Gravity	2.63
Water Absorption (%)	0.52 %
Free Moisture Content (%)	2 %

3.3.2.2 Coarse Aggregates

Two size fraction of coarse aggregates, 20mm down and 10mm down obtained from a stone crusher at Burj kotian near chandimandir were used for making concrete mixtures. The coarse aggregates fractions were washed to remove dust, dirt and then dried to surface dried conditions. Sieve analysis and other tests were performed in the laboratory Crushed stone aggregate of 20mm and 10mm size were mixed in 60 :40 proportions to meet reqirements of IS 383-2011. The results of sieve analysis are listed in Table 3.4. The physical properties are listed in table 3.5.

Table 3.4 Sieve Analysis of Proportioned Coarse Aggregates

IS Sieve Designation	Wt. Retained on Sieve (10mm Agg.) (g)	Wt. Retained on Sieve (20mm Agg.) (g)	Proportion-ed Wt. Retained (g)	Cumulative Wt. Retained (g)	Cumulative %age Wt. Retained (g)	%age Passing
80mm	0.00	0.00	0.00	0.00	0.000	100.00
40 mm	0.00	0.00	0.00	0.00	0.000	100.00
20 mm	0.00	9.00	5.40	5.40	0.108	99.890
10 mm	738.00	4891.00	3229.80	3235.20	64.704	35.290
4.75 mm	4200.00	92.00	1735.20	4970.40	99.408	0.5920
Pan	62.00	8.00	29.60	5000.00	-	-

Fineness Modulus (F.M.) = $\frac{0.108 + 64.704 + 99.408 + 500}{100}$ = 6.64

Table 3.5 Physical Properties of Coarse Aggregates

Characteristics	Value
Colour	Grey
Type	Crushed
Shape	Angular
Specific gravity	2.65
Water absorption	1%
Fineness modulus	6.64
Moisture Content (%)	Nil

3.3.3 Fly Ash

Fly ash was procured from Guru Nanak Dev Thermal Power plant (GNDTP) bathinda and supplied by the Ultratech Cement Pvt Ltd., panchkula in one lot. To assess the properties of fly ash, the properties based on laboratory tests conducted by Central Soil and Material Research Station, New Delhi and CBRI, Roorkee were used. The Chemical and Index properties are presented in table 3.6 and table 3.7

Table 3.6 Chemical properties of fly ash

S.N.	Characteristics	GNDTP, bathinda fly ash value %
1	Loss on ignition	4.52
2	Silica (SiO_2)	56.32
3	Alumina (Al_2O_3)	30.87
4	Iron Oxide (Fe_2O_3)	4.94
5	Calcium oxide (CaO)	1.58
6	Magnesium oxide (MgO)	0.70

Table 3.7 Index properties of GNDTP, Bathinda fly ash

S.N.	Property	Value	Requirements as per IS: 1727-1967 (reaffirmed 2004)
1	Bulk density in kg/m^3	1000	
2	Surface area in m^2/kg	400.6	Min. 320
3	Specific gravity	2.03	-
4	Lime reactivity in N/mm^2	4.8	Min. 4.5
5	Compressive strength as percent of corresponding plain cement concrete (P.C.C.)	85	Not less than 80% of the strength of corresponding plain cement mortar

3.3.4Metakaolin

Metakaolin is white, amorphous, highly reactive aluminiumsilicate pozzolan forming stabile hydrates after mixing with lime stone in water and providing mortar with hydraulic properties. Heating up of clay with kaolinite Al2O3.2SiO2.2H2O as the basic mineral component to the temperature of 500 °C - 600°C causes loss of structural water with the result of deformation of crystalline structure of kaolinite and formation of an unhydrated reactive form – so-called metakaolinite.

It can be seen in the chemical composition and physical characteristics listed in Table 3.8 and Table 3.9, metakaolin have got the unique chemical composition mainly of SiO_2 58.03% and Al_2O_3 36.32%. Physically the product is unique with regards to its particle size distribution.

Table 3.8 Chemical properties of metakaolin

SiO_2	58.03%	Al_2O_3	36.32%
Fe_2O_3	0.95%	TiO_2	1.3%
Cao	0.06%	MgO	0.36%
Na_2O	0.12%	K_2O	0%
LOI	2.85%	SO_4	0.5%

Table 3.9 Physical Properties of metakaolin

Specific gravity	2.40 to 2.60
Physical form	Powder
Colour	Light Pink
Brightness	80-82 Hunter L
BET	15 m^2/gram
Specific surface	8-15 m^2/g

Plate 3.1 Metakaolin sample

The metakaolin used in this study is, obtained from Jeetmull Jaichandlall (M) Pvt Ltd. Chennai. It was pinkish in colour and is shown above in plate 3.1 . Chemical and physical properties are provided by National Cera Laboratory , Morbi ,Tamil Nadu.

3.3.5 Superplasticizer

The superplasticizer ―Fosroc Conplast SP430G8‖ procured from M/s Fosroc Chemicals Pvt Ltd. Chandigarh was used in the present study. The properties of superplasticizer as supplied by the supplier are reported in Table 3.10. The optimum dosage is best determined by site trials with the concrete mix which enables the effects of workability, strength gain or cement reduction to be measured.

It is based on Sulphonated Napthalene formaldehyde Polymers and is supplied as a brown liquid instantly dispersible in water. It has been specially formulated to give high water reductions upto 25% without loss of workability or to produce high quality concrete of reduced permeability. It is mainly used for improving workability, increasing strength, increasing quality that is denser, close textured concrete with reduced porosity and hence enhanced durability.

Table 3.10 Properties of Super plasticizer

S.N.	Test	Values obtained	Limit as per IS 9103:1999
1	Specific Gravity	1.236	0.02 of the value stated by manufacturer
2	pH	7.36	Min. 6.00
3	Dry Material Content	43.78	5% of the value stated by manufacturer (% by mass)
4	Chloride Content	0.029	Within 10% of the value or within 0.2% whichever is greater as stated by manufacturer (% by mass)

3.3.6 Water

Water to be used for both mixing and curing of concrete should be free from injurious amounts of deleterious materials. As per code IS: 456-2000 potable water is generally considered satisfactory for making and curing of concrete.In the present study, potable tap water which is available in P.G. Structure Engineering. Laboratory was used for casting the specimens and for curing purposes.

3.4 DESIGN OF CONCRETE MIX

The concrete mix should be designed to give the most economical and practical proportions of the materials, which will produce necessary workability in fresh concrete and required qualities in the hardened concrete. Thus, the mix design was done to rationalize various parameters in the application of concrete. Mix design facilitates to know correct input of cement, aggregates and water to cement ratio to attain the desired workability and strength, all culminating in techno economic optimization associated with feasibility. In pursuit of the goal of obtaining concrete with certain desired performance characteristics, the selection of component materials is the first step; the next step is a process called mix design by which one arrives at the right combination of the components

3.4.1 Mix Design by Indian Standard Recommended Guidelines

Present study includes design of concrete mix (non-air entrained) for medium strength concrete. Specific relationships, charts, graphs that are given in this method of mix design have been developed from extensive experimental investigation at the cement research institute of India as well as on the basis of data on concrete being designed and produced in the country. The guidelines given in various codes like IS: 10262-2009 and IS: 456-2000 have been adopted for mix design of concrete.

3.4.1.1 Design Stipulation

- Characteristic strength of concrete at 28 days (f_{ck}) 30 N/mm^2
- Maximum Nominal Size of Crushed Aggregate 20 mm
- Degree of Workability (Slump value) 75 mm
- According to IS: 456-2000 the value of Statistical coefficient (k) 1.65
- According to IS: 456-2000 the value of Standard Coefficient (S) 5.00
- Type of Exposure Moderate

3.4.1.2 Characteristics of the materials

- Cement Used OPC
- Specific Gravity of Cement 3.12
- Specific Gravity of Coarse Aggregate 2.65
- Specific gravity of Fine Aggregate 2.63
- Water Absorption of Coarse Aggregate. 1 %
- Water absorption of Fine Aggregate 0.52 %
- Free Surface Moisture of Coarse Aggregate 0.00 %
- Free Surface Moisture of Fine Aggregate 2 %
- Sieve Analysis of Coarse Aggregate Conforming to Table 2 of IS: 383-2011
- Sieve Analysis of Fine Aggregate Conforming Grading Zone II of IS: 383-2011

3.4.1.3 Target Mean Strength of Concrete

Target mean strength is given by $f_t = f_{ck} + KS$ eq. (1)

Where f_t = Target mean strength at 28 days.

f_{ck} = Characteristics compressive strength at 28 days.

S = Standard coefficient.

K= statistical coefficient.

Target Mean Strength of Concrete, f_t = 30 + 1.65 x 5.00 = 38.25 N/mm^2

3.4.1.4 Selection of Water Cement Ratio:

- Water Cement Ratio for Target Mean Strength 0.43
- Maximum Water Cement Ratio from Durability consideration

  (As per code IS 456-2000) 0.50
- The lower value of above two W/C ratios is selected 0.43
- To fix the Right W/C Ratio, Preliminary Trails has to made by

  Varying the W/C Ratio 10%
- Therefore W/C Ratio for trails is 0.43

3.4.1.5 Selection of Water:

- Water Content for per Cubic meter of Concrete 186 kg
- From table 2 of IS: 10262:2009 maximum water content for 20mm aggregates is 186kg

Estimated water content for 75mm slump is = —— =191.58 L

- As super plasticizer was used the water content can be reduced up to 20%
- Therefore corrected water quantity is 162.843 kg

3.4.1.6 Determination of Cement Content:

- Water Cement Ratio = 0.43
- Quantity of Water = 162.84L
- Cement Content = 162.84 / 0.43

  = 379 kg/m^3
- Minimum Cement Content Required for Moderate Exposure = 300 kg/m^3

  (As per code IS 456-2000) Hence okay.

3.4.1.7 Proportion of volume of coarse aggregate and fine aggregate.

From table 3 of IS: 10262:2009, volume of coarse aggregate corresponding to 20mm size aggregate (zone II) for water- cement ratio = 0.5 is 0.62

Volume of coarse aggregate is required to be increased to decrease the fine aggregate content at the rate of -/+ 0.01 for every +/- 0.05 change in water-cement ratio.

Therefore corrected volume of coarse aggregate is 0.634

And volume of fine aggregate is = 1- 0.634 = 0.366

3.4.1.8Mix Calculations

The mix calculations per unit volume of concrete is as follows

1. Volume of concrete = $1m^3$
2. Volume of cement = eq. (2)

   $=379/(3.15x1000)=0.1203\ m^3$
3. Volume of waters = eq. (3)

   $=0.1628\ m^3$
4. Volume of chemical admixture = eq. (4)

(@0.7% by mass of cementitious Material) =

$= 0.0022\ m^3$

5. Volume of all in aggregate =[1-(2+3+4)]

   = 1-(0.113+0.163+0.003)

   $=0.7147\ m^3$

The fine and coarse aggregate contents per cubic meter of concrete are calculated from following equations:

$$V = \left[W + \frac{C}{S_C} + \frac{A}{Sa} + \frac{1}{p} \cdot \frac{F_a}{S_{fa}} \right] \frac{1}{1000}$$ eq. (5)

$$V = \left[W + \frac{C}{S_C} + \frac{A}{Sa} + \frac{1}{1-p} \cdot \frac{C_a}{S_{Ca}} \right] \frac{1}{1000}$$

$$1 = \left[162.83 + \frac{379}{3.15} + \frac{2.653}{1.2} + \frac{1}{0.634} \times \frac{C_a}{2.65} \right] \times \frac{1}{1000}$$

This gives,

- Fine Aggregate Content in Total Volume of Concrete FA = 687.85 kg/m^3
- Coarse Aggregate Content in Total Volume of Concrete CA = 1200.68 kg/m^3

CA 10mm = 480.27 kg/m^3

CA 20mm = 720.41 kg/m^3

Correction of moisture and water absorption

Corrections for moisture and water absorption were applied and corrected water content is reported in Table 3.11 as follows:

Table 3.11Corrected water content after corrections.

Material	Initial Quantity (kg)	Free Surface Moisture(%)	Absorption (%)	Revised Quantity (kg)	Extra Water (L)
CA 10	480.27	-	1%	475.47	4.80
CA 20	720.41	-	1%	713.21	7.20
FA	687.85	2%	0.52%	698.09	-10.24
				Total	1.76
				Revised Water Content	164.6

The revised quantities of materials after making corrections in aggregates and water content are given in table 3.12.

