Certificate

This is to certify that the thesis entitled "**Stress-Strain Behaviour of Flyash Concrete With Steel Fibre**" which is being submitted herewith by **Mr. Harbir Singh (Roll No. 8012302)** in partial fulfillment for the award of the degree of **Master of Civil Engineering (Structures)** of **Thapar Institute of Engineering & Technology (Deemed University), Patiala** is an authentic record of student's own work carried out under my supervision and guidance. The matter presented in the thesis has reached the standards fulfilling the requirements of the regulation for the award of said degree.

Dr. M.L. Gambhir
Professor
Department of Civil Engineering,
Thapar Institute of Engineering and
Technology, (Deemed University),
Patiala

Head
Department of Civil Engineering,
Thapar Institute of Engineering and
Technology, (Deemed University),
Patiala

Dr. D.S. Bawa
Dean, Academic Affairs
Thapar Institute of Engineering and
Technology, (Deemed University),
Patiala

ACKNOWLEDGEMENT

The work reported here in this dissertation has been carried out in the Department of Civil Engineering, Thapar Institute of Engineering & Technology, Patiala, under the valuable guidance and consistent encouragement of Dr. M.L. Gambhir, Professor, Department of Civil Engineering. I feel honoured in expressing my profound thanks, indebtness and deep sense of gratitude to my guide from the core of my heart for his timely suggestions, generous help and right direction throughout the course of present work.

I am greatly thankful to Dr. R. Trivedi, Assistant Professor and Head, Department of Civil Engineering, Thapar Institute of Engineering and Technology, Patiala for his kind help and extending all possible facilities for carrying out the dissertation work.

I owe thanks to Dr. Maneek Kumar and Mr. Varinder Singh Kanwar, Department of Civil Engineering T.I.E.T., Patiala for their all out help, painstaking efforts, able guidance and persistence encouragement during the study.

Thanks are due to Miss Sweta Goyal, Laboratory Incharge, Shri Om Parkash Verma, Laboratory Superintendent and Shri Amarjit Singh and Shri Simranjeet, Laboratory Attendants, other staff members of the Department and Library staff of Thapar Institute of Engineering & Technology, Patiala for their help and support during the experimental work.

I acknowledge with thanks the support provided by my best friend Miss Ashu Singh (Delhi University, Delhi).

Last but not the least to my family for their tolerance, patience and guidance over many long months.

Place : Patiala **(HARBIR SINGH)**

Date :

ABSTRACT

With the ever-increasing population of the world, in general, and the developing countries, in particular, there is tremendous pressure on Civil Engineers to develop cost-effective and eco-friendly structures to fulfill the needs of the mankind. Within current practices of utilisation, cement and concrete construction industries throughout the world has been the largest user of flyash, an industrial by-product, whose use and production have increased many fold during last three decades and have exploited it to the best advantage. Flyash nowadays is a four fold issue : reduction in air/water pollution, beneficial conversion of waste into wealth, reduction in expenditure on disposal and augmenting the demand of much needed construction materials which is economical and sound. Fibres on other hand have provided to improve strength, stiffness and ductility of reinforced concrete members with their addition. They act as crack arrestors, change all modes of failure, and increase ultimate strain of the composite.

Experimental investigation has been carried out to study the effect of the flyash content and steel fibres on the properties of both fresh and hardened concrete. Cement has been replaced by mass with 15,20 and 25 per cent flyash content. Three percentages of steel fibres (0.25, 0.50 and 0.75 per cent) of aspect ratio 100, have been used in the investigation. Tests have been performed for Slump, Vee-Bee Time, Compressive Strength and Compressive Stress-Strain.

Test results indicate that the Slump increases and Vee-Bee time decreases as the flyash percentage increases, whereas steel fibres decreases the slump and increase the Vee-Bee time sharply. The addition of steel fibres increases the compressive strength of concrete. The compressive strain of concrete increases with the increase in the percentages of fly ash. The addition of steel fibres doesn't significantly affect the modules of elasticity of fly ash concrete.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

CHAPTER-1

INTRODUCTION

1.1 GENERAL

The future of concrete industry appears to be bright from projections based on current trends in population growth, and increasing industrialization and urbanization. However, this optimism must be tempered with changing attitudes in the society on ecological issues such as conservation of natural resources, environmental pollution from the point of view of disposal of byproducts and above all apart from this, the economy which has always been a field of interest to all. At present about 200 million cum. of concrete is being used in India and it is expected that the concrete requirement by the year 2005 will be 250 million cum. In concrete mix, cement is the most cost and energy intensive component, hence cost of unit concrete can be reduced by replacement of cement with some cheaper material or any similar industrial by product. Flyash is one such material which has been replaced for cement in various per centage by weight.

Flyash which is a byproduct of the thermal power plant poses a serious problems of its dumping to the environmentalists. Utilization of flyash in concrete as partial replacement with cement not only solves the problems of dumping to some extent but also it is used as mineral admixture in concrete and helps to attain reduction in cost of concrete by saving cement. This pozzolana is beneficially used to attain certain properties in concrete as lower water demand for similar workability, reduced bleeding and lower evolution of heat. It has been used particularly in mass concrete applications and large volume placement to control expansion due to heat of hydration and also helps in reducing cracking at early ages.

Plain concrete is weak in tension and has limited ductility and little resistance to cracking. Microcracks are present in concrete and because of its poor tensile strength; the cracks propagate with the application of load, leading to brittle fracture of concrete.

Microcracks in concrete are formed during its hardening stage. A discontinuous heterogeneous system exits even before the application of any external load. When the load is applied, microcracks start developing along the planes, which may experience relatively low tensile strains, at about 25-35% of the ultimate strength in compression. Further application of the load leads to uncontrolled growth of the microcracks. The low resistance to tensile crack propagation in turn results in a low fracture toughness, and limited resistance to impact and explosive loading.

The low tensile strength of concrete is being compensated for in several ways, and this has been achieved by the use of reinforcing bars and also by applying prestressing method.

Though these methods provide tensile strength to concrete, they do not increase the inherent tensile strength of concrete itself. Further, conventionally reinforced concrete is not a two phase material in true sense. Conventionally reinforced concrete a true two phase material only after cracking when cracked matrix is held by the reinforcing bars. Existence of one phase (i.e. steel or concrete) does not improve the basic strength characteristics of the other phase and consequently the overall performance of the traditional reinforced concrete composite is dictated by the individual performance of the concrete and steel phase separately.

These deficiencies have led researchers to investigate and develop a material could perform better in areas where conventional concrete has several limitations. Current research has developed a new concept to increase the concrete ductility and its energy absorption capacity, as well as to improve overall durability. This new generation technology utilizes discrete steel or synthetic fibres from 19 to 64 mm in length. The fibres are randomly dispersed throughout the concrete matrix providing for better distribution of both internal and external stresses by using a three dimensional reinforcing network.

The primary role of the fibres in hardened concrete is to modify the cracking mechanism. By modifying the cracking mechanism, the macro cracking becomes microcracking. The cracks are smaller in width, thus reducing the permeability of concrete and the ultimate cracking strain of the concrete is enhanced. The fibres are capable of carrying a load across the crack.

1.2 CONSTITUENT MATERIALS

The two major components of flyash fibres reinforced concrete are the matrix and the fibres. The matrix generally consists of Portland cement, flyash aggregates, and water. Fibres used can be metallic, polymeric and natural fibres, but here only steel fibres have been used.

1.2.1. Cement

The type of cement is important mainly through its influence on the rate of development of compressive strength of concrete. The choice of the type of cement depends upon the requirements of performance at hand. The most commonly used cement is called ordinary Portland cement. Variation in the cement quality will cause the concrete compressive strength to vary more than any other single material. Ordinary Portland cement of different grades OPC-33, OPC-43 and OPC-53 are available in the market and are generally used for producing flyash fibre reinforced concrete.

1.2.2 Aggregates

The aggregates suitable for plain concrete can be suitably used in flyash fibre reinforced concrete. The aggregates are normally divided into two categories i.e. fine and coarse aggregates.

Fine aggregate normally consists of natural, crushed, or manufactured sand. Natural sand is the usual component for normal weight concrete. In some cases manufactured lightweight particles are used for lightweight concrete and mortar. Heavy weight particles made of metallic components are sometimes used to produce heavy weight concrete for nuclear shielding purposes.

Fine aggregate is needed for both flyash Fibre reinforced concrete and mortar. The maximum grain size and size distribution depends on the type of product being manufactured. For example, fine sand is normally used for manufacturing thin sheets and relatively small diameter pipes, whereas sand containing coarse particles is used for shotcreting applications and for large diameter pipes with wall thickness exceeding 25 mm.

Coarse aggregates can be normal-weight, light weight, or heavy weight in nature. Normal-weight coarse aggregates can be made of natural gravel or crushed stone. Light-weight coarse aggregates are generally made of expanded clay (such as shale, pumice) or blast furnace slag.

The graded coarse aggregate is described by its nominal size, i.e. 40 mm, 20 mm, 16 mm and 12.5 mm, etc. For example, a graded aggregate of nominal size 12.5 mm means an aggregate most of which passes the 12.5 mm IS sieve.

1.2.3. Flyash

Flyash is a byproduct of the combustion of pulverized coal collected from the flue gases using electrostatic or mechanical precipitators or bag house in thermal power plants. Its composition varies with the type of fuel burnt, load on boiler and type of separator, etc. It is generally finer than Portland cement and consists of spherical glassy particles ranging from 1 to 150 micron in diameter, of which the bulk passes through a 45 mm sieve. The range of particle sizes in any given flyash is largely determined by the type of dust collection equipment used.

The flyash obtained from electrostatic precipitators may have a specific surface of about 350000 to 500000 mm^2/g, i.e. it is finer than Portland cement. The flyash obtained from cyclone separators is comparatively coarser and may contain larger amounts of unburnt fuel.

The major components of flyash reported in oxide form are silica (SiO2), alumina (Al_2O_3), and oxides of calcium and iron (CaO and Fe_2O_3). Flyash composition varies with the source of coal. Because of its fineness and mineralogy including amorphous nature, flyash is generally pozzolanic and sometimes also self-cementitious. The flyash has been established and is widely used as mineral admixture or supplementary cementing material in cement concrete to import specific properties to concrete for field applications. Flyash is generally used in following three ways: -

- As partial replacement of cement.
- As partial replacement of fine aggregate.
- As a simultaneous replacement of cement and fine aggregate.

Due to different densities of cement and flyash 3100 to 3200 $Kglm^3$ and 2200 to 2400 $kglm^3$, respectively, a part replacement by equal mass increases the volume of cementitious material, where as replacement by equal volume reduces the mass. In practice the replacement is usually on a mass basis. The use of flyash influences the volume yield of concrete. It has little effect on the drying shrinkage of concrete.

Classification of Flyash

ASTM-C 618-93 Categories natural pozzolons and flyash into the following three categories: -

CLASS N : Raw or calcined natural pozzolons such as some diatomaceous earths, opaline chert and shale, stuffs, volcanic ashes and pumice are come in this category.

CLASS F: Flyash normally produced from burning anthracite or bituminous coal falls in this category. This class of flyash exhibits pozzolanic property but rarely if any, self hardening property due to low lime content (<10%)

CLASS C: Flyash normally produced from lignite or subbituminous coal is the only material included in this category. It has both pozzolanic and varying degree of self cementitious properties due to high lime content (> 10%)

According to IS : 3812-1981 flyash shall be supplied in the following grade corresponding to the properties specified in tables.

Grade 1: For incorporation in cement mortar and concrete and in lime pozzolana mixture, and for manufacture of Portland pozzolana cement.

Grade 2: For incorporation in cement mortar and concrete and in line pozzolana mixture.

Table 1.1 and 1.2 give the chemical and physical requirements of flyash respectively.

1.2.4 Fibres

A fibre is defined as a small piece of reinforcing material having certain dimension and a convenient numerical parameter for describing a fibre is, its aspect ratio. The aspect ratio is defined as the ratio of the fibre length to an equivalent fibre diameter.

i.e. Aspect Ratio = Fibre Length (l) / Equivalent fibre Diameter (d)

The equivalent fibre diameter is the diameter of circle with an area equal to the cross-sectional area of the fibre.

Fibre used in concrete may be classified into two categories:

(a) High modulus fibres improve both flexural and impact resistance simultaneously. Such type of fibres are steel, asbestos, carbon and glass having high strength.

(b) Low modulus fibres improve impact resistance of concrete but do not contribute much to flexural strength. Such type of fibres have lower elastic modulus than concrete mix e.g. Nylon, Polypropylene and Vegetable fibres.

(Since here only steel fibres have been used in the experimental program, therefore only steel fibres will be described in detail)

Steel Fibres

A number of steel-Fibre types are available as reinforcement. Round steel fibres, the commonly used type, are produced by cutting round wires into short lengths. The typical diameters lie in the range of 0.25 to 0.75 mm. Steel Fibres having a rectangular cross-section are produced by slitting the sheets about 0.25mm thick. For improving the mechanical bond between the Fibre and matrix, indented, crimped, machined and hook-ended Fibres are normally produced. The aspect ratio of Fibres which have been employed vary from about 30 to 250.

Fibres made from mild steel drawn wire conforming to IS : 280-1976 with the diameter of wire varying from 0.3 to 0.5 mm have been practically used in India. The efficiency of Fibre distribution depends on the geometry of the fiber, the Fibre content, the mixing and compaction technique, the size and shape of the aggregates inclusion and the mix proportions.

Steel Fibre reinforced concrete materials have been used for overlays and overslabbing for roads, pavements, air fileds, bridge decks, and industrial and other flooring, particularly those subjected to wear and tear, and chemical attack. Guiniting has been successfully applied with steel fibers.

1.2.5 Water

Water is needed for hydration of cement and moulding of concrete to the desired shape. The relationship between compressive strength and water cement ratio is well established. An increase in water cement ratio leads to a reduction in compressive strength. A water cement ratio of about 0.28 provides sufficient water for hydration. However, a water cement ratio of about 0.6 is needed to obtain a plastic workable mixture that can be transported, placed, properly compacted, and finished to the final form.

TABLE 1.1 CHEMICAL REQUIREMENTS OF FLYASH (IS: 3812-1981)

Sr. No	Characteristic	Requirement
1.	Silicon dioxide (SiO_2) plus aluminum oxide (Al_2O_3) plus iron oxide (Fe_2O_3), per cent by mass, Min.	70
2.	Silicon dioxide (SiO_2), per cent by mass, Min	35.0
3.	Magnesium oxide (MGO), per cent by mass, max	5.0
4.	Total sulphur trioxide (SO_3), per cent by mass, max	2.75
5.	Available alkalis as sodium oxide Na_2O, per cent by mass, max	1.5
6.	Loss in ignition, per cent by mass, max	12.0

TABLE 1.2 PHYSICAL REQUIREMENTS OF FLYASH (IS: 3812-1981)

Sr. No.	Characteristics	Requirement	
		Grade of Flyash	
		I	II
1.	Fineness, specific surface in m^2/kg by Blaine's permeability method, Min	320	250
2.	Lime reactivity Average compressive stress in N/mm^2, Min	4.0	3.0
3.	Compressive strength at 28 days in N/mm^2, Min	Not less than 80% of the strength of corres ponding plain cement mortar cubes	
4.	Drying shrinkage, per cent, max	0.15	0.10
5.	Soundness by autoclave test expansion of specimens, per cent, Max.	0.8	0.8

CHAPTER-2

Literature review

In this chapter research work related to fibres, flyash and flyash fibre reinforced concrete as reported by various authors has been presented in respective sequence.

Rajagopalan, et al.[5] have carried out experimental work on the behaviour of fibre reinforced concrete in direct tension and flexure. Based on their study they have concluded that closely spaced and well bonded steel fibres increases the strength of concrete beams both at first crack and at failure. The inclusion of fibres to the concrete imparts enormous ductility. Significant increase in flexural strength is obtained by the inclusion of fibres in the tension zone. They have presented empirical formula to predict the strength of fibre reinforced concrete beams.

Anon[3] has reported the advantages of using fibrous concrete. Increase in tensile strength, flexural strength, first crack strength and ultimate crack strength have been reported. Data on properties like compressive ductility, higher fatigue and shear have also been reported.

Shah and Ranjan[1] have investigated mechanical properties of concrete and mortar reinforced with randomly distributed smooth steel fibres. Different volumes, lengths, orientations and types of fibres were used. Fibres were compared with conventional reinforcement in flexural tension and compression. It was observed that the significant reinforcing effect of fibres is derived after the cracks are initiated in the matrix. The post cracking resistance of fibres in considerably influenced by their lengths orientation on stress-strain relationship. The spacing of reinforcement appears to have little influence on crack propagation below a certain length. The reinforcing action of fibres was analytically predicted by using the composite materials approach based on the properties of individual components.

Snyder and Lankard[2] in their paper on "Factors affecting the flexural strength of steel fibrous concrete" have concluded that the first crack strength and ultimate flexural strength of steel fibrous mortars is influenced by the length diameter, and quantity of the steel fibres. Significant increase in the first crack flexural strength up to three fold and ultimate flexural strength upto four fold of mortar and concrete can be achieved through the use of short 6.4 to 63.5mm, small diameter 0.15 to 0.75 mm steel fibre. For 0.25 mm diameter fibre in length of 12.7 to 38.1mm, 2.0 volume per cent represented a practical upper bound of adequate workability for the mortar investigated. When 0.41mm and 0.51mm diameter fibres were used this limit was about 3 to 4 volume per cent, respectively. There is an essential linear relationship between first crack flexural strength and ultimate flexural strength as a function of fibre content for 0.25 x 25.44 mm fibre in mortars containing upto 4.0. volume per cent fibre.

Gunasekran[9] has conducted tests to investigate the flexural strength and load deflection behaviour of light weight concrete beams (150mm x 150mm x 900mm) made with sintered flyash aggregates and regulated set cement and included steel fibre reinforcement. Three different aspect ratios of about 47, 50 and 63 were used for the fibres. It was found that beams containing fibres with an aspect ratio of 50 had the best flexural strength 34.5 Kg/m but the beams containing fibres with an aspect ratio of 62.5 had better ductility, although lower flexural strength, 25.3 kg/cm2. They have concluded that for equal quantities of fibre reinforcement, a blend of fibres consisting of both long and short fibres results in greater structural benefits in concrete than identical fibres with a high aspect ratio, and low aspect ratio fibers act as crack arresters in the finite volume enclosed by the high aspect ratio fibres, the latter are primarily responsible for the enhanced ductility of fibre reinforced concrete.