Table 3.12 The estimated actual mix proportion for one cubic meter of concrete

Water (L)	Cement (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	
			10 mm	**20 mm**
164.6	379	698.09	475.47	713.21
0.434	1	1.84	3.136	

3.4.1.9 Mix Design Report

Based on the concrete mix design by IS method, three trial mixes were prepared with water cement ratio of 0.43, casting 6 cubes for each mix and were tested at 7 days and 28 days. Compressive strength, slightly more than target mean strength (38.25 N/mm^2) was achieved for trial mix no. 3 of Table 3.13 and as such this mix was adopted for this study. The mix proportions for various constituent mixes have been summarized in table 3.13.

Table 3.13 Trial Mix for M30 Grade

Trial Mix.	W/C Ratio	Water (L)	Cement (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	Super plasticizer (kg)
Mix 1	0.41	167	408	627	1273	2.695
Mix 2	0.45	176	391	754	1133	2.695
Mix 3	0.43	165	385	719	1149	2.695

From the test results of trial mix 1, 2 and 3 as shown in table 3.14, suitable target mean strength of 38.48MPa is arrived with trial mix 3 at w/c ratio of 0.43. So trial mix 3 with cement content 385 Kg/m^3 was adopted for study. Thus the proportions of various ingredients (by weight) of reference mix (M0) are shown in table 3.15:

Table 3.14 Test Results of Compressive Strength at 28 days

Sr No.	Grade of Concrete	Trial Mix	Load at Failure (ton)	Cube Compressive Strength(f_{ck}) (N/mm^2)	Average Compressive Strength(N/mm^2)
1	M30	Mix 1	93.73	41.66	40.23
			92.54	41.13	
			85.27	37.9	
2	M30	Mix 2	68.85	30.60	32.36
			73.03	32.46	
			87.8	34.02	
3	M30	Mix 3	76.54	38.52	38.48
			87.77	39.01	
			85.29	37.91	

Table 3.15 Proportioning of reference mix adopted (M0) for 1m^3 of mix

Water (liters)	Cement (kg)	Fine Aggregate (Kg)	Coarse Aggregate (Kg)	Super plasticizer (kg)
165	385	719	1149	2.695
0.43	1.00	1.87	2.98	0.7%

The quantity of cement 385 kg/m^3 also satisfies the IS code 456-2000 requirements of minimum cement content.

3.5 Proportioning of binary, ternary and quaternary mixes

Flyash ,metakaolin ,ACBFS composites contain cement, fine aggregate, coarse aggregate, water, fly ash , ACBFS and metakaolin. In the mix, the major variables that control strength and workability are cement content, maximum aggregates size, gradation (size distribution), the presence of entrained air, fly ash. Generally mix designs focuses on target mean strengths, ignoring durability considerations. However, IS: 456-2000 has given emphasis on durability consideration. Fly ash supplements the quantitative requirements of cementitious input in a mix design, controlling simultaneously the heat of hydration and surplus free lime. Chemical admixture may bring down the W/C or increase the slump, but certainly cannot participate in hydration chemistry. Whereas, fly ash has direct role in the chemistry for mineralogy improvement. Being comparatively cheaper than cement, it has been used in concrete mixes as the partial replacement material. Various investigations showed that for the optimum useof fly ash, it should be proportioned in concrete on the basis of economy andequal strength requirements.

Thomas has stated that it is possible to proportion fly ash mixes for strength equivalent to that of 28 days strength of control mixes by using fly ash quantity in excess of quantity of cement replaced. As per Smith and Raba, it is possible to design fly ash concrete mixes of equal strength to that of controlled concrete without fly ash and covering a strength range of up to 50 N/mm^2 at 28 days. Smith formulated a method of design of orthodox concrete on the basis of extensive experimental investigations on concrete with fly ash from over twenty five generating stations. This method can be applied equally well to those concrete in which fly ash replaced the cement.

3.6 Detail of mixes

In the present study, cement was replaced by fly ash on equal weight basis. The sand was kept the same as that in the original plain concrete mix. The partial replacement of cement by fly ash was done in varying percentages that is 10%, 15%, 20% and 25% on equivalent weight basis to prepare the fly ash binary mixes. The metakaolin added to fly ash mixes in different percentages by weight of cement to replace fly ash that is 5%, 10% and 15% to get ternary mix containing fly ash and metakaolin. ACBFS was replaced by coarse aggregate in varying percentages that is 20%,40% and 60% to get quaternary mix containing fly ash , metakaolin and ACBFS .The details of all themixes are described below:

M0 - Reference mix

M1-25% cement replacement by fly ash

M2 - 25% cement replacement by fly ash and 20% coarse aggregate replacement by ACBFS

M3 - 25% cement replacement by fly ash and 40% coarse aggregate replacement by ACBFS

M4 - 25% cement replacement by fly ash and 60% coarse aggregate replacement by ACBFS

M5 -25% replacement of cement (20% by incorporating fly ash and 5% by incorporating metakaolin)

M6 -25% replacement of cement (20% by incorporating fly ash and 5% by incorporating matakaolin) and 20% coarse aggregate replacement by ACBFS

M7 – 25% replacement of cement (20% by incorporating fly ash and 5% by incorporating meatakaolin) and 40% coarse aggregate replacement by ACBFS

M8 - 25% replacement of cement (20% by incorporating fly ash and 5% by incorporating metakaolin) and 60% coarse aggregate replacement by ACBFS

M9 - 25% replacement of cement (15% by incorporating fly ash and 10% by incorporating metakaolin)

M10 - 25% replacement of cement (15% by incorporating fly ash and 10% by incorporating metakaolin) and 20% coarse aggregate replacement by ACBFS

M11 - 25% replacement of cement (15% by incorporating fly ash and 10% by incorporating metakaolin) and 40% coarse aggregate replacement by ACBFS

M12 - 25% replacement of cement (15% by incorporating fly ash and 10% by incorporating metakaolin) and 60% coarse aggregate replacement by ACBFS

M13 - 25% replacement of cement (10% by incorporating fly ash and 15% by incorporating metakaolin)

M14 - 25% replacement of cement (10% by incorporating fly ash and 15% by incorporating metakaolin) and 20% coarse aggregate replacement by ACBFS

M15 - 25% replacement of cement (10% by incorporating fly ash and 15% by incorporating metakaolin) and 40% coarse aggregate replacement by ACBFS

M16 - 25% replacement of cement (10% by incorporating fly ash and 15% by incorporating metakaolin) and 60% coarse aggregate replacement by ACBFS

the mix proportions for the above mixes are shown in tables 3.16 to 3.19 respectively.

Table 3.16 Mix proportions for different specimens per cubic meter of binary and ternary mix containing fly ash and ACBFS

Sr. No.	**Mix designation**	**Cement (C) in kg**	**Water (W) in L**	**Fine aggregates (FA) in kg**	**Coarse aggregates (CA) in kg**	**ACBFS Aggregates in kg**	**Fly ash (FA) in kg**
1	M0	385.00	165	719	1149.0	0	0
2	M1	288.75	165	719	1149.0	0	96.25
3	M2	288.75	165	719	919.2	229.8	96.25
4	M3	288.75	165	719	689.4	459.6	96.25
5	M4	288.75	165	719	459.6	689.4	96.25

Table 3.17 Mix proportions for different specimens per cubic meter of ternary and quaternary mix containing fly ash and ACBFS by incorporating metakaolin by 5%

Sr. No.	Mix designation	Cement (C) in kg	Water (W) in L	Fine aggregates (FA) in kg	Coarse aggregates (CA) in kg	ACBFS Aggregates in kg	Fly ash (FA) in kg	Metakaolin in kg
1	M0	385.00	165	719	1149.0	0	0	0
2	M5	288.75	165	719	1149.0	0	77	19.25
3	M6	288.75	165	719	919.2	229.8	77	19.25
4	M7	288.75	165	719	689.4	459.6	77	19.25
5	M8	288.75	165	719	459.6	689.4	77	19.25

Table 3.18 Mix proportions for different specimens per cubic meter of ternary and quaternary mix containing fly ash and ACBFS by incorporating metakaolin by 10%

Sr. No.	Mix designation	Cement (C) in kg	Water (W) in L	Fine aggregates (FA) in kg	Coarse aggregates (CA) in kg	ACBFS Aggregates in kg	Fly ash (FA) in kg	Metakaolin in kg
1	M0	385.00	165	719	1149.0	0	0	0
2	M9	288.75	165	719	1149.0	0	57.75	38.5
3	M10	288.75	165	719	919.2	229.8	57.75	38.5
4	M11	288.75	165	719	689.4	459.6	57.75	38.5
5	M12	288.75	165	719	459.6	689.4	57.75	38.5

Table 3.19 Mix proportions for different specimens per cubic meter of ternary and quaternary mix containing fly ash and ACBFS by incorporating metakaolin by 15%

Sr. No.	Mix designation	Cement (C) in kg	Water (W) in L	Fine aggregates (FA) in kg	Coarse aggregates (CA) in kg	ACBFS Aggregates in kg	Fly ash (FA) in kg	Metakaol in in kg
1	M0	385.00	165	719	1149.00	0	0	0
2	M13	288.75	165	719	1149.00	0	38.5	57.75
3	M14	288.75	165	719	919.20	229.80	38.5	57.75
4	M15	288.75	165	719	689.40	459.60	38.5	57.75
5	M16	288.75	165	719	459.60	689.40	38.5	57.75

3.7 Moulds for specimens

Standard cubical moulds of size 150 mm x 150 mm x 150 mm made up of cast iron were used to prepare the concrete specimens for the determination of Compressive Strength of concrete. Standard beam moulds of size 100mm X100mm X500mm made up of cast iron were used to prepare the concrete specimens for the determination of flexural strength of concrete.

3.7.1 Mixing

The material was weighted in batches in required proportions given as per Table 3.16 to 3.19 and was put into the mixer. The required quantity of water was added slowly to get a uniform mix. All the moulds were cleaned and were applied with oil on the inner faces well before concreting operation for casting of specimen so that oil may not affect concrete ingredients. These were securely tightened to correct dimensions before casting. Care was taken that there was left no gap, where cement slurry could leak.

3.7.2 Batching, Casting and Curing of Specimens for Compressive Strength

As per IS: 516-1959 (reaffirmed 1999), the complete procedures were adopted in the making and casting operations. The quantities of cement, coarse aggregates (20 mm size), fine aggregate, fly ash, ACBFS ,metakaolin, superplasticizer and water for each batch i.e.

for different percentage of fly ash replacement with varying percentage of metakaolin was weighed accurately and for different percentage of coarse aggregate replacement with varying percentage of ACBFS was weighed accurately. The aggregates and ACBFS were put into the mixer and over that cement, fly ash and metakaolin were added, mixer started to rotate to mix the dry ingredients. Then water was added carefully and mixer was started to rotate again at last super plasticizer mixed with some water was added, until the concrete appeared to be homogenous and of the desired consistency as shown in Plate No. 3.2. The prepared concrete was then out from rotating drum into M.S. Plate. Then concrete was filled into the previously prepared moulds in three layers. Electric vibrator was used for compaction of concrete. Vibrations were stopped as soon as cement slurry appeared on the top surface of the mould. The surface of the concrete was finished level with the top of the mould using a trowel and marked properly to indicate the mix proportions date of casting etc as shown in Plate No. 3.3. The finished specimens were left to harden. The specimens were removed from the moulds after 24 hours of casting. Then they were placed in the water tank filled with the potable tap water in the laboratory for curing until the time of testing, as shown in Plate No.3.4. For plain cement concrete specimens, no fly ash and metakaolin was added to the mix and all the specimens for a particular testing age were cast in one batch. The specimens for fly ash concrete replacing cement by fly ash and incorporating metakaolin with varying percentages of fly ash , ACBFS and metakaolin were cast in separate batches. This procedure was adopted to ensure uniform properties of the specimens in each batch. The details of the specimens tested in the study are given in table 3.20.