Swamy and Mangat[6] have presented equations using a composite mechanics approach to predict the first crack and ultimate flexural strength of the concrete reinforced with short discontinuous steel fibres randomly oriented and uniformly distributed throughout the concrete mass. From these equations, design equations are derived which are sufficiently lower bound to be usable in practice. The equations are shown to be valid for a wide range of mix proportions, aggregate size and fibre geometry that is likely to be met in construction practice.

Kukreja, C.B. et.al.[13] have reported that tests conducted to compare the direct tensile strength, indirect tensile strength and flexural tensile strength of the fibrous concrete with that of plain concrete. They used fibre obtained by cutting the wires on a hand-operated machine in three lengths 46mm, 36.8 and 27.6mm having aspect ratio of 100, 80 and 60 respectively. They observed that the per centage increase in the direct tensile strength is directly proportional to fibre concentration for a constant aspect ratio. Maximum increase of 46.33 per cent was obtained with fibres of aspect ratio 80 with 1%

volume concentration and the maximum increase in indirect tensile strength is 40% for the fibres having aspect ratio 80 and volume per centage of 1.5% flexural strength increases by 46.15% for fibres having aspect ratio 80 and volume per centage 1.5

They have concluded that indirect tensile cracking stress is an inverse function of the fibre spacing and fibre reinforcement is more effective in improving the post cracking strength than the first cracking strength of the composite. They have further added that the energy absorption capacity of fibrous composite in flexure increase by 14.98 times due to addition of fibre of aspect ratio 80 and volume concentration 1.5% over plain concrete composite.

Ramakrishnan et.al.[14] have presented a comparative evaluation of two types of steel fibres used as reinforcing materials in concrete. The fibres used were 25.4 mm long straight fibres and 51 mm long fibres with deformed ends which were glued together into bundles with water soluble adhesive. They conducted tests for (1) Flexural fatigue (2) Static flexural strength including strain, deflection, modulus of rupture, load deflection curves, determination of first crack load and determination of post cracking strength of two sizes of beams (3) Impact strength (4) Compressive Strength and (5) Plastic workability. The complete series of tests was run for two concentrations of the collected and hooked fibres and with pozzolana and straight cement mixes.

Based on the experimental investigation they concluded that balling of fibres occurred in the case of hooked fibres even though they were dumped into the mixes all at once along with the aggregate. The compressive strength of the fibrous concrete is slightly higher than the compressive strength of plain concrete mix. The static flexural test showed that an excellent and enchorage is established between the hooked fibre and the matrix, resulting in a high ultimate flexural strength, high load carrying capacity and high ductility of the composite material. The hooked fibre reinforced concrete shows a greater ability to absorb impact loading than straight fibre reinforced concrete.

For the two hooked fibre concentrations, no significant difference was recorded in the ultimate flexural strength, post cracking load carrying capacity and ductility. However impact resistance and toughness increased with fibre content.

Swamy and Al-Tann[15] have presented an extensive experimental data on the deformation characteristics and ultimate strength in flexure of concrete beams made with 20 mm maximum size of aggregates and reinforced with bar reinforcement. Fibres were provided either over the whole depth of beams or in the effective tension zone only surrounding the steel bars. It was shown that the ultimate strength is increased marginally, the fibres arrest cracks and increases post cracking stiffness at all stages of loading upto failure which results in narrow crack widths and less deformation. The tests showed that at failure, the compressive strains reached values of 0.005 to 0.006. and reinforcing bars attain stresses well in excess of their yield strengths. They further proposed on ultimate strength theory, which shows good agreement with the experimental data.

Parmasivam et.al.[22] have given idealized stress-strain curves for steel fibre reinforced concrete with reinforcing steel and suggested simplified analytical expressions for moment curvature and load deflection behaviour of simply supported reinforced steel fibre concrete beams in flexure. Analytically predicted moment-curvature and load-deflection curves for test beams were found to agree well with experimental data. The reinforced steel fibre concrete beams showed higher flexural strength and curvature ductility at ultimate load when compared to similarly reinforced plain concrete beams. They concluded that the approach suggested is a useful tool in the analytical study and design of reinforced steel fibre concrete.

Achyutha and Sabapathi[21] have presented results of an experimental investigation on the effects of inclusion of steel fibres in conventionally reinforced concrete beams on their cracking characteristics. They concluded that load at first visible crack increases by 50 to 128% due to inclusion of steel fibres over the whole section of a reinforced concrete beam. But the increase is of the order of 30% only in the beams with fibres around the tension steel only, compared to beams without fibres and beams with extra reinforcement equivalent to the quantity of fibre around tension steel. The presence of fibres reduces the crack height by 25%. There is a reduction of 50 to 90% in the maximum crack width at working load depending upon the fibre aspect ratio. The effect of fibres on maximum or mean crack spacing has been found to be insignificant irrespective of the fibre aspect ratio and volume per centage. The general trend is that an increase in the fibre content and aspect ratio enhances the per centage increase in load at a specified crack width.

Ramakrishnan and Josifok[20] have reported the results of an experimental investigation to determine flexural fatigue strength of concrete reinforced with deformed (corrugated) and melt extract steel fibres. They conducted test on flexural fatigue and endurance limit static flexural strength including load-deflection curve, determination of first crack load, toughness index, compressive strength, static modulus, pulse velocity and unit weight and workability of fresh concrete. They concluded that there was no balling or tangling of fibres during mixing and placing. Due to addition of fibre, the ductility and the post crack energy capacity were greatly increased. There was a tremendous increase in the static flexural strength and a very significant increase in the flexural fatigue strength. There was a considerable improvement in the endurance limit over plain concrete.

Halvorsen and Kesler[8] have presented that the failure of steel fibre reinforced concrete beam is typically characterised by cracking of the matrix followed by pull out of the individual fibres. To compare the behaviour of concrete reinforced with plain and deformed steel fibres, moment curvature relationships have been determined experimentally for flexural specimens 100x150x1625 mm. Two fibre contents with each of six fibre geometries were used. The result indicate that post cracking resistance may vary considerably depending on the fibre ductility and failure mode of the individual fibres, as well as fibre content.

Kukreja and Chawla[25] published their paper on “Flexural characteristics of steel fibre reinforced concrete.” They used three shapes of fibres viz. straight, bent and crimped with varying volume per centages viz. 0.5, 1.0 and 1.5 aspect ratio being the same as 80 in al the cases. Based on their study they concluded that the flexural strength alone does not adequately describe the behaviour of fibrous concrete. Depending upon steel fibre content its type and orientation, behaviour can range from brittle to very ductile, all for the same range of flexural strength. Flexural stiffness of the fibrous concrete is higher than that of ordinary concrete, emphasizing the ability of the fibres to arrest cracks due to the bridging action of fibres.

Sabapathi and Achyutha[24] have presented a flexural theory for analysis of steel fibre reinforced concrete beams in a post cracking range based on the load slip curves obtained from the pull out tests of fibres. Modulus of rupture or ultimate moment values of SFRC beams, based on the proposed theory are found to be in good agreement with the present experimental and some of earlier investigations.

Sasturkar[32] in an experimental investigation reported on simply supported and grossly under-reinforced RCC beams containing steel fibres, tested upto failure under flexure. He concluded a significant increase in the load carrying capacity both at initial cracking and ultimate stage, strains on concrete surface, deflections both at serviceability and ultimate stage and considerable decrease in the crack width and crack spacing is achieved in grossly under-reinforced concrete beams implying that fibrous concrete is an economical means to gain structural advantages.

Kaushik & Pande[31] have reported the behaviour of conventionally reinforced steel fibre concrete beams under pure bending (flexure). They concluded that with the use of steel fibres increase in indirect tensile strength and flexural tensile strength was 69% and 38% respectively. Crack widths and crack spacing decrease with an increase in the per centage of fibres. The addition of steel fibres improves the load-deflection behaviour for beam under flexure indicating a significant improvement of ductility and energy absorption capacity.

Swamy[26] in their paper reported that Mineral admixture such as flyash is ideal constituent for high-strength concrete as they have the inherent ability to contribute to continued strength development through their pozzolanic/ cementitious reactivity and chemical resistance through their pore refinement characteristics. Concrete containing 50 per cent replacement by weight of class F flyash can be designed to have one-day and 28-cube strengths of 20N/mm^2 and 60N/mm^2 respectively. At 1 year this concrete can develop about 90N/mm^2 . At the same time shrinkage and creep of such concrete can be very favourable to design and they are highly comparable to those of concrete without flyash.

Haque et.al.[17] in their paper reported that the high flyash concrete with flyash comentitious ratio upto 75% (by weight) and aggregate-cement ratio of 6 have compressive and flexural strength that are more than adequate for beam concrete base or sub base application in pavement structure.

Chittaranjan[33] has carried out a research programme to ascertain the feasibility of using flyash concrete for reinforced flexural member for the whole section or for the sectional area below the predicted neutral axis, and reported the mechanical properties of flyash concrete of comparable strength. The service load deflection of flyash concrete beam and those with flyash concrete in tension zones are well within the limit prescribed by the code for reinforced concrete beam.

Bayasi and Soroushian[23] have studied the effects of partial substitution of cement with flyash in steel fibre reinforced concrete on the fresh and the hardened material properties. The 28-day flexural cracking and ultimate loads and the corresponding flexural deformations, as well as the flexural energy absorption capacity and toughness tend to increase with increasing flyash content of the mix upto a flyash cementitious ratio of 0.3. The increase of flyash cementitious ratio from 0.3 to 0.4, however, adversely influences all aspects of the flexural performance of the fibrous materials.

Ali et.al.[30] have reported the structural behaviour of steel fibre reinforced flyash concrete under compression and flexure by conduction test on standard control specimens. Fibre reinforced concrete is very much effective in resisting the flexural tensile stresses as compared to compressive stresses as long as flyash replacement is less than 30% Specimens containing 0.5& and 1.0% fibres with 20% and 30% replacement of cement by flyash are most effective in doing the same. However, sharp decrease in strength curves for 40% replacement were observed.

Swamy and Mangat[6] in their paper " A theory of the flexural strength of steel fibre reinforced concrete" have concluded that final failure occurs due to unstable crack propagation when fibres pull out and the interfacial shear stress reaches the ultimate bond strength.

Pokatiprapha et al[7] in their paper, which was published in March 1974, have investigated the mechanical properties of the composite in flexure, torsion, axial compression and tension analytically by the application of the laws of mixture. Based on their study they found that the mechanical properties of the composite can be determined from the laws of the mixture with the mortar acting as the matrix and the short steel wires as fibre reinforcement. In bending the composite slab element behave as a two layered bilinear element. The presence of the steel fibres does not significantly influence the repture strength of the matrix in bending. This is differs from those reported by Romualdi and Mandel[2]. However, steel fibres considerably increase the resistance of the mortar to crack propagation. The ultimate strength in axial compression of the composite is less than the ultimate strength of the mortar. However, the presence of the fibre increases the ductility of the composite. They further suggested that stronger material could be obtained if the wires of the smaller diameter and longer length were used, provided that the problem of bundling is overcome. The latter can be avoided by trial mining as suggested by Romualdi and Mandel.

Mangat[10] has concluded that the standard law of mixture rule can be successfully modified to determine the tensile strength of concrete reinforced with short steel fibres of length less than the critical one. Experimental results on circular and rectangular fibres show good correlation with the theory. He also concluded that the relation between effective spacing and tensile strength is non-linear decreasing with increasing effective spacing.

Hughes and Fattuhi[11] have concluded that the workability of the fresh fibrous concrete mix depends upon the properties and proportions of the constituents. Increasing the sand content and gravel content, and the volume fraction, aspect ratio and length of the fibres, and decreasing the fibre diameter and water cement ratio of the mix, decrease the workability of the composite. The maximum size of the aggregate (10 or 20mm) did not have a significant effect upon the workability for law coarse aggregate content concrete mix tested. The workability measured by the slump or Vee-Bee consistometer methods showed single relationships for a particular mix which depends only upon the fibre properties. These relationships can be useful when fibrous mixes are being designed.

Walkus et al[12] have studied the cracking behaviour, strength properties and deformations properties of tensile specimens of concrete reinforced with short steel fibres. They noticed that the addition of cut steel fibres to the concrete increases the strength but only upto some critical amount of micro reinforcement (i.e. 1.2% to 1.8% by volume). A volume of steel fibres of about 1.2% seems to be the best. The influence of micro reinforcement arrangement on cracking behaviour was analyzed on the basis of x-ray photography. It was observed that the location of cracks depends on orientation and number of fibres in the cross-section.

ACI Committee 544[16] have published a guide for specifying, mixing, placing and finishing steel fibres reinforced concrete. This guide describes the current technology in specifying, mixing, placing and finishing of steel fibre reinforced concrete (SFRC). The emphasis in this guide is on the differences between conventional concrete and SFRC and on how to deal with them. Guidance is provided in mixing techniques to achieve uniform mixtures, placement techniques to assume adequate compaction, and finishing technology to assume satisfactory surface texture.

ACI Committee 544[16] have published a report on the measurement of properties of fibre reinforced concrete. The report gives a review on the existing test methods and suggesting new methods where necessary. New testing methods are suggested for (1) toughness energy absorption (2) impact strength (3) workability. The applicability of the existing test methods to fibre reinforced concrete are reviewed for air content, yield, unit weight, compressive strength, split tensile strength, shrinkage, creep, modules of elasticity, cavitation, corrosion and abrasion resistance.

Barr and Mohd Noor[18] have proposed an alternative definition of toughness index. According to them, toughness index can be obtained from the load deflection graph and is given by the ratio of the area under the graph (at the point of two times the deflection at first crack) divided by four times the area under the graph at the point of first crack. They have presented toughness index results which were obtained from three notched test specimens geometries.: compact compression, notched beam and compact tension test specimens. Based on the study, they concluded that results for toughness were independent of both geometry and notch depth and the toughness index of steel FRC increased by 100% as the fibre content was increased in the range of 0.03 to 0.9% by volume.

Dwarkanath and Nagaraj[27] studied the effect of presence of steel fibres in conventionally reinforced concrete beams and observed that the partial inclusion of the fibres over half the depth in case of under reinforced beams, is usually as beneficial as the full depth inclusion.

Dwarkanath and Nagaraj[27] have studied experimentally the deformational behaviour of conventionally reinforced steel fibre concrete beams in pure bending. They conducted the experiments with two groups of the beams. One group of beams has steel fibres dispersed in the entire volume of the beam and the second has fibres dispersed over half the depth of the beam on the tension side. Based on their study they have concluded that the half depth fibre inclusion requiring only half the quantity of fibres of full depth inclusion is found to be equally effective in improving the deformational behaviour of the beams.

Entesham Syed[29] and Rasheeduzzafar have carried a experimental study of Accelerated corrosion test on reinforced concrete specimens made with plain and fly ash blended cement (30% fly ash on weight basis) and reported that corrosion initation time of steel in 30 per cent fly ash blended cement concrete was more than those in corresponding plain cement concrete.

Bisallion Andre et al[28] in their paper reported that high volume fly ash concrete has adequate early-age and later age strength development and considerably lower temperature rise, compared with concrete made with ASTM type 1 portland cement.

CHAPTER-3
EXPERIMENTAL PROGRAMME

3.1 GENERAL

The experimental programme consisted of casting and testing of 234 cube specimens [150x150x150 mm] and 117 cylinder specimens [150x300mm]with thirteen different type of concrete mixes by varying flyash percentage and steel fibre concentration. The specimens have been tested for compressive strength and stress-strain behaviours.

The main objective of this study is to develop stress- strain curves, to investigate compressive strength and modulus of elasticity at different early ages for different mixes.

3.2 MATERIALS USED

Cement, fine aggregates, coarse aggregates, flyash, steel fibres and water used throughout the investigation, had the following properties :

3.2.1 Cement

Ordinary Portland Cement of grade – 53 (source Birla plus cement) conforming to Indian standard IS: 12269-1987 has been used in the present study. The results of the various tests on cement properties are given in Table 3.1.

3.2.2 Flyash

Flyash used in the study has been obtained from Bathinda thermal power plant. Its composition is given in Table 3.2.

3.2.3 Fine aggregate

Locally available sand has been used as fine aggregate. The particle size distribution and properties are given in Table 3.4. Other foreign matter present in the sand have been separated before use.

3.2.4 Coarse Aggregate

Locally available crushed stone aggregate of maximum size 20 mm has been used. The properties are listed in Table 3.6. Coarse aggregate has been sieved through IS : 150-micron sieve to remove dirt and other foreign materials.

3.2.5 Fibres

Mild steel fibres having 41 mm length and 0.41 mm diameter i.e. having aspect ratio 100 which are straight and obtained through cutting of steel wires have been used. The fibres have been cut by fiber cutting machine to an accurate size. Three different proportion of fibres (0.25, 0.50, and 0.75 %) have been used. Properties of steel fiber used are tabulated in Table 3.7.

3.2.6 Water

According to IS: 456-2000, water for concrete should be of portable quality (PH-6.8 to 8.0). Ordinary tap water, which is fit for drinking, have been used in preparing all concrete mixes and curing in this investigation.

3.2.7 Concrete Mix

Concrete mix having a cube strength of 25 N/mm2 at 28 days has been designed using the British mix design method. The proportions for the concrete are determined as 1:1.84:3.26 by weight with a w/c ratio of 0.549. 13 mixes having combinations of various percentages of flyash and fibres have been casted.

3.3 CONCRETE MIX DESIGNATION

For the compressive strength and modulus of elasticity of the concrete cube and cylinder, the standard 150x150x150 mm cast iron cube mould and 150mm diameter and 300 mm long cast iron cylindrical moulds have been used respectively. Total 234 cube specimens and 117 cylinder specimens have been casted. 6 sample of cube specimens and 3 sample of cylinder specimens of each types of mix for three ages (7,14 and 28 days) have been casted.