Table No. 3.20 Details of specimens

S. N.	Type of Test	Type of specimen	Age of testing (days)	No. of specimens																	Total No. of Speci-mens
				Ref. Mix	Replacement of cement by fly ash and coarse aggregate by ACBFS				cement by fly ash and coarse aggregate by ACBFS with incorporating fly ash replacement by				cement by fly ash and coarse aggregate by ACBFS with incorporating fly ash replacement by 10% metakaolin				Replacement of cement by fly ash and coarse aggregate by ACBFS with incorporating fly ash replacement by 15% metakaolin				
				Mix Designation																	
				M0	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	
1	Compressive Strength	150mm X 150mm X 150mm	7	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	102
			28	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	
2	Flexural Strength	100mm X 100mm X 500mm	7	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	102
			28	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	

Plate .3.2: Mixing of materials in the mixer

Plate 3.3: Test Specimens For Compressive Strength

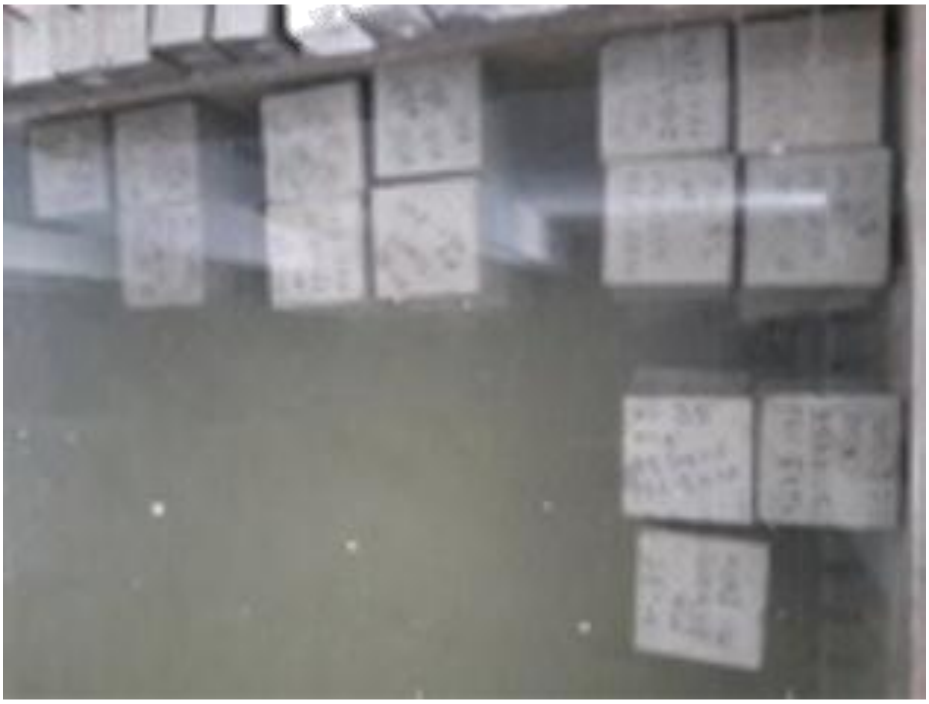


Plate 3.4 Moist curing stage of test specimens in the laboratory

3.8 Testing of specimens

The following tests have been carried out on the cube, and beam specimen:

- Compressive strength test
- Flexural strength test

3.8.1 Compressive Strength test

The test was conducted on cubes according to IS code 516-1959(reaffirmed 1999). Specimens were taken out from curing tank at the age of 7 and 28 days of moist curing and tested immediately after removal from water. Surface water was allowed to drip down. Specimens were tested on 200 ton capacity of Universal Testing Machine (UTM).The position of the cube while testing was at right angles to that of casting position as shown in Plate 3.5 axis of specimens were carefully aligned with the centre of thrust of the spherically seated plates. The load was applied gradually without any shock and increased at constant rate of 14 N/mm²/minute until failure of specimen takes place, thus the compressive strength of specimen was found out and specimen after testing are shown in Plate No. 3.6.

Plate 3.5 Test Set up for Compression Test

Plate 3.6 Cracks developed after testing in cubes

3.8.2 Flexural Strength

The flexural strength was tested in the laboratory, the changes in the length of 100 mm x 100 mm x 500 mm concrete specimens shown in Plate No. 3.7. The bearing surfaces of the supporting and loading rollers was wiped clean and any looses and or other material removed from the surfaces of the specimen where they were to make contact with the rollers. The specimen was then placed in the machine in such a manner that the load was applied to the uppermost surface as cast in the mould , at center of the specimen . The axis of the specimen was carefully aligned with the axis of the loading device . The load was applied without shock and increasing continuously at a rate such that the extreme fiber stress increases at approximately 7 kg/sq cm/min , that is , at a rate of loading of 180kg/min for the 10.0 cm specimens. The load was increased until the specimen fails and maximum load applied to the specimen during the test was recorded .The specimens are tested for flexural strength after 7 and 28 days of curing.

Plate No. 3.7: Beam Specimens for Measurement of Flexural Strength

Chapter 4
Results and Discussion

4.1 General

A systematic study was undertaken to achieve the objective of present investigation.The results obtained on concrete containing cement, flyash, metakaolin and ACBFS are presented and discussed in this chapter**.**Total number of 102 cubes and 102 beams were cast for compressive strength and flexural strength respectively, using different proportions of fly ash , ACBFS and metkaolin. The specimens were tested at different ages of 7 and 28 days. Following aspects of concrete were investigated:

- The effect of percentage of fly ash ,metakaolin and ACBFS as a partial replacement of cement and fly ash and coarse aggregates respectively on compressive strength of concrete.
- The effect of percentage of fly ash ,metakaolin and ACBFS as a partial replacement of cement and fly ash and coarse aggregates respectively on flexural strength of concrete.

4.2 Test results

4.2.1 Compressive Strength

The effect of fly ash and metakaolin on compressive strength of concrete was investigated for the following replacements

- Cement partially replaced by fly ash forming binary mix.
- Fly ash partially replaced by metakaolin forming ternary mix.
- Coarse aggregates replaced by ACBFS forming quaternary mix.

The results of compressive strength tests using 25% fly ash as partial replacement of cement and ACBFS in varying percentages (i.e. 20% , 40% and 60%) as partial replacement of coarse aggregates atmoist curing ages of 7 and 28 days are presented in tables 4.1 to 4.6 and are plotted in fig. 4.1and fig. 4.2 which show the variations of compressive strength of concrete with different replacement levels of fly ash and ACBFS at various moist curing ages of 7 and 28 days.

Table 4.1: compressive strength(Reference Mix)

Sr. No	Mix Designation	Moist Curing (Days)	Load at failure (kN)	Compressive strength (N/mm^2)	Average compressive Strength (N/mm^2)
1	M0	7	577.3	25.66	26.01
			587.7	26.12	
			590.4	26.24	
2	M0	28	866.7	38.52	38.48
			877.7	39.01	
			852.9	37.91	

Table 4.2: compressive strength
(M1- cement replaced by 25% fly ash)

Sr. No	Mix Designation	Moist Curing (Days)	Load at failure (kN)	Compressive strength (N/mm^2)	Average compressive Strength (N/mm^2)
1	M1	7	379.3	16.86	16.06
			365.4	16.24	
			339.5	15.09	
2	M1	28	647.3	28.77	28.92
			642.6	28.56	
			662.4	29.44	

Table 4.3: compressive strength
(M2- Cement replaced by 25% fly ash and Coarse Aggregate replaced by 20% ACBFS)

Sr. No	Mix Designation	Moist Curing Days	Load at failure (kN)	Compressive strength (N/mm^2)	Average compressive Strength (N/mm^2)
1	M2	7	490.6	21.8	20.93
			465	20.7	
			457	20.31	
2	M2	28	818.1	36.36	34.58
			699.7	31.10	
			816.5	36.29	

Table 4.4: compressive strength
(M3- Cement replaced by 25% fly ash and Coarse Aggregate replaced by 40% ACBFS)

Sr. No.	Mix Designation	Moist Curing (Days)	Load at failure (kN)	Compressive strength (N/mm^2)	Average compressive Strength (N/mm^2)
1	M3	7	498	22.13	21.29
			488	21.69	
			451	20.05	
2	M3	28	813.7	36.16	35.82
			811	36.05	
			793	35.24	

Table 4.5: compressive strength
(M4- Cement replaced by 25% fly ash and Coarse Aggregate replaced by 60% ACBFS)

Sr. No.	Mix Designation	Moist Curing (Days)	Load at failure (kN)	Compressive strength (N/mm^2)	Average compressive Strength (N/mm^2)
1	M4	7	530	23.56	22.92
			510	22.67	
			507	22.53	
2	M4	28	830	36.89	36.3
			813	36.13	
			807	35.87	

Table 4.6: Compressive strength for different replacement levels of cement by fly ash and ACBFS

Mix Designation	Percentage Replacement by fly ash	Percentage Replacement by ACBFS	Compressive Strength (N/mm^2) Duration of moist Curing (days)	
			7	28
M0	0%	0%	26.01	38.48
M1	25%	0%	16.06	28.92
M2	25%	20%	20.93	34.58
M3	25%	40%	21.29	35.82
M4	25%	60%	22.92	36.30

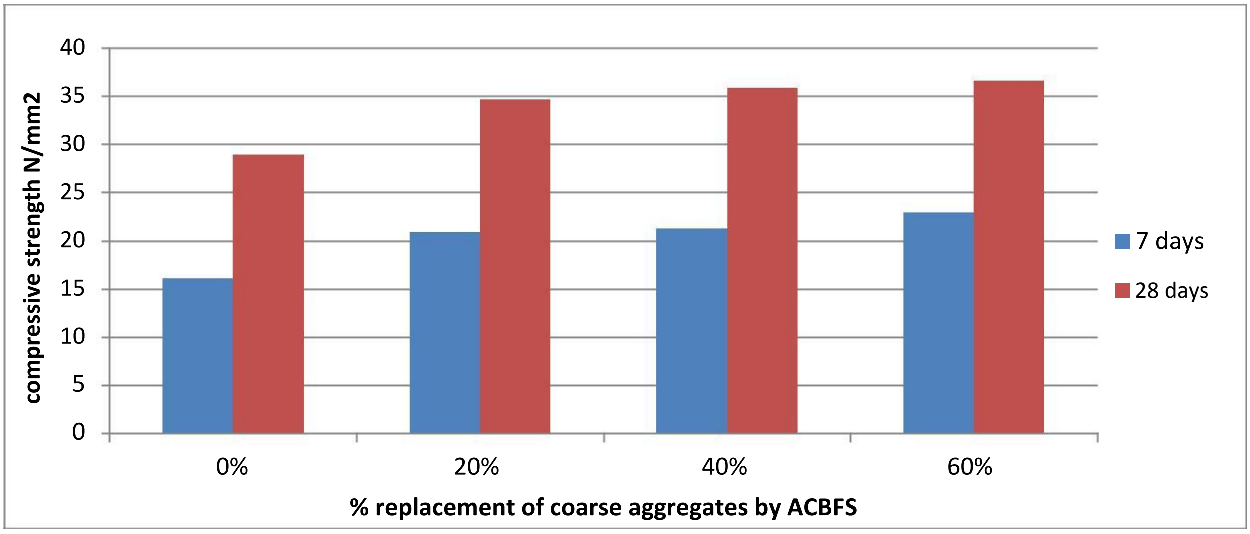


Fig 4.1: Compressive strength Vs percentage replacement of coarse aggregate by ACBFS in fly ash concrete .

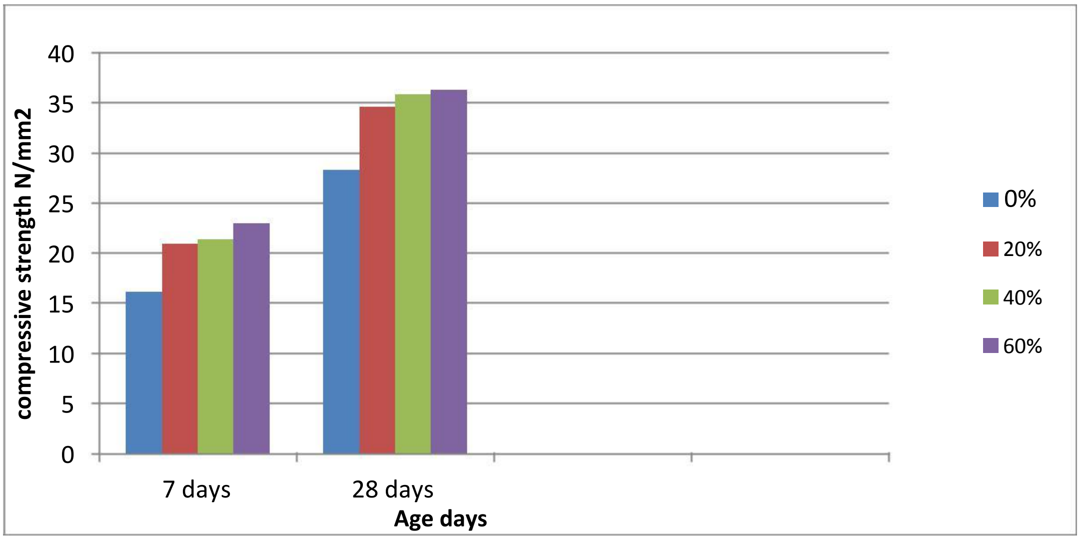


Fig.4.2: compressive strength at different replacement levels of coarse aggregate by ACBFS in fly ash concrete.