The specimens have been classified as PC and FC, which denote plain concrete and flyash concrete followed by percentage replacement of cement with flyash and steel fibre percentage by volume. Now depending upon the percentage composition of flyash (by mass of cement) and fibres (by volume of concrete) they have been designated as:

PC : Plain Concrete

FC15	:	Flyash concrete with 15 % flyash.
FC20	:	Flyash concrete with 20 % flyash.
FC25	:	Flyash concrete with 25 % flyash.
FC15-STF-0.25	:	Flyash concrete with 15 % flyash and 0.25 % fibres.
FC15-STF-0.50	:	Flyash concrete with 15 % flyash and 0.50 % fibres.
FC15-STF-0.75	:	Flyash concrete with 15 % flyash and 0.75 % fibres.
FC20-STF-0.25	:	Flyash concrete with 20 % flyash and 0.25 % fibres.
FC20-STF-0.50	:	Flyash concrete with 20 % flyash and 0.50 % fibres.
FC20-STF-0.75	:	Flyash concrete with 20 % flyash and 0.75 % fibres.
FC25-STF-0.25	:	Flyash concrete with 25 % flyash and 0.25 % fibres.
FC25-STF-0.50	:	Flyash concrete with 25 % flyash and 0.50 % fibres.
FC25-STF-0.75	:	Flyash concrete with 25 % flyash and 0.75 % fibres.

3.4 MOULDS

Standard cast iron moulds of (150x150x150 mm) cube and (150dia.x300 mm) cylinder have been used for casting the specimens. All the moulds have been cleaned and oiled before use every time. Moulds are being cast by placing them over plastic sheets.

3.5 MIXING, COMPACTION AND CURING

3.5.1 Mixing

After weighting accurately cement, sand and coarse aggregate, these have been mixed dry to get uniform colour. Proper mixing of flyash and cement has been ensured before adding to the mix. Fibers have been mixed by sprinkling them with the hand while mixing in such manner that fibers are distributed uniformly throughout. Water has been added to mix and proper mixing is ensured. Balling or lump formation if found anywhere has been loosened to achieve a homogeneous mix.

3.5.2 Compaction

For compacting fibre reinforced concrete usual methods of mechanical vibration such as obtained in a needle or table vibrator, can be used. Needle vibration however, is not preferred with higher volume content of fibres, as the holes left by the needle may remain unfilled due to interlocking effect of the fibres. Table vibrator is the most suitable as it gives the advantages of fibres acquiring a tendency to align themselves in a plane perpendicular to the direction of vibration. This results in random planer orientation. A fibre mix generally requires somewhat greater vibration to move the mix and consolidate it into the moulds. The compaction of the specimens has been done on a platform-vibrating table.

3.5.3 Curing

Identification marks have been etched into the specimens after 4 –5 hour of casting. They are allowed to set in the moulds for 24 hours after which they have been taken out of the moulds and immersed in fresh water for curing for a specified period of times. The specimens have been then removed from water and stored in a room till their time of testing.

3.6 TESTING PROCEDURE

The testing of cubes and cylinder specimens for compressive strength as well as stress-strain have been done at early ages of 7,14 and 28 days.

The following tests were performed in the present research work :

- Stress – Strain behaviour.
- Compressive Strength test.
- Modulus of elasticity

3.6.1 Stress- Strain Behaviour

In the present research, specimens have been tested under the 3000 KN capacity Automatic Compression Testing Machine (ACTM). This machine fulfills all the requirement for compression testing as per IS: 516-1959.

Specimens stored for curing have been tested immediately on removal from the water, while they are in the wet condition. Surface water and grit has been wiped off the specimens. The bearing surfaces of the testing machine also have been wiped clean and any loose sand or other material is removed. Cube specimens have been placed centrally in the machine in such a manner that the load is applied to opposite sides of the cubes as cast, that is not to the top and bottom. The load is applied in a continuous and uniform fashion without shock with the help of computer attached to the machine at a pace rate of approximately 5.25 KN/s automatically. Thus, the specimens have been tested under stress control loading. The data and graphs have been saved in computer automatically which is used for stress-strain curves. The results displayed on the computer screen are recorded at failure of specimens. To get the stress/strain, average values of six specimens have been used.

3.6.2 Compressive Strength Test

Compressive strength measurements are primary concern in the testing of plain as well as high strength concrete. In the above same test the maximum load carried by each specimen during test have been recorded. Compressive strength is calculated by dividing the maximum load obtained by the cross-sectional area of the specimen. To get the compressive strength, average value of six specimens has been used.

3.6.3 Modulus of Elasticity

In the above said tests chord modulus of elasticity is calculated for each type of mix and each type of curing condition. The chord elastic moduli has been calculated from stress-strain diagrams. The lower point is taken where the strain is 0.0005, while the upper point is taken where stress is equal to 60% of the ultimate stress.

TABLE 3.1: PHYSICAL PROPERTIES OF PORTLAND CEMENT

Sr. No.	Characteristics	IS-specifications (IS: 12269-1987)	Test Results	Remarks
1.	Standard Consistency	…	33.5%	
2.	Setting time in minutes			
	(i) Initial Setting Time	>30	112	Satisfactory
	(ii) Final Setting Time	<600	240	Satisfactory
3.	Specific Gravity	3.15	3.12	Mix design changes accordingly
4.	Compressive Strength in N/mm^2			
	(i) 3 days	>27	25.25	Satisfactory
	(ii) 7 days	>37	37.6	Satisfactory
	(iii) 28 days	>53	54.0	Satisfactory

TABLE 3.2: PHYSICAL AND CHEMICAL PROPERTIES OF FLYASH

PHYSICAL PROPERTIES	VALUE
Colour	Whitish gray to gray with slight black
Bulk density	1120 kg /m^2
Specific gravity	2.14 to 2.42
Fineness	2800 to 3200 cm^2/gm
CHEMICAL PROPERTIES	
Constituent	WEIGHT%
Silica (SiO_2)	40 to 79
Alumina ($Al2O_3$)	23 to 33
Ferric Oxide ($Fe2O_3$)	0.6 to 4
Calcium Oxide (CaO)	2.8 to 20
Magnesia (MgO)	1.5 to 5.0
Ignition Loss	1.0 to 3.0

TABLE 3.3 : SIEVE ANALYSIS OF FINE AGGREGATE

Weight of Sample = 1000gm

Sr. No.	IS Sieve designation	Weight retained (gm)	Percentage retained	Percentage passing	Cumulative percentage retained
1.	10mm	0	0	100	0
2.	4.75mm	5	0.5	99.5	0.5
3.	2.36mm	8.5	0.85	98.65	1.35
4.	1.18mm	65	6.5	92.15	7.85
5.	600 micron	106	10.6	81.55	18.45
6.	300 micron	696	69.6	11.95	88.05
7.	150 micron	105.5	10.55	1.4	98.6
8.	Pan	14	1.4	0	_
Total		1000 gm	_	_	$\sum F$ =214.8

Total percentage retained , $\sum F$ =214.8

Fineness modulus of fine aggregates, $\frac{\sum F}{100} = \frac{214.8}{100}$

F.M. $\approx$2.15

(which is between acceptable limits of 2.0 and 3.5)

By viewing column No. 5 (Percentage passing) of Table 3.3, sand confirmed to Zone-III of IS: 383-1970 classification.

TABLE 3.4: PHYSICAL CHARACTERISTICS OF FINE AGGREGATES

Sr. No.	CHARACTERISTICS	TEST RESULTS
1.	Specific gravity	2.56
2.	Percentage water absorption	0.80
3.	Fineness modulus	2.15

TABLE 3.5: SIEVE ANALYSIS OF COARSE AGGREGATE

Weight of Sample = 5000gm

Sr. No.	IS Sieve designation	Weight retained (gm)	Percentage retained	Percentage passing	Cumulative percentage retained
1.	80mm	0	0	100	0
2.	40mm	0	0	100	0
3.	20mm	56	1.12	98.88	1.12
4.	10mm	4401.5	88.03	10.85	89.15
5.	4.75	512	10.24	0.61	99.39
6.	Pan	30.5	0.61	0	_
Total		5000gm	_	_	$\sum C$ =189.66

Fineness modulus of coarse aggregates= $\frac{\sum C+500}{100}$

$$= \frac{189.66+500}{100} = 6.898$$

F.M. ≈ 6.9

(Which is well within acceptable limits of 5.5 and 8.0)

TABLE 3.6: PHYSICAL CHARATERISTICS OF COARSE AGGREGATES

Sr. No.	CHARACTERISTICS	TEST RESULTS
1.	Specific gravity	2.61
2.	Maximum size	20mm
3.	Percentage water absorption	1.8%
4.	Fineness modulus	6.9

TABLE 3.7: PHYSICAL PROPERTIES OF STEEL FIBERS

CHARACTERISTICS	VALUE OBTAINED
Diameter	0.41
Length, mm	41
Density	7850 kg /m^3
Tensile strength	8500 kg / cm^2
Specific gravity	7.85

TABLE 3.8: DETAILS OF TESTS

NAME OF TEST	**Size of specimen**	**No. of mix.**	**No. of specimens for each mixture**	**Total number of specimens**
Compressive strength test	150x150x150mm cube	13	6	78
Stress-strain behaviour	150x300mm cylinder	13	3	39

PLATE 3.1 STEEL FIBRES

CHAPTER-4

Results and discussion

This chapter includes the test result in respect of the flyash and flyash steel fibre cubes and cylinders. It includes the effect of addition percentage of flyash to concrete and subsequent addition of steel fibres (aspect ratio 100) to flyash concrete on its workability, compressive strength, modules of elasticity and stress-strain relationship.