It is clear from the tables 4.1 to table 4.6 and the figures 4.1 and 4.2 that at 7 days compressive strengthof binary mix containing fly ash were lower than that of the reference mix. The compressive strength at 28 days of binary mix is also less than that for concrete without fly ash for all replacement levels of ACBFS.The compressive strength achieved by ternary concrete mixes containing fly ash and ACBFS at all replacement levelsincreased with increase in percentage of ACBFS, which may be due to reaction of lime and silica present in ACBFS with cement clinker to produce C-S-H gel .

The reference mix (M0) achieved a compressive strength of 38.48MPa at 28 days. The fly ash concrete mixes with fly ash contents of 25% and varying percentage of ACBFS i.e. 0%, 20%, 40% and 60% attained strength of 28.92MPa, 34.58MPa, 35.82MPa and 36.30MPa respectively.

It can be seen from fig 4.1 and fig 4.2 that there is maximum decrease in compressive strength of concrete containing 25% flyash. However, maximum strength at 7 and 28 days was observed for the reference mix.Fly ash concrete gained strength at a slower rate during the initial age of time, it acquires strength at quicker rate at 28 days because of pozzolanic action of fly ash.

The compressive strength is lower at initial ages due to reduction in the quantity of cement by the replacement with fly ash, resulting in weakening the cohesion of cement paste and adhesion to the aggregates particles. As approximately 75% strength rendering primary mineralogical phases is developed at the ultimate hydration of OPC. The balance $Ca(OH)_2$ whose contribution for strength is insignificant as the fly ash is replaced for cement do not contribute for chemical reaction, because of the fact that sufficient cementitious action of fly ash is not activated at the initial stages.

At the later ages improvement in strength is observed due to the reason that the surplus lime released form OPC hydration becomes the source of pozzolanic reactions, contributing for additional mineralogy as secondary hydrated mineralogy, majorly contributing for additional strength. This reaction contributes for the mechanism of pore refinement and grain refinement, resulting in enhanced strength and strong transition zone. The mechanism of primary and secondary hydrated mineralogy is as follows:

$$\text{OPC} + \text{H} \xrightarrow{\text{Fast}} \text{Primary hydrated mineralogy} + \text{CH}$$

$$\text{Pozzolona} + \text{CH} + \text{H} \xrightarrow{\text{Slow}} \text{Secondary hydrated mineralogy.}$$

The unreactive portion of fly ash fills up the matrix to render packing effect i.e. physical effect of improving the micro structure of the hydrated cement paste.Lewandowski, R. has reported the presence of as much as 50 percent of unreacted fly ash afterone year as the pozzolanic reaction of class F fly ash is slow. So the unreactive portion may also be considered a micro aggregate to contribute for the strength. However, the role played by reactive portion of fly ash is decisive and dominant in comparison to the strength drived out of unreactive portion through packing effect. Therefore, it is anticipated that the compressive strength of fly ash concrete should significantly improve beyond the age of 28days.

The results of compressive strength at different ages with varying percentages of fly ash , ACBFS and metakaolin are presented in Tables 4.7 to 4.20. The variation in compressive strength with age or different percentage of fly ash , ACBFS and metakaolin contents is presented at fig 4.3 to fig 4.8

Table 4.7: compressive strength
(M5- cement replaced by 20% fly ash and 5%.metakaolin)

Sr. No	Mix Designation	Moist Curing (Days)	Load at failure (kN)	Compressive strength (N/mm^2)	Average compressive Strength (N/mm^2)
1	M5	7	540	24	22.95
			514	22.85	
			493	21.91	
2	M5	28	781.3	34.72	33.92
			748	33.24	
			760	33.78	

Table 4.8: compressive strength
(M6- cement replaced by 20% fly ash and 5 %metakaolin and coarse aggregate replaced by 20% ACBFS)

Sr. No	Mix Designation	Moist Curing (Days)	Load at failure (kN)	Compressive strength (N/mm^2)	Average compressive Strength (N/mm^2)
1	M6	7	596	26.49	25.84
			588	26.09	
			560	24.89	
2	M6	28	812	36.09	35.19
			765	34	
			798	35.47	

Table 4.9: compressive strength
(M7- cement replaced by 20% fly ash and 5% metakaolin and coarse aggregate replaced by 40% ACBFS)

Sr. No.	Mix Designation	Moist Curing (Days)	Load at failure (kN)	Compressive strength (N/mm^2)	Average compressive Strength (N/mm^2)
1	M7	7	557	24.76	25.85
			602	26.75	
			586	26.05	
2	M7	28	802.6	35.67	36.36
			816	36.27	
			836	37.15	

Table 4.10: compressive strength
(M8- cement replaced by 20% fly ash and 5% metakaolin and coarse aggregate replaced by 60% ACBFS)

Sr. No.	Mix Designation	Moist Curing (Days)	Load at failure (kN)	Compressive strength (N/mm^2)	Average compressive Strength (N/mm^2)
1	M8	7	582	25.87	26.26
			606.5	26.95	
			584	25.95	
2	M8	28	854	37.95	38.16
			851	38.71	
			871	38.71	

Table 4.11: Compressive strength for different replacement levels of cement by fly ash and metakaolin and different replacement levels of coarse aggregate by ACBFS

Mix Designation	Percentage Replacement by fly ash	Percentage Replacement by metakaolin	Percentage Replacement by ACBFS	Compressive Strength (N/mm^2) Duration of moist Curing (days)	
				7	28
M0	0%	0%	0%	26.02	38.48
M5	20%	5%	0%	22.95	33.92
M6	20%	5%	20%	25.84	35.19
M7	20%	5%	40%	25.85	36.36
M8	20%	5%	60%	26.26	38.16

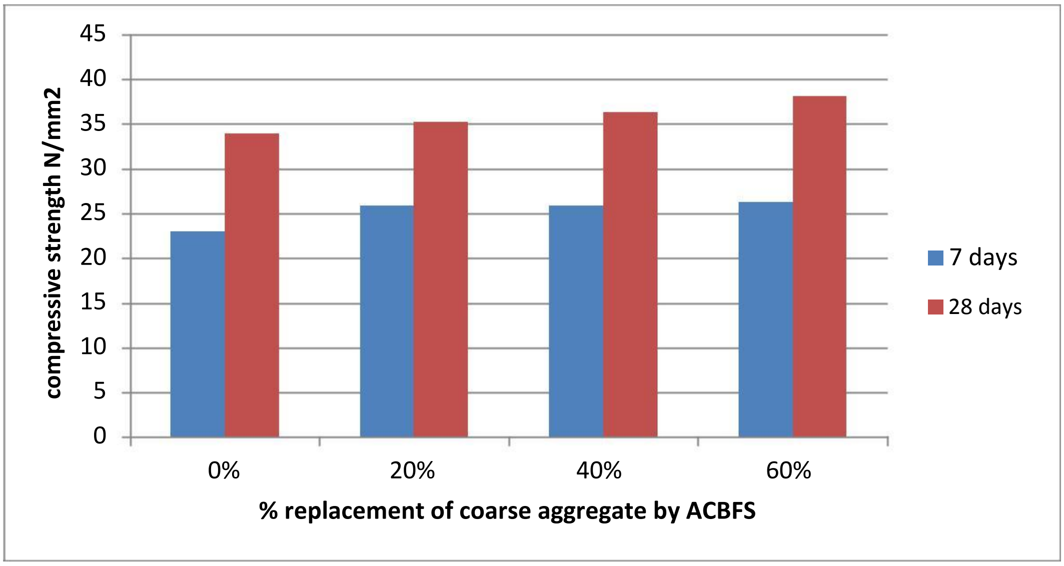


Fig 4.3: Compressive strength Vs percentage replacement of ACBFS in which cement is replaced by fly ash incorporating metakaolin of 5%.

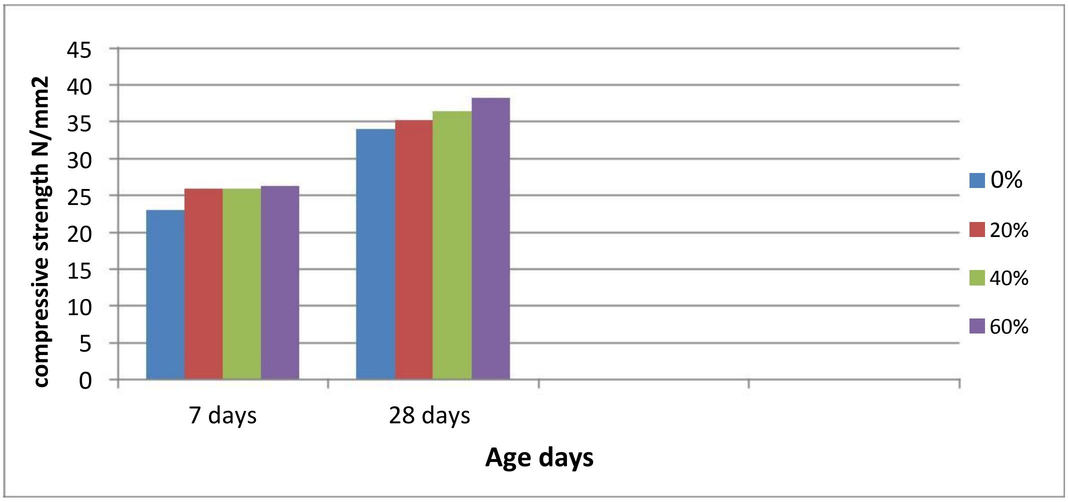


Fig.4.4: compressive strength at different replacement levels of ACBFS in which cement is replaced by fly ash incorporating metakaolin of 5%.

The results of compressive strength tests using metakaolin in varying percentages (i.e. 5% , 10% and 15%) as partial replacement of fly ash along with use of ACBFS to make ternary and quaternary mixes at moist curing ages of 7 and 28 days are presented in tables 4.7 to 4.21 and are plotted in fig. 4.3 to fig. 4.8 which show the variations of compressive strength of concrete with different replacement levels of metakaolin and at various ages of moist curing.

It can be seen from the tables 4.7 to table 4.11 and the figures 4.3 and 4.4 that at 7 days and 28 days compressive strength of ternary and quaternary mixes containing fly ash and metakaolin were lower than that of the reference mix but higher thanbinary mixes. The compressive strength increased with increase in dosage of metakaolin. The compressive strength achieved by concrete mixes containing fly ash with metakaolin (20% fly ash and 5% metakaolin) with ACBFS replacement level of 0% , 40% and 60% at 7days of moist curing is in excess of 20MPa.

The ternary and quaternary mixes of concrete with fly ash content of 20% and 5% of metakaolin attained strengths of 33.92MPa, 35.19MPa ,36.36MPa and 38.16MPa at ACBFS content of 0% , 20% , 40% and 60% respectively .

The comparison of ternary and quaternary mixes shows that the replacement of fly ash by metakaolin resulted in further increase in compressive strength strength of mixes at all displacement levels of ACBFS. The maximum increase of compressive strength was obtained for mix M8. The mix M8 achieved 32 % higher strength than mix M1 containing 25 % flyash only. Further mix M8 achieved compressive strength of 5 % higher than mix M4 containing 25% flyash and 60 %ACBFS at 28 days. The increase in compressive strength with addition of metakaolin is attributed due to its fine particle distribution and reaction of metakaolin with CH released during hydration of cement.

The results obtained for addition of 10% metakaolin as partial replacement of fly ash and partial replacement of coarse aggregate by ACBFS are shown in tables 4.12 to 4.16 and comparison is shown is fig 4.5 and fig. 4.6.

Table 4.12: compressive strength
(M9- cement replaced by 15% fly ash and 10% metakaolin)

Sr. No	Mix Designation	Moist Curing (Days)	Load at failure (kN)	Compressive strength (N/mm^2)	Average compressive Strength (N/mm^2)
1	M9	7	571	25.38	24.04
			520	23.11	
			532	23.64	
2	M9	28	778	34.58	34.98
			785	34.88	
			798	35.46	

Table 4.13: compressive strength

(M10- cement replaced by 15% fly ash and 10% metakaolinand coarse aggregate replaced by 20% ACBFS)

Sr. No	Mix Designation	Moist Curing (Days)	Load at failure (kN)	Compressive strength (N/mm^2)	Average compressive Strength (N/mm^2)
1	M10	7	549	24.4	24.67
			572	25.42	
			544	24.18	
2	M10	28	812	36.09	35.79
			799	35.51	
			805	35.78	

Table 4.14: compressive strength

(M11- cement replaced by 15% fly ash and 10% metakaolinand coarse aggregate replaced by 40% ACBFS)

Sr. No.	Mix Designation	Moist Curing (Days)	Load at failure (kN)	Compressive strength (N/mm^2)	Average compressive Strength (N/mm^2)
1	M11	7	570	25.38	26.30
			600	26.67	
			605	26.89	
2	M11	28	861	38.26	36.49
			811	36.04	
			791	35.16	

Table 4.15: compressive strength
(M12- cement replaced by 15% fly ash and 10% metakaolin and coarse aggregate replaced by 60% ACBFS)

Sr. No.	Mix Designation	Moist Curing (Days)	Load at failure (kN)	Compressive strength (N/mm^2)	Average compressive Strength (N/mm^2)
1	M12	7	603	26.8	26.96
			620	27.56	
			597	26.53	
2	M12	28	860	38.22	38.48
			882	39.2	
			855	38	

Table 4.16: Compressive strength for different replacement levels of cement by fly ash and metakaolin and different replacement levels of coarse aggregate by ACBFS

Mix Designation	Percentage Replacement by fly ash	Percentage Replacement by metakaolin	Percentage Replacement by ACBFS	Compressive Strength (N/mm^2) Duration of moist Curing (days)	
				7	**28**
M0	0%	0%	0%	26.02	38.48
M9	15%	10%	0%	24.04	34.98
M10	15%	10%	20%	24.67	35.79
M11	15%	10%	40%	26.30	36.49
M12	15%	10%	60%	26.96	38.48

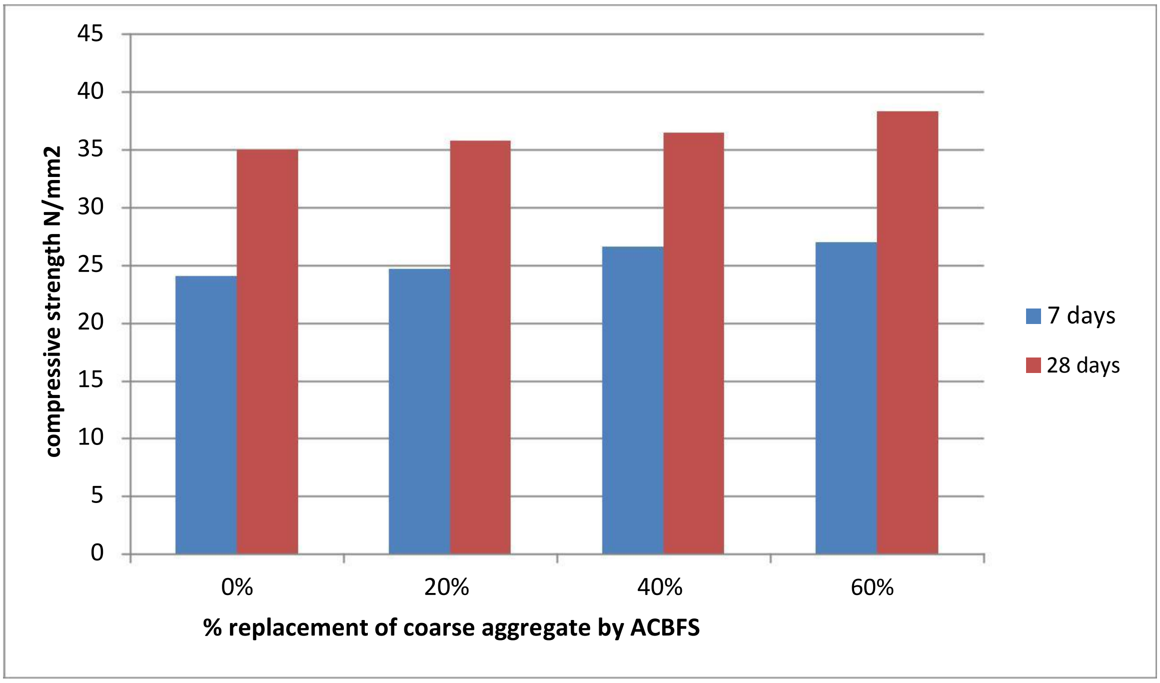


Fig 4.5: Compressive strength Vs percentage replacement of coarse aggregate by ACBFS and cement replacement by fly ash incorporating metakaolin of 10%.

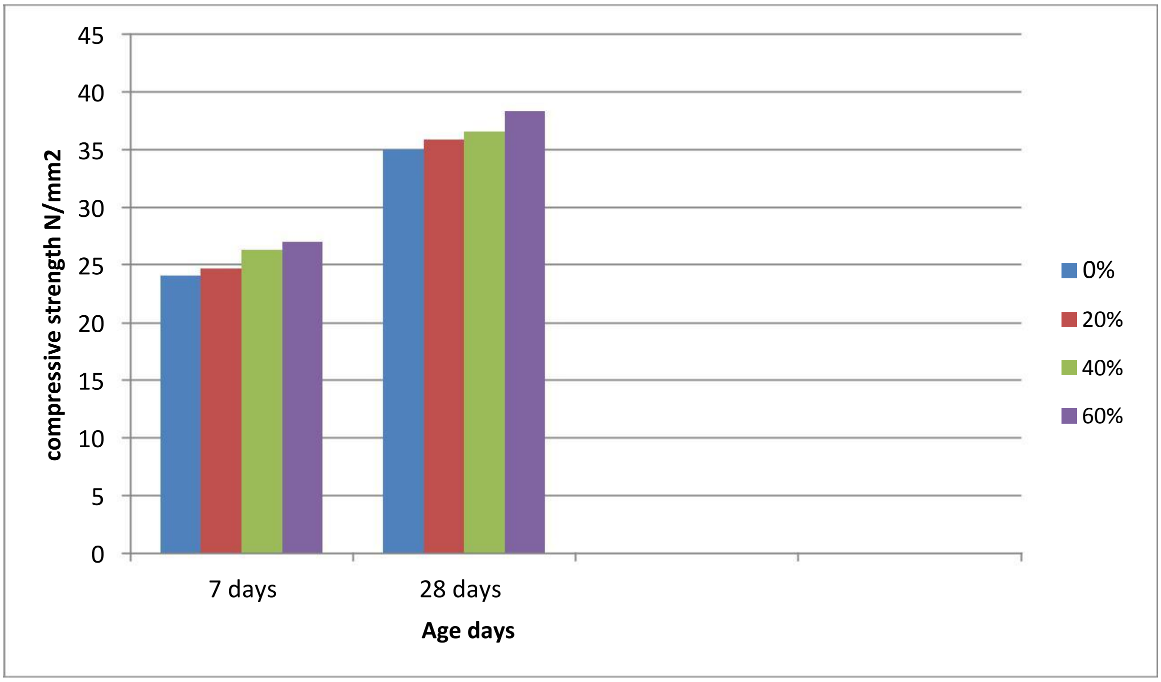


Fig.4.6: compressive strength at different replacement levels of coarse aggregate by ACBFS and cement replacement by fly ash incorporating metakaolin of 10%.

The ternary and quaternary mixes of concrete with fly ash content of 15% and 10% of metakaolin having 0%, 20%, 40% and 60% ACBFS attained strengths of 34.98MPa, 35.79MPa, 36.49MPa and 38.33MPa respectively as shown in table 4.12 to table 4.16 and comparison of various mixes in fig 4.5 and fig. 5.6.

Variation of compressive strength with age with 15% replacement level of metakaolin along with varying replacement level of ACBFS is shown in table 4.17 to 4.21 and fig 4.7 and fig 4.8.

Table 4.17: compressive strength (M13- cement replaced by 10% fly ash and 15% metakaolin)

Sr. No	Mix Designation	Moist Curing (Days)	Load at failure (kN)	Compressive strength (N/mm^2)	Average compressive Strength (N/mm^2)
1	M13	7	634	28.18	28.15
			611	27.16	
			655	29.11	
2	M13	28	805	35.78	35.67
			806	35.82	
			797	35.42	

Table 4.18: compressive strength
(M14- cement replaced by 10% fly ash and 15% metakaolin and coarse aggregate replaced by 20% ACBFS)

Sr. No	Mix Designation	Moist Curing (Days)	Load at failure (kN)	Compressive strength (N/mm^2)	Average compressive Strength (N/mm^2)
1	M14	7	612	27.2	28.21
			635	28.2	
			657	29.2	
2	M14	28	853	37.91	38.12
			851	37.82	
			869	38.62	

Table 4.19: compressive strength
(M15- cement replaced by 10% fly ash and 15% metakaolin and coarse aggregate replaced by 40% ACBFS)

Sr. No.	Mix Designation	Moist Curing (Days)	Load at failure (kN)	Compressive strength (N/mm^2)	Average compressive Strength (N/mm^2)
1	M15	7	688	30.57	29.79
			671	29.82	
			652	28.97	
2	M15	28	898	39.91	38.96
			861	38.26	
			871	38.71	

Table 4.20: compressive strength
(M16- cement replaced by 10% fly ash and 15% metakaolin and coarse aggregate replaced by 60% ACBFS)

Sr. No.	Mix Designation	Moist Curing (Days)	Load at failure (kN)	Compressive strength (N/mm^2)	Average compressive Strength (N/mm^2)
1	M16	7	622	27.64	29.05
			650	28.89	
			689	30.62	
2	M16	28	905	40.22	39.59
			889	39.51	
			878	39.02	

Table 4.21: Compressive strength for different replacement levels of cement by fly ash and metakaolin and different replacement levels of coarse aggregate by ACBFS

Mix Designation	Percentage Replacement by fly ash	Percentage Replacement by metakaolin	Percentage Replacement by ACBFS	Compressive Strength (N/mm^2) Duration of moist Curing (days)	
				7	28
M0	0%	0%	0%	26.02	38.48
M13	10%	15%	0%	28.15	35.67
M14	10%	15%	20%	28.21	38.12
M15	10%	15%	40%	29.79	38.96
M16	10%	15%	60%	29.05	39.59

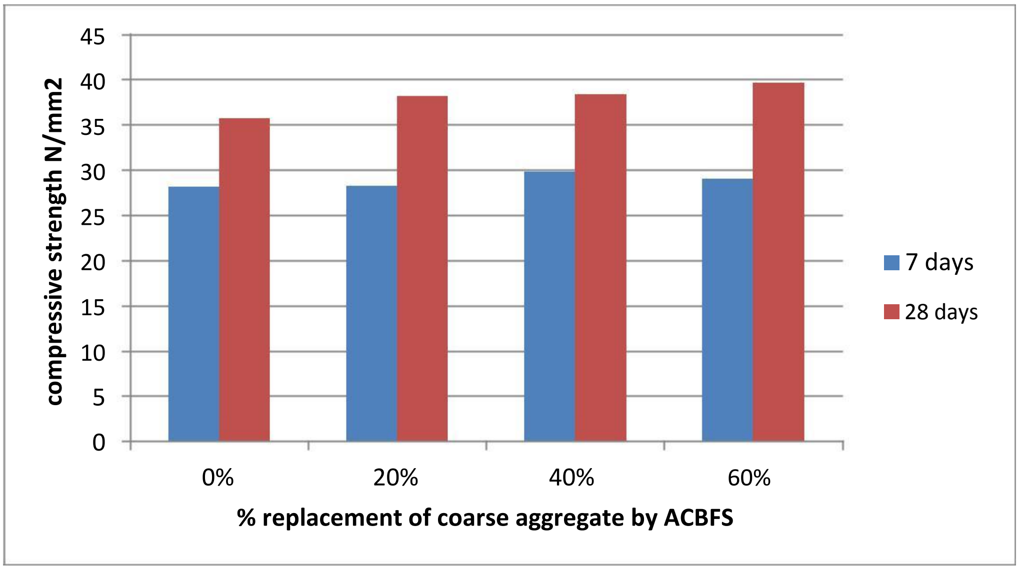


Fig 4.7: Compressive strength Vs percentage replacement of coarse aggregate by ACBFS and cement replacement by fly ash incorporating metakaolin of 15 %.