4.1 WORKABILITY

The workability of various types of flyash concrete and flyash fibre reinforced concrete has been measured by slump test and Vee-Bee test as per I.S. 1199-1959. The test results have been tabulated in Table 4.1 and shown in figs. (4.1) & (4.2).

The effect of replacement of cement (by mass) with three percentage of flyash on workability are given in Table 4.1 and shown in fig. (4.1). It is clear from the table and figure that as the flyash percentage (15, 20 and 25 per cent) increases, the workability of the mixtures increases. The increase in the workability is due to the 'ball bearing' action of the spherical particle of the flyash. Similarly, when the percentage of the steel fibre is added to flyash concrete, the workability of the mixture goes on decreasing as the percentage volume of steel fibre increases as evident from figs (4.3) & (4.4). This is because of the introduction of steel fibre result in an apparent increase the stiffness of the mixture.

No measurable slump has been noticeable for fibre concentration of 0.75 per cent or more. It is evident form figs. (4.4) & (4.5) that for a constant volume percentage of fibre, the slump increase with increase in the flyash content. It has been observed that slump is practically zero for steel fibres beyond the fibre concentration of 0.75 per cent. Excessive balling of the fibres has been faced practically fire concentration of 0.75 per cent or above.

4.2 COMPRESSIVE STRENGTH

The compressive strength of various type of flyash concrete and flyash fibre reinforced concrete has been measured by compression test as per IS: 516-1959. The compressive strength for plain, flyash and flyash steel fibre reinforced concrete have been summarized in Tables 4.2 to 4.7. Graphs are plotted between the flyash percentage vs compressive strength and percentage fibres vs compressive strength for different percentage of flyash as shown in figs. (4.5) to (4.8) respectively.

It is evident from the Tables 4.2, 4.4and 4.6 and fig. (4.5) that replacement of cement by 15, 20 and 25 per cent of flyash by weight of cement reduces the compressive strength of plain concrete by 9.13 to 29.58, 30 to 37.5 and 11.86 to 27.12 per cent for 7,14 and 28 days testing. Maximum decrease observed is 37.12 per cent for 25 per cent flyash content at 14 days, curing period.

The results of addition of steel fibres on compressive strength of flyash concrete are given in Tables 4.3,4.5 and 4.7and shown in figs. (4.6) to (4.8). It is clear from the figs. (4.6) to (4.8) that for a particular percentage of flyash, there is increase in the compressive strength of flyash concrete as the fibre percentage is increased from 0.25 to 0.75 per cent. The increase in the compressive strength is of the order of 1.28 to 10.05, 17.4 to 26.58 and 1.92 to 8.96 per cent in case of 15 per cent flyash content, 1.5 to 14.75,6.52 to 17.42 and 2.79 to 14.58 per cent with 20 per cent flyash and 1.65 to 6.49, 4.5 to 20.45 and 2.33 to 24.05 per cent with 25 per cent flyash content at 7,14 and 28 days, curing period respectively. Maximum increase observed is with addition to 0.75 per cent of fibres, which are 10, 26.58 and 8.96 per cent for

15 per cent flyash, 14.75, 17.42 and 14.58 per cent for 20 per cent flyash and 6.49, 20.45 and 24.05 per cent for 25 per cent flyash content at age 7, 14 and 28 days, curing period respectively.

4.3 STRESS-STRAIN BEHAVIOUR

The compressive stress-strain curves of flyash steel fibres reinforced concrete are shown in figs (4.9) to (4.20). It is evident form figs. (4.9), (4.13) & (4.16) that compressive strain of plain concrete are 0.0045, 0.005 and 0.0053 and the compressive strain of flyash concrete increases as the percentage of flyash is increased. The maximum increase in the compressive strain are 17.8, 28 and 23.54 per cent with 25 per cent replacement of cement by flyash for all the three ages (7,14 and 28 days). It is clear from figs.(4.10) to (4.12), (4.14) to (4.16) & (4.18) to (4.20) that addition of steel fibres increases the compressive strain of flyash concrete for all percentages of flyash. The maximum compressive strain are 0.646, 0.723 and 1.03 per cent which occurs at 25 per cent flyash and 0.75 per cent of fibre content and are 21.42, 13 and 57 per cent more with references of 25 per cent flyash concrete and 43.46, 44.6 and 93.97 per cent more with references to plain concrete. This increase in the compressive strains of flyash fibre reinforced concrete indicates that the ductility of flyash concrete increases with the increase in the percentages of fibre content.

4.4 MODULUS OF ELASTICITY

The modulus of elasticity which is also called recent modulus, is taken as the slope of the chord from the origin to some arbitrary point on the stress-strain curve. The recent modules calculated in this study is for 33 per cent of the maximum stress and is the average of the calculated values from three samples.

The stress-strain curves for plain concrete, flyash concrete and flyash fibre reinforcement concrete having different percentage of flyash and different percentage of fibre volume have been plotted and shown in figs.(4.9) to (4.20). The values of the secant modulus for various combination are shown in Tables 4.8 to 4.13

The values of modulus of elasticity for plain concrete ranges from 1.4×10^4 N/mm^2 for high quality concrete at early ages to 4.5×10^4 N/mm^2 for high quality concrete at later ages. It increases with age and with reduction in water-cement ratio as does the strength. The aggregate has a high elastic modulus than cement paste and therefore, a leaner mix will give a higher value of the modulus than a richer mixture with same water- cement ratio. The type and elastic modulus of aggregates also effect the elastic modulus of concrete.

The Tables 4.8, 4.10 and 4.12 shows that the modulus of elasticity of plain concrete decreases sharply with the increase in the percentage of flyash content. The maximum decrease in the modulus of elasticity is 14.06, 15.87and 48.72 per cent with 25 per cent flyash content. From the Table 4.9, 4.11 and 4.13 it is clear, that the addition of steel fibres does not have very significant effect on the secant modulus of flyash concrete. The modulus of elasticity is increased as age of concrete increased. figs. (4.9) to (4.20) shows the stress-stain curves for flyash concrete, flyash steel fibre reinforced concrete.

TABLE 4.1 : WORKABILITY OF FLYASH AND STEEL FIBRE REINFORCED FLYASH CONCRETE

Type of Mix	Slump (mm)	Vee-Bee Time (Seconds)
PC	44	35
FC-15	57	28
FC-20	60	26
FC-25	65	21
FC-15STF-0.25	12	41
FC-15STF-0.50	7	56
FC-15STF-0.75	0	67
FC-20STF-0.25	15	39
FC-20STF-0.50	9	53
FC-20STF-0.75	0	64
FC-25STF-0.25	16	37
FC-25STF0.50	9	51
FC-25STF0.75	0	63

TABLE 4.2 :COMPRESSIVE STRENGTH OF FLYASH CONCRETE AT 7 DAYS, curing period

Type of Mix	Compressive strength, (MPa)	Ratio FC/PC	Percentage Decrease in strength
PC	14.67	-	-
FC-15	13.33	0.909	9.13
FC-20	11.33	.772	22.77
FC-25	10.33	.704	29.58

TABLE 4.3 : COMPRESSIVE STRENGTH OF FLYASH STEEL FIBRE REINFORCED CONCRETE AT 7 DAYS, CURING PERIOD

Type of Mix	Compressive strength, (MPa)	Ratio FFRC/FC	Percentage Improvement
FC-15STF-0.25	13.5	1.013	1.28
FC-15STF-0.50	14.16	1.062	5.78
FC-15STF-0.75	14.67	1.101	10.05
FC-20STF-0.25	11.5	1.015	1.5
FC-20STF-0.50	11.67	1.03	3.0
FC-20STF-0.75	13	1.147	14.75
FC-25STF-0.25	10.5	1.016	1.65
FC-25STF0.50	10.66	1.032	3.20
FC-25STF0.75	11	1.064	6.49

TABLE 4.4 : COMPRESSIVE STRENGTH OF FLYASH CONCRETE AT 14 DAYS, CURING PERIOD

Type of Mix	Compressive strength, (MPa)	Ratio FC/PC	Percentage Decrease in strength
PC	23.33	-	-
FC-15	16.33	0.7	30
FC-20	15.33	0.657	34.3
FC-25	14.67	0.629	37.12

TABLE 4.5 : COMPRESSIVE STRENGTH OF FLYASH STEEL FIBRE REINFORCED CONCRETE AT 14 DAYS, CURING PERIOD

Type of Mix	Compressive strength, (MPa)	Ratio FFRC/FC	Percentage Improvement
FC-15STF-0.25	19.17	1.174	17.40
FC-15STF-0.50	20	1.225	22.47
FC-15STF-0.75	20.67	1.266	26.58
FC-20STF-0.25	16.33	1.065	6.52
FC-20STF-0.50	17.17	1.12	12.00
FC-20STF-0.75	18	1.175	17.42
FC-25STF-0.25	15.33	1.045	4.5
FC-25STF0.50	16.83	1.147	14.72
FC-25STF0.75	17.67	1.204	20.45

TABLE 4.6: COMPRESSIVE STRENGTH OF FLYASH CONCRETE AT 28 DAYS, CURING PERIOD

Type of Mix	Compressive strength, (MPa)	Ratio FC/PC	PERCENTAGE DECREASE IN STRENGTH
PC	29.5	-	-
FC-15	26	0.881	11.86
FC-20	24	0.814	18.64
FC-25	21.5	0.729	27.12

TABLE 4.7 : COMPRESSIVE STRENGTH OF FLYASH STEEL FIBRE REINFORCED CONCRETE AT 28 DAYS, CURING PERIOD

Type of Mix	Compressive strength, (MPa)	Ratio FFRC/FC	Percentage Improvement
FC-15STF-0.25	26.5	1.02	1.92
FC-15STF-0.50	27.2	1.05	4.62
FC-15STF-0.75	28.33	1.09	8.96
FC-20STF-0.25	24.67	1.03	2.79
FC-20STF-0.50	26	1.08	8.33
FC-20STF-0.75	27.5	1.15	14.58
FC-25STF-0.25	22	1.02	2.33
FC-25STF0.50	24	1.12	11.62
FC-25STF0.75	26.67	1.24	24.05

TABLE 4.8 : MODULUS OF ELASTICITY OF FLYASH CONCRETE AT 7 DAYS, CURING PERIOD

Type of mix	Cylindrical Compressive Strength (MPa)	Max. Compressive Strain	33% of Max Cube Comp. Strength (MPa)	Strain at 33% of Max. Stress	Secant Modulus x 10^3 (MPa)
PC	14	0.0045	4.84	0.00183	2.645
FC-15	9.83	0.00478	4.4	0.00176	2.5000
FC-20	8.5	0.00505	3.74	0.0016	2.338
FC-25	8.43	0.00532	3.41	0.0015	2.273

TABLE 4.9 : MODULUS OF ELASTICITY OF FLYASH FIBRE REINFORCED CONCRETE AT 7 DAYS, CURING PERIOD

Type of mix	Cylindrical Compressive Strength (MPa)	Max. Compressive Strain	33% of Max Cube Comp. Strength (MPa)	Strain at 33% of Max. Stress	Secant Modulus x 10^3 (MPa)
FC-15STF-0.25	12.4	0.0050	4.46	0.00178	2.506
FC-15STF-0.50	13.67	0.00576	4.67	0.00177	2.638
FC-15STF-0.75	14.33	0.00568	4.84	0.00173	2.798
FC-20STF-0.25	12	0.00546	3.8	0.00152	2.500
FC-20STF-0.50	12.67	0.00583	3.85	0.00144	2.674
FC-20STF-0.75	13.33	0.00632	4.29	0.0016	2.681
FC-25STF-0.25	11.67	0.00562	3.47	0.00139	2.690
FC-25STF-0.50	12.33	0.00602	3.52	0.00131	2.687
FC-25STF-0.75	13	0.00646	3.63	0.00135	2.689

TABLE 4.10 : MODULUS OF ELASTICITY OF FLYASH CONCRETE AT 14 DAYS, CURING PERIOD

Type of mix	Cylindrical Strength (MPa)	Max. Compressive Strain	33% of Max. Cube Comp. Strength (MPa)	Strain at 33% of Max. Stress (MPa)	Secant Modulus x 10^3 (MPa)
PC	21	0.005	7.7	0.00166	4.639
FC-15	19	0.0053	5.39	0.00131	4.115
FC-20	18	0.0058	5.06	0.00013	3.892
FC-25	17.5	0.0064	4.84	0.00124	3.903

TABLE 4.11 : MODULUS OF ELASTICITY OF FLYASH FIBRE REINFORCED CONCRETE AT 14 DAYS, CURING PERIOD

Type of mix	Cylindrical Strength (MPa)	Max. Compressive Strain	33% of Max. Cube Comp. Strength (Mpa)	Strain at 33% of Max. Stress (MPa)	Secant Modulus x 10^3 (Mpa)
FC-15STF-0.25	19.5	0.0059	6.33	0.00152	4.164
FC-15STF-0.50	20	0.0063	6.6	0.00152	4.342
FC-15STF-0.75	21	0.0069	6.82	0.00156	4.372
FC-20STF-0.25	18.5	0.0061	5.39	0.0012	4.492
FC-20STF-0.50	19.5	0.00643	5.67	0.00142	4.648
FC-20STF-0.75	20.8	0.0070	5.94	0.00126	4.714
FC-25STF-0.25	18	0.0066	5.06	0.0011	4.600
FC-25STF-0.50	19	0.0069	5.56	0.00116	4.793
FC-25STF-0.75	19.75	0.00723	5.83	0.00122	4.779

TABLE 4.12 : MODULUS OF ELASTICITY OF FLYASH CONCRETE AT 28 DAYS, CURING PERIOD

Type of mix	Cylindrical Compressive Strength (MPa)	Max. Compressive Strain	33% of Max Cube Comp. Strength (MPa)	Strain at 33% of Max. Stress	Secant Modulus x 10^3 (MPa)
PC	23.33	0.00531	9.74	0.00178	5.472
FC-15	19	0.0060	8.58	0.00227	3.780
FC-20	17.67	0.00629	7.92	0.00247	3.206
FC-25	17	0.00656	7.1	0.00253	2.806

TABLE 4.13 : MODULUS OF ELASTICITY OF FLYASH FIBRE REINFORCED CONCRETE AT 28 DAYS, CURING PERIOD

Type of mix	Cylindrical Compressive Strength (MPa)	Max. Compressive Strain	33% of Max Cube Comp. Strength (MPa)	Strain at 33% of Max. Stress	Secant Modulus x 10^3 (MPa)
FC-15STF-0.25	22.25	0.0087	8.75	0.00231	3.788
FC-15STF-0.50	23.5	0.0091	9.13	0.00213	4.286
FC-15STF-0.75	25.5	0.00948	9.35	0.00217	4.309
FC-20STF-0.25	18.5	0.0078	8.14	0.00254	3.205
FC-20STF-0.50	19.5	0.00805	8.58	0.00231	3.714
FC-20STF-0.75	21	0.0083	9.08	0.00245	3.706
FC-25STF-0.25	20	0.00715	7.26	0.00258	2.814
FC-25STF-0.50	20.5	0.00799	8.09	0.00285	2.839
FC-25STF-0.75	22.5	0.0103	8.8	0.00307	2.866

‘

PLATE 4.1 AUTOMATIC COMPRESSION TESTING MACHINE

PLATE 4.2 CUBE SPECIMEN UNDER COMPRESSION

PLATE 4.3 NOS. OF CUBE SPECIMENS AFTER COMPRESSION FAILURE

PLATE 4.4 CYLINDER SPECIMEN UNDER COMPRESSION

PLATE 4.5 NOS. OF CYLINDER SPECIMENS AFTER COMPRESSION FAILURE

CHAPTER-5

CONCLUSION

The following conclusions can be drawn from the present study.

(1) The replacement of cement with flyash (15, 20 and 25 per cent) increases the workability of concrete to the "ball bearing" action of the spherical particle of the flyash. It has been observed that the workability improves as the flyash percentage increase where as the addition of steel fibres decrease the workability of flyash concrete sharply.

(2) The replacement of cement with flyash by mass in percentage (15, 20 and 25 per cent) decreases the compressive strength as replacement percentage incareases. Decrease is of the order of 9.13 to 29.58, 30 to 37.12 and 11.86 to 24.12 per cent for age of 7, 14 and 28 days, curing period respectively.

(3) The addition of steel fibres to flyash concrete by volume (0.25, 0.5 and 0.15 per cent) increases the compressive strength of flyash concrete for all the three ages (7, 14 and 28 days). In 15, 20 and 25 per cent flyash contents, with 0.25 to 0.75 per cent fibres, increase is in the range of 1.28 to 10, 1.5 to 14.75 and 1.65 to 6.49 per cent for 7 days, 17.40 to 26.58, 6.52 to17.42 and 4.5 to 20.45 per cent for 14 days and 1.92 to 8.96, 2.79 to 14.58 and 2.33 to 24.05 per cent for 28 days, curing period respectively.

(4) The replacement of cement with flyash by mass in percentage (15,20 and 25 per cent) decreases the static modulus of elasticity of concrete. Decrease are of the order of 5.482 to 14.06, 11.3 to 15.87 and 30.9 to 48.12 per cent for 7, 14 and 28 days, curing period respectively.

(5) The addition of steel fibres does not have significant effect on the modulus of elasticity of flyash concrete.

(6) The compressive strain of concrete increases with the increase in the percentages of flyash concrete. Increase is of the order of 6.2 to 18, 6 to 28 and 13 to 23.5 for 7,14 and 28 days, curing period respectively.

(7) The addition of steel fibres increases the strain for all the three ages. The maximum increase are 21.42, 13 and 57 per cent with 25 per cent with flyash for 7, 14 and 28 days, curing period respectively.