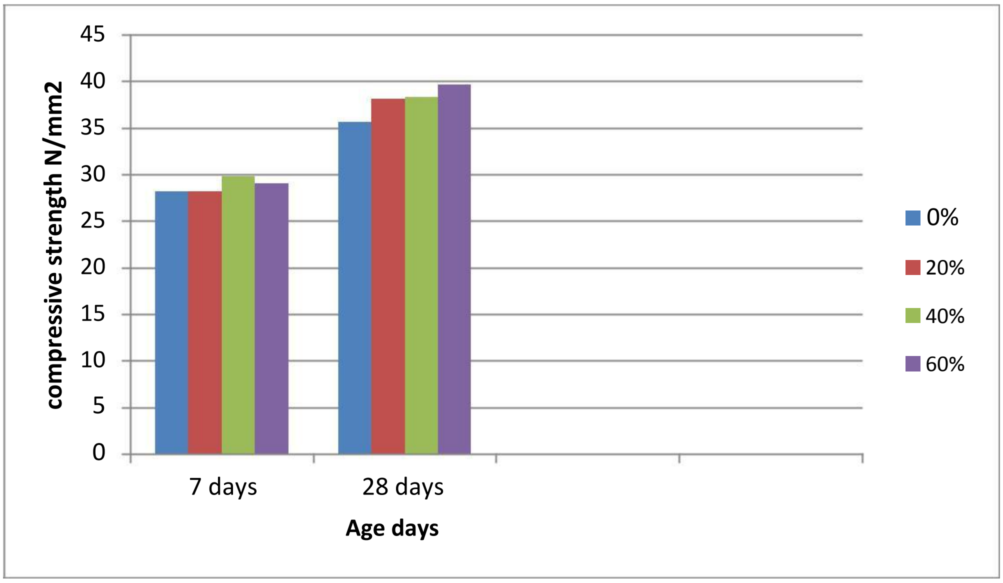


Fig.4.8: compressive strength at different replacement levels coarse aggregate by ACBFS and cement replacement by fly ash incorporating metakaolin of 15 %.

The ternary and quaternary mixes of concrete with fly ash content of 10%and 15% of metakaolin attained strengths of 35.67MPa, 38.12MPa, 38.33MPa and 39.59Mpa respectively for ACBFS replacement of 0%, 20%, 40% and 60% as shown in tables 4.17 to 4.21 and fig 4.7 and fig. 4.8.

It can be seen from above tables and figures that the concrete containing metakaolin achieved strength at higher rate than concrete with flyash and ACBFS, and the concrete with flyash only.

At 7 days the quaternary mixes achieved about 0.75 times the compressive strength at 28 days, which is higher than the compressive strength achieved by binary and ternary mixes, which may be due to the fact that the reaction between fly ash and CH takes place at moderate rate at intial stage compare to metakaolin CH reaction.

It can be seen from above tables and figures that the compressive strength of M16 mix is higher than all the other mixes at 7 days and at 28 days therefore the mix M16 is recommended .

4.2.2 Flexural strength

The flexural strength of all the mixes was determined at the ages of 7 and 28 days for the various replacement levels of fly ash, metakaolin and ACBFS with cement , fly ash and coarse aggregate respectively. Flexural strength of various mixes at 7 and 28 days is presented in tables 4.22 to 4.42. Figures 4.9 to 4.16 shows the variation of flexural strength with different percentages of fly ash, metakaolin and ACBFS for various mixes

Table 4.22: flexural strength
(M0- Reference mix)

Sr. No	Mix Designation	Moist Curing (Days)	Flexural strength (N/mm^2)	Average flexural Strength (N/mm^2)
1	M0	7	4.15	4.05
			4.05	
			3.95	
2	M0	28	5.70	5.90
			6.10	
			5.90	

Table 4.23: flexural strength
(M1-Cement replaced by 25% fly ash)

Sr. No	Mix Designation	Moist Curing (Days)	Flexural strength (N/mm^2)	Average flexural Strength (N/mm^2)
1	M1	7	3.20	3.30
			3.40	
			3.30	
2	M1	28	4.70	4.90
			5.10	
			4.90	

Table 4.24: flexural strength
(M2-Cement replaced by 25% fly ash and coarse aggregate replaced by 20% ACBFS)

Sr. No	Mix Designation	Moist Curing (Days)	Flexural strength (N/mm^2)	Average flexural Strength (N/mm^2)
1	M2	7	3.20	3.40
			3.40	
			3.60	
2	M2	28	5.00	5.00
			5.10	
			4.90	

Table 4.25: flexural strength
(M3-Cement replaced by 25% fly ash and coarse aggregate replaced by 40% ACBFS)

Sr. No	Mix Designation	Moist Curing (Days)	Flexural strength (N/mm^2)	Average flexural Strength (N/mm^2)
1	M3	7	3.52	3.52
			3.42	
			3.62	
2	M3	28	5.03	5.01
			5.01	
			4.99	

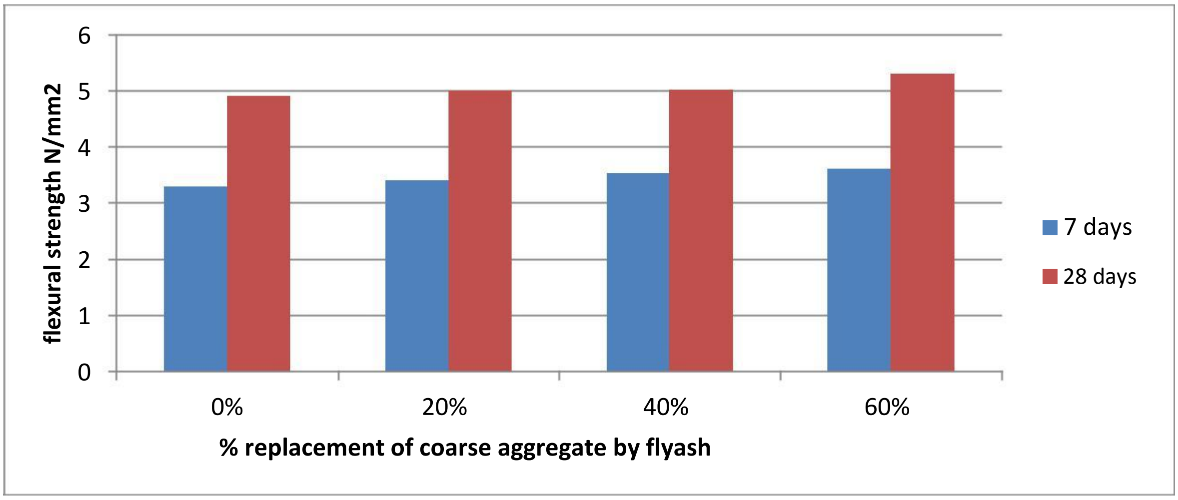
Table 4.26: flexural strength
(M4-Cement replaced by 25% fly ash and coarse aggregate replaced by 60% ACBFS)

Sr. No	Mix Designatio n	Moist Curing (Days)	Flexural strength (N/mm^2)	Average flexural Strength (N/mm^2)
1	M4	7	3.80	3.60
			3.40	
			3.60	
2	M4	28	5.30	5.30
			5.10	
			5.50	

Table 4.27: Flexural strength for different replacement levels of cement by fly ash and different replacement levels of coarse aggregate by ACBFS

Mix Designation	Percentage Replacement by fly ash	Percentage Replacement by metakaolin	Percentage Replacement by ACBFS	Flexural Strength (N/mm^2) Duration of moist Curing (days)	
				7	28
M0	0%	0%	0%	4.05	5.90
M1	25%	0%	0%	3.30	4.90
M2	25%	0%	20%	3.40	5.00
M3	25%	0%	40%	3.52	5.01
M4	25%	0%	60%	3.60	5.30

Fig 4.9: Flexural strength Vs percentage replacement of coarse aggregate by ACBFS and cement replacement by fly ash.



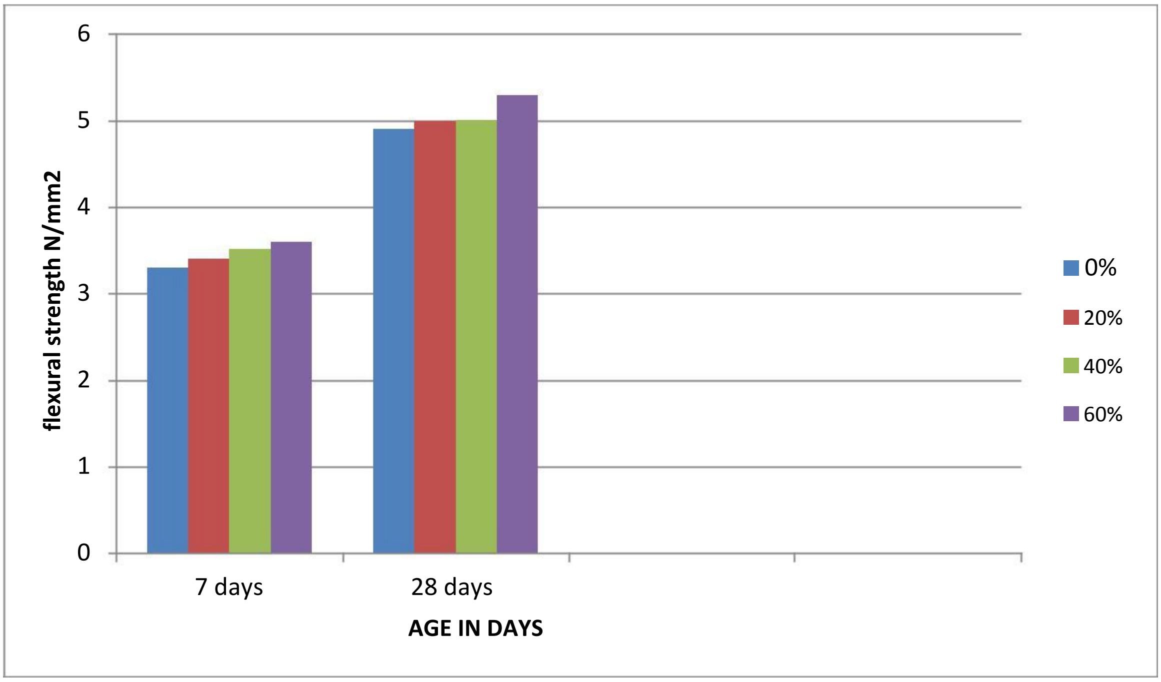


Fig.4.10: flexural strength at different replacement levels coarse aggregate by ACBFS and cement replacement by fly ash.

It is clear from tables above tables and figures that the flexural strength of mixes M1, M2, M3 and M4 is less than the reference mix M0 , however flexural strength improved with increase in percentages of ACBFS. The reason for this trend is same as already discussed in case of compressive strength

Table 4.28: flexural strength

(M5-Cement replaced by 20% fly ash and 5% metakaolin)

Sr. No	Mix Designation	Moist Curing (Days)	Flexural strength (N/mm²)	Average flexural Strength (N/mm²)
1	M5	7	3.40	3.4
			3.1	
			3.7	
2	M5	28	5.1	4.95
			5.04	
			4.73	

Table 4.29: flexural strength

(M6-Cement replaced by 20% fly ash and 5% metakaolin and coarse aggregate replaced by 20% ACBFS)

Sr. No	Mix Designation	Moist Curing (Days)	Flexural strength (N/mm²)	Average flexural Strength (N/mm²)
1	M6	7	3.82	3.76
			3.9	
			3.56	
2	M6	28	5.23	5.03
			5.1	
			4.76	

Table 4.30: flexural strength

(M7-Cement replaced by 22.5% fly ash and 2.5% metakaolin and coarse aggregate replaced by 40% ACBFS)

Sr. No	Mix Designation	Moist Curing (Days)	Flexural strength (N/mm²)	Average flexural Strength (N/mm²)
1	M7	7	3.54	3.58
			3.51	
			3.7	
2	M7	28	5.45	5.31
			5.4	
			5.1	

Table 4.31: flexural strength
(M8-Cement replaced by 20% fly ash and 5% metakaolin and coarse aggregate replaced by 60% ACBFS)

Sr. No	Mix Designation	Moist Curing (Days)	Flexural strength (N/mm^2)	Average flexural Strength (N/mm^2)
1	M8	7	3.57	3.56
			3.43	
			3.69	
2	M8	28	5.48	5.39
			5.37	
			5.34	

Table 4.32: Flexural strength for different replacement levels of cement by fly ash and metakaolin and different replacement levels of coarse aggregate by ACBFS

Mix Designation	Percentage Replacement by fly ash	Percentage Replacement by metakaolin	Percentage Replacement by ACBFS	Flexural Strength (N/mm^2) Duration of moist Curing (days)	
				7	**28**
M0	0%	0%	0%	4.05	5.90
M5	20%	5%	0%	3.4	4.95
M6	20%	5%	20%	3.76	5.03
M7	20%	5%	40%	3.58	5.31
M8	20%	5%	60%	3.56	5.39

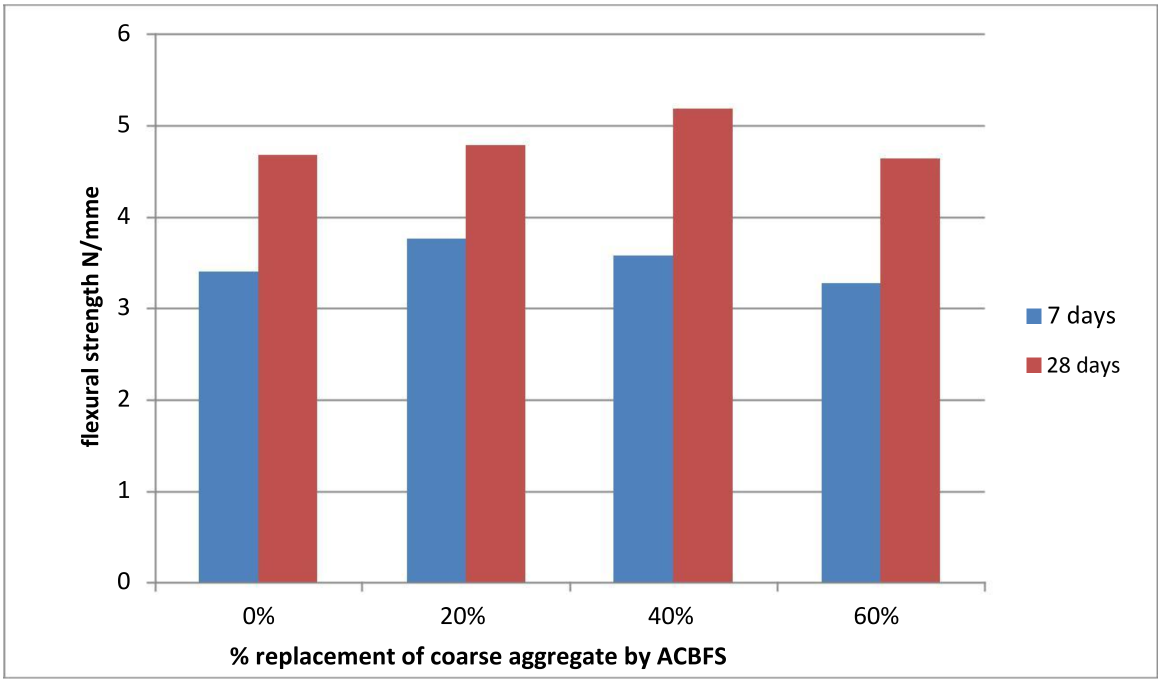


Fig 4.11: Flexural strength Vs percentage replacement of coarse aggregate by ACBFS and cement replacement by fly ash incorporating 5% metakaolin.

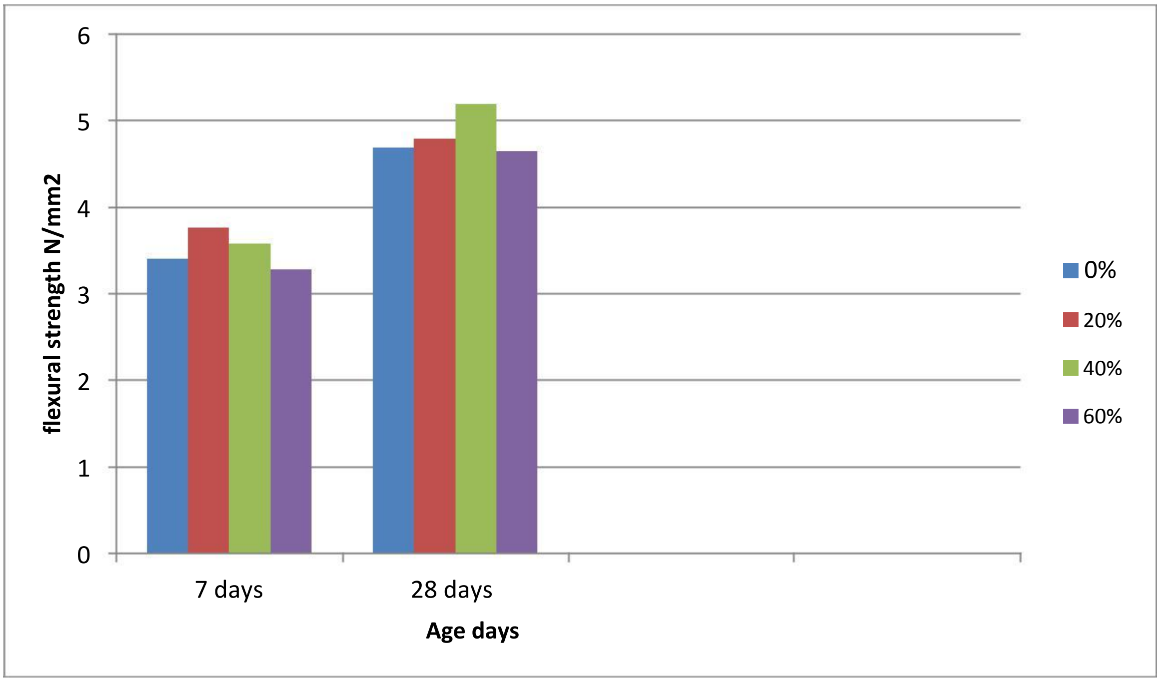


Fig.4.12: flexural strength at different replacement levels coarse aggregate by ACBFS and cement replacement by fly ash incorporating 5% metakaolin.

It can be seen from above tables and figures M5,M6, M7, M8 achieved flexural strength of 4.95N/mm2, 5.03N/mm2, 5.31N/mm2, 5.39N/mm2 respectively , it can be seen further that the flexural strength increased with increase in percentages of metakaolin and ACBFS,this trend is similar to that of compressive strength

Table 4.33: flexural strength
(M9-Cement replaced by 15% fly ash and 10% metakaolin)

Sr. No	Mix Designation	Moist Curing (Days)	Flexural strength (N/mm^2)	Average flexural Strength (N/mm^2)
1	M9	7	3.40	3.60
			3.60	
			3.80	
2	M9	28	5.04	5.02
			5.00	
			5.02	

Table 4.34: flexural strength
(M10-Cement replaced by 15% fly ash and 10% metakaolin and coarse aggregate replaced by 20% ACBFS)

Sr. No	Mix Designation	Moist Curing (Days)	Flexural strength (N/mm^2)	Average flexural Strength (N/mm^2)
1	M10	7	3.67	3.72
			3.77	
			3.72	
2	M10	28	5.80	5.40
			5.40	
			5.00	

Table 4.35: flexural strength
(M11-Cement replaced by 15% fly ash and10% metakaolin and coarse aggregate replaced by 40% ACBFS)

Sr. No	Mix Designation	Moist Curing (Days)	Flexural strength (N/mm^2)	Average flexural Strength (N/mm^2)
1	M11	7	3.80	4.00
			4.20	
			4.00	
2	M11	28	5.80	5.80
			5.75	
			5.85	

Table 4.36: flexural strength
(M12-Cement replaced by 15% fly ash and10% metakaolin and coarse aggregate replaced by 60% ACBFS)

Sr. No	Mix Designation	Moist Curing (Days)	Flexural strength (N/mm^2)	Average flexural Strength (N/mm^2)
1	M12	7	4.00	3.96
			3.92	
			3.96	
2	M12	28	6.00	5.76
			5.50	
			5.80	

Table 4.37: Flexural strength for different replacement levels of cement by fly ash and metakaolin and different replacement levels of coarse aggregate by ACBFS

Mix Designation	Percentage Replacement by fly ash	Percentage Replacement by metakaolin	Percentage Replacement by ACBFS	Flexural Strength (N/mm^2) Duration of moist Curing (days)	
				7	28
M0	0%	0%	0%	4.05	5.90
M9	15%	10%	0%	3.60	5.02
M10	15%	10%	20%	3.72	5.40
M11	15%	10%	40%	4.00	5.80
M12	15%	10%	60%	3.96	5.76

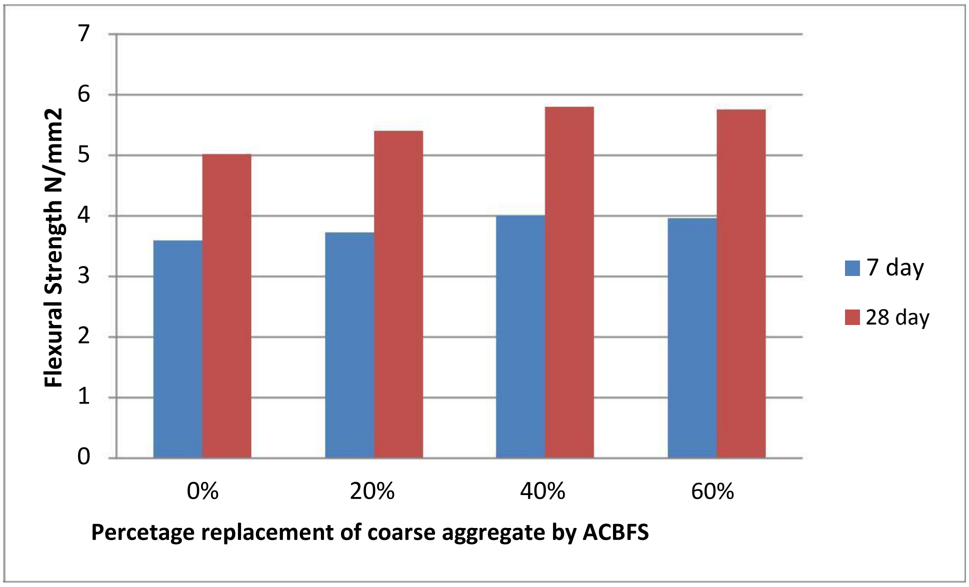


Fig 4.13: Flexural strength Vs percentage replacement of coarse aggregate by ACBFS and cement replacement by fly ash incorporating 10% metakaolin.

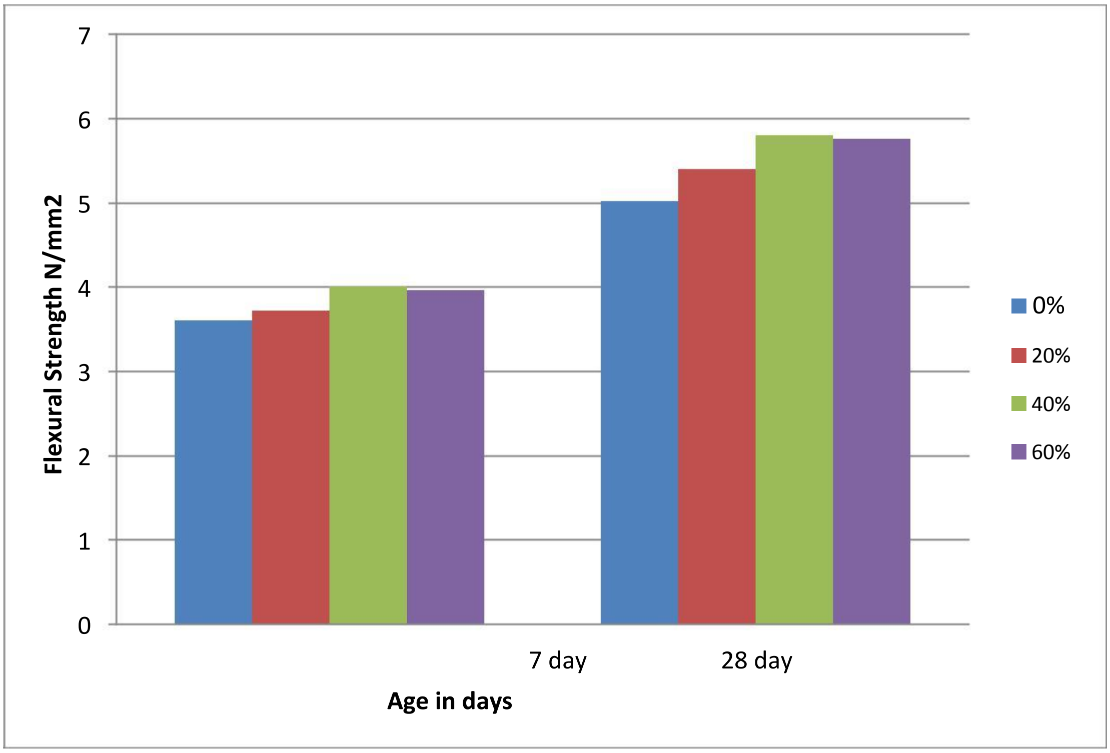


Fig.4.14: flexural strength at different replacement levels coarse aggregate by ACBFS and cement replacement by fly ash incorporating 10% metakaolin.

Table 4.38: flexural strength

(M13-Cement replaced by 10% fly ash and 15% metakaolin)

Sr. No	Mix Designation	Moist Curing (Days)	Flexural strength (N/mm^2)	Average flexural Strength (N/mm^2)
1	M13	7	3.62	3.85
			4.00	
			3.95	
2	M13	28	5.3	5.36
			5.25	
			5.54	

Table 4.39: flexural strength

(M14-Cement replaced by 10% fly ash and 15% metakaolin and coarse aggregate replaced by 20% ACBFS)

Sr. No	Mix Designation	Moist Curing (Days)	Flexural strength (N/mm^2)	Average flexural Strength (N/mm^2)
1	M14	7	3.9	3.95
			4.06	
			3.89	
2	M14	28	5.80	5.73
			5.66	
			5.74	

Table 4.40: flexural strength

(M15-Cement replaced by 10% fly ash and 15% metakaolin and coarse aggregate replaced by 40% ACBFS)

Sr. No	Mix Designation	Moist Curing (Days)	Flexural strength (N/mm^2)	Average flexural Strength (N/mm^2)
1	M15	7	4.41	4.32
			4.45	
			4.1	
2	M15	28	6.00	5.92
			6.3	
			5.72	

Table 4.41: flexural strength (M16-Cement replaced by 10% fly ash and 15% metakaolin and coarse aggregate replaced by 60% ACBFS)

Sr. No	Mix Designation	Moist Curing (Days)	Flexural strength (N/mm^2)	Average flexural Strength (N/mm^2)
1	M16	7	4.3	4.30
			4.33	
			4.29	
2	M16	28	6.09	6.0
			6.01	
			5.78	

Table 4.42: Flexural strength for different replacement levels of cement by fly ash and metakaolin and different replacement levels of coarse aggregate by ACBFS

Mix Designation	Percentage Replacement by fly ash	Percentage Replacement by metakaolin	Percentage Replacement by ACBFS	Flexural Strength (N/mm^2) Duration of moist Curing (days)	
				7	**28**
M0	0%	0%	0%	4.05	5.90
M13	10%	15%	0%	3.85	5.36
M14	10%	15%	20%	3.95	5.73
M15	10%	15%	40%	4.32	5.92
M16	10%	15%	60%	4.30	6.0

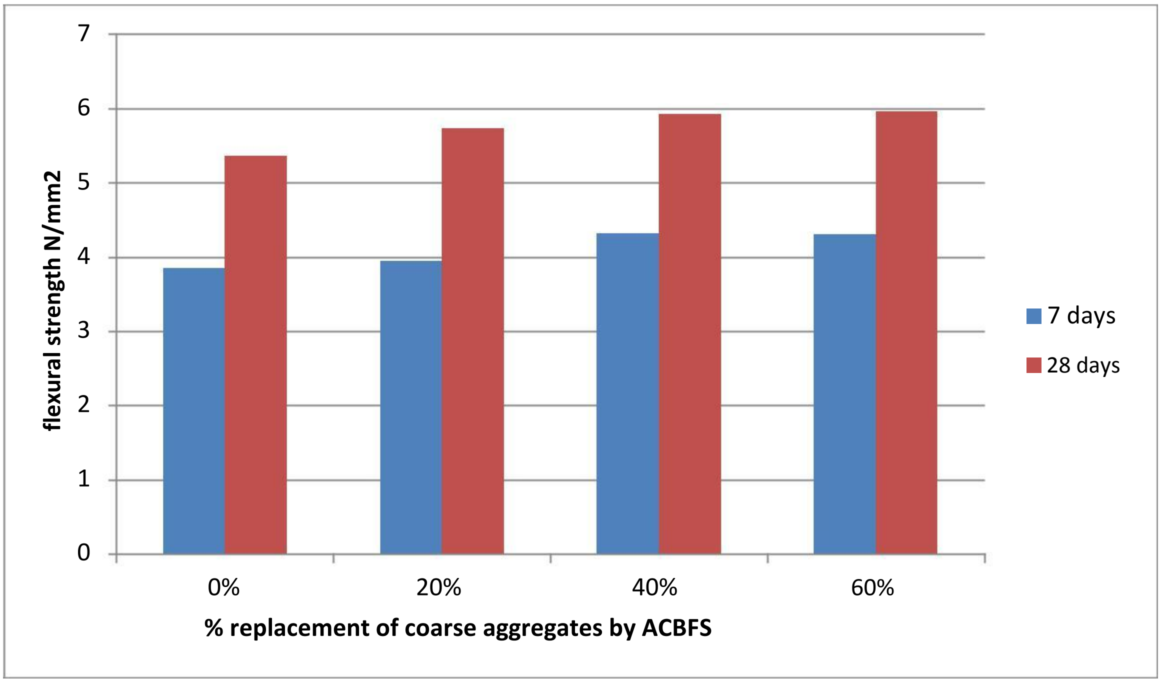


Fig 4.15: Flexural strength Vs percentage replacement of coarse aggregate by ACBFS and cement replacement by fly ash incorporating 15% metakaolin.

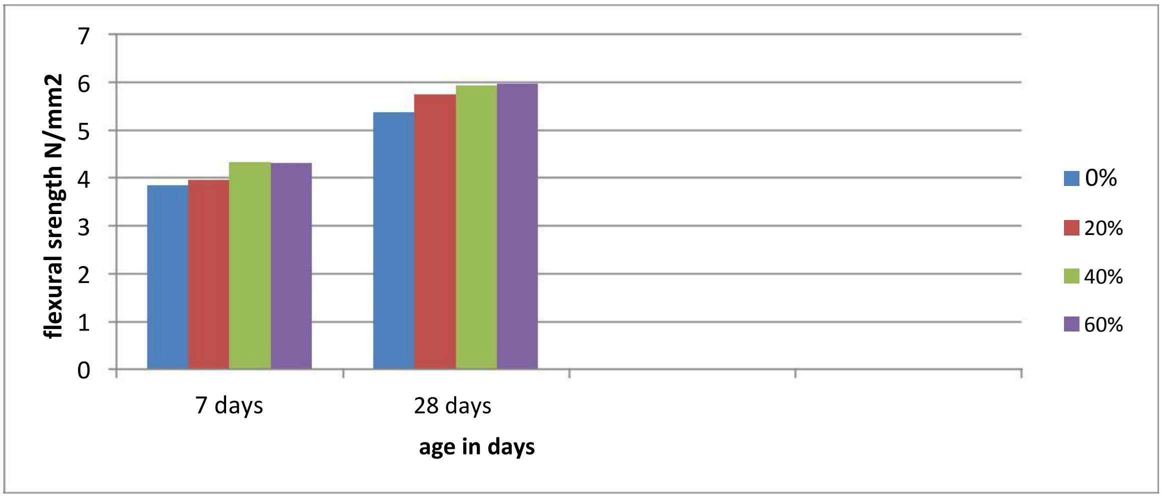


Fig.4.16: flexural strength at different replacement levels coarse aggregate by ACBFS and cement replacement by fly ash incorporating 15% metakaolin.

It can be seen from the above tables and figures that similar to compressive strength the flexural strength of ternary and quaternary mixes increased with increase in percentages of metakaolin and ACBFS , mix M15 and M16 achieved comparable flexural strength at 7 and 28 day

4.3 Cost Analysis

Though the compressive strength of fly ash concrete decreases with addition of fly ash, but the strength improved with incorporation of metakaolinand ACBFS

The cost of concrete decreases with increase in percentage of cement replacement, by fly ash whereas the compressive strength of concrete decreases with addition of fly ash. However, it is observed that for M12 compressive strength at 28 days is comparable that of reference mix (M0), therefore the cost comparison of mixes M0 and M12 is carried out, table 4.43 shows the comparison of mix M0 and M12

Table 4.43 : Cost analysis of concrete mix without fly ash and concrete mix containing both fly ash , ACBFS and metakaolin for similar compressive strength

MIX DESIGNATION	**Rate (Rs/kg)**	**M0 (reference mix)**		**M12 (15% Fly ash , ACBFS=60% and 10% metakaolin)**	
Compressive Strength (MPa)		38.48		38.48	
Material		**Quantity kg/m^3**	**Amount Rs**	**Quantity kg/m^3**	**Amount Rs**
Cement	7	385	2695	288.75	2021.2
Fly ash	1.2	0	0	57.75	69.3
Sand	0.53	719	381	719	381
Aggregates	0.6	1149	689.4	459.6	275.56
ACBFS	0.4	0	0	689.4	275
Metakaolin	12	0	0	38.5	462
Water	-	165	-	165	-
Super plasticizer	38	2.695	102.5	2.695	102.5
TOTAL			3868		3587
% SAVING					7.3% for 1 m^3

It can be seen from above table that there is saving of quantity of cement and aggregates in quaternary mix as compared to reference mix that is plain cement concrete. Therefore, the replacement of cement by fly ash and addition of metakaolin for partial replacement of fly ash along with partial replacement of coarse aggregates with ACBFS is a viable proposition.

Chapter 5
Conclusion

5.1General

The effects of replacement of cement by flyash and metakaolin, coarse aggregates by ACBFS on compressive and flexural strength of concrete have been investigated in the present study, the conclusion drawn on the basis of present study have been reported in this chapter. Results of investigation indicate that compressive strength and flexural strength of concrete show similar trend that is increase in strength with addition of metakaolin and ACBFS, while decrease in strength with addition of fly ash in general .

5.2Conclusion

The following conclusion are drawend on the basis of results obtained in this investigation

i. The partial replacement of cement by flyash resulted in decrease in compressive and flexural strength of concrete at 7 and 28 days. With replacement of 25% of cement by flyash the compressive strength decreased by 25% and flexural strength decreased by 17% as compared to reference mix at the age of 28 days

ii. The addition of Air cooled blast furnace slag resulted in increase in compressive strength and flexural strength of concrete at 7 and 28 days . Further with increase in percentages of Air cooled blast furnace slag the compressive and flexural strength increased. A maximum increase of 25% in compressive strength and 8% in flexural strength was obtained for mix containing 25% flyash and 60% Air cooled blast furnace slag (M4) as compared to reference mix (M0)

iii. The partial replacement of flyash by metakaolin resulted in increase in compressive and flexural strengths of concrete. Further with increase in percentages of metakaolin the strength of mixes increased.

iv. The maximum compressive strength and flexural strength was obtained for mix containing 10% flyash, 15% metakaolin and 60 % Air cooled blast furnace slag (M16) .

v. The cost comparison of the comparable mixes that is reference mix (M0) and the mix containing 15% flyash 10% metakaolin 60% Air cooled blast furnace slag (M12) shows that the replacement of cement by flyash and metakaolin along with replacement of coarse aggreagate by Air cooled blast furnace slag is a viable proposition.

5.3 Future Scope of Study

Within the limited scope of present study, the conclusions have been drawn and reported. However, further studies can be planned in following directions:

i) The effect of fly ash for cement replacement and metakaolin for fly ash replacement along with effect of ACBFS for coarse aggregate replacement prepared with various sizes of aggregates on compressive strength and flexural strength of concrete i.e. 40mm

ii) The effect of metakaolin and ACBFS along with other supplementary materials like alccofine , rise husk, glass waste powder etc and their role in high performance concrete.

iii) The effect of fly ash , ACBFS and metakaolin on other parameters like durability, split tensile strength, drying shrinkage etc.

iv) Effect of fly ash , ACBFS and metakaolin on compressive strength and shrinkage of concrete beyond 28 days.

v) The effect of higher percentages of ACBFS on compressive , flexural and split tensile strength can be investigated

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