(8) The addition of steel fibres increases the ductility of flyash concrete.

R E F E R E N C E S

1. Shah, S.P. and Vijayaranjan, B., “Fibre Reinforced Concrete Properties”, Journal of American Concrete Institute Proceedings, Vol. 68, No. 2, February 1971, pp. 126-135.

2. Synder, M.J.and Lankard, D.R., “Factors affecting the Flexural Strength of Steel Fibrous Concrete”, Journal of American Concrete Institute Proceedings, Vol. 69, No.2, February 1972, pp. 96-100.

3. Anon, “Fibrous Concrete Overlay gets the big test”, Concrete Construction, Vol. 19, No.3, March 1974, pp. 103-105.

4. Swamy, R.N. and Mangat, P.S., “Flexural Strength of Steel Fibre Reinforced Concrete”, Institute of Civil Engineers Proceedings Part-2, Vol. 57, Dec. 1974, pp.701-707.

5. Rajagopalan, K., Parameshwaran, V.S. and Ramaswamy, G.S., “Strength of Steel Fibre Reinforced Concrete Beam”, ICJ, Vol. 48, No.1, January 1974, pp. 17-25.

6. Swamy, R.N. and Mangat, P.S., “A theory for the Flexural Strength of Steel Fibre Reinforced Concrete”, Magazine of cement and concrete research, Vol. 4, No.2, March 1974, pp. 313-315.

7. Pakitiprapha, B., Pama, R.P. and Lee, S.L., “Mechanical Properties of Cement Mortar with Randomly Oriented Short Steel Wires”, Magazine of Concrete Research, Vol. 26, No.86, March 1974, pp.3-15.

8. Halvorsen, G.T. and Kesler, C.E., “Moment Curvature Relationships for Concrete Beams with Plain and Deformed Fibres”, Journal of the American Concrete Institute Proceedings Vol. 76, No.3, June 1975, pp. 697-706.

9. Gunasekran, M., “The Strength and Behaviour of Light Weight Concrete Reinforced with metallic fibres of mixed aspect ratios”, ICJ, Vol. 49, No.2, February 1975, p. 48-49 & 55.

10. Mangat, P.S., “Tensile Strength of Steel Fibre Reinforced Concrete”, Cement and Concrete Research, Vol. 4, March 1976, pp. 245-252.

11. Hughes, B.P. and Fatfuhi, N.I., “The workability of Steel Fibre reinforced concrete”, Magazine of concrete research, Vol. 28, No.96, September 1976, pp. 157-161.

12. Walkuz, B.R., Januszkiewics, A. and Jeuzal, J., “Concrete composite with cut steel fibre reinforcement subjected to uniaxial tension”, Journal of the American Concrete Institute, Vol. 76, October 1979, pp. 1079-1092.

13. Kukreja, C.B. Kaushik, S.K., Kanchi, M.B. and Jain, O.P., “Flexural characteristics of Steel Fibre Reinforced Concrete”, ICJ Vol. 54, No.7, July 1980, pp. 184-188.

14. Ramakrishnan, V. Bradshang, T., Coyle, H.V., and Sehrader, A., “A Comparative Evaluation of Concrete Reinforced with Steel Fibres of Deformed Ends glued together into bundles”, Journal of American Concrete Institute Proceedings, Vol.77, No.3, May-June 1980, pp. 135-143.

15. Swamy, R.N. and Al-Taan, S.A. “Deformation and Ultimate Strength in Flexure of Reinforced Concrete Beams made with Steel Fibre Concrete”, Journal of the American Concrete Institute, Vol. 78, No.5, September-October 1981, pp. 395-405.

16. “Guide for specifying, mining, placing and finishing steel fibre reinforced concrete”, Journal of the American Concrete Institute, March–April 1984, pp. 140-147.

17. Haque, M.N. et al., “High Flyash Concrete” ACI Journal, No.1, January-February 1984, pp. 56-60.

18. Barr, B. and Mohamad Noor, M.R., “The Toughness index of Steel Fibre Reinforced Concrete”, American Concrete Institute Journal, September-October 1985, pp. 622-629.

19. Malhotra, V.M., “Flyash in Concrete”, Published by E.E. Berry and Associates, February 1986.

20. Ramakrishan, V. and Josifok, C., “Performance Characteristics and Flexural Fatigue Strength of Concrete Steel Fibre Composites”, Proceedings of the International Symposium on Fibre Reinforced Concrete, Madras, December 16-19, 1987, pp. 2.237-2.555.

21. Achyutha, H. and Sabapathi, P., "Cracking Characteristics of Reinforced Concrete Beams with Steel Fibres", Proceedings of the Internal Symposium on Fibre Reinforced Concrete, Madras, December 16-19, 1987, pp. 2.59-2.68.

22. Parmasivam, P., Lim, T.Y. and Lee, S.L., "Flexural Behaviour of Reinforced Steel Fibre Concrete Beams", Proceedings of the International Symposium on Fibre Reinforced Concrete, Madras, December 16-19, 1987, pp. 1.79-1.89.

23. Ziad, B. and Soroushian, P., "Flyash Application to Steel Fibre Reinforced Concrete", Proceedings 8th International Ash Utilization Symposium, Vol. 2, Washington D.C., October 28-31, 1987, pp. 15.1 - 15.21.

24. Sabapathi, P. and Achyutha, H., "Analysis of Steel Fibre Reinforced Concrete Beams", ICJ, Vol. 63, No.5, May 1989, pp. 246-252.

25. Kukreja, C.B. and Chawla, S., "Flexural Characteristics of Steel Fibre Reinforced Concrete", ICJ, vol. 63, No.3, March 1989, pp. 184-188.

26. Swamy, R.N., "Mineral Admixtures for High Strength Concrete", ICJ, Vol. 65, No.6, June 1991, pp. 265-271.

27. Dwarkanath, H.V. and Nagraj, T.S., "Deformational Behaviour of Reinforced Fibre Concrete Beams in Bending", Journal of Structural Engg., ASCE, Vol. 118, No.10, October 1992, pp. 2697-2698.

28. Bisaillon Andre, Michel Rivest and Malhotra V.M., "Performance of High Volume Fly ash Blended Cement Concrete", ACI Material Journal, March-April 1994, pp. 178-187.

29. Syed Entesham Hussain and Rasheeduzzafar, "Corrosion Resistance Performance of fly ash Blended Cement Concrete", ACI Material Journal, May-June 1994, pp. 264-272.

30. Shoukat Ali, M. et.al., "Fibre Reinforced Flyash Concrete", Proceedings of the National Conference on Civil Engineering Materials and Structures, January 19-21, 1995, pp. 42-48. Edited by Reddy and Ravande Kishore (Universities Press).

31. Kaushik, S.K. and Pande, M.M., "Behaviour of Conventionally Reinforced Steel Fibre Concrete Beams", Civil Engineering Practices (Proc.), Roorkee, Feb. 26-28,

1996, pp. 526-648 Edited by Kaushik, Asawa and Ahuja (New Age Int. (P) Ltd. Publishers)

32. Sasturkar, P.J., “Grossly Reinforced Fibrous Beams Under Flexure”, Civil Engineering Practices (Proc.), Roorkee, Feb. 26-28, 1996, pp. 526-648 Edited by Kaushik, Asawa and Ahuja (New Age Int. (P) Ltd. Publishers).

33. Chittaranjan, N., “Feasibility Study of Using Flyash Concrete for Reinforced Flexural Members”, ICJ, Vol. 70, No. 9, September 1996, pp. 503-508.

34. Joshi, R.C. and Lohtia, R.P., “Flyash in Concrete Production, Properties and Uses”, by Gordon and Breach Science Publishers, 1997.

35. IS:456-2000, “Code of Practice for Plain and Reinforces Concretes”.

36. IS:12269-1987.

37. SP 23:1982; “Handbook on Concrete Mixes”.

38. Gambhir, M.L., “Concrete Manual” by Dhanpat Rai and Sons, New Delhi, 1992.

39. Gambhir, M.L., “Concrete Technology”, New Delhi, Tata McGraw Hill, 1992.

APPENDIX

MIX DESIGN

CALCULATION FOR MIX DESIGN

Mixes were designed using the British mix design method. This is the suitable method for designing 28-day cube compressive strength as high as 75 N/mm^2. The step-by-step procedure of mix proportioning is as follows:

DESIGN FOR M25 MIX

Characteristic compressive strength, f_{ck}	= 25 N/mm^2
Degree of quality control	= Good
Type of exposure	= Mild
Degree of workability	= High
(i) Slump	= 60-180 mm
(ii) Vee-Bee	= 0-3 sec.
Type of cement	= OPC
Max. Aggregate size	= 20 mm
Specific gravity of cement	= 3.13
Specific gravity of fine aggregate	= 2.56
Specific gravity of coarse aggregate	= 2.61
F. M. of fine aggregate	= 2.15
Grading zone of fine aggregates as per IS: 383-1970	= Zone III

(i) Target Mean Strength

The target mean strength (f_t) is determined by using the relation:

$$f_t = f_{ck} + K.S$$

Where f_{ck} is the characteristic compressive strength at 28 days, S is standard deviation and K is statistical coefficient. For the definition of characteristic strength given in IS: 456 – 2000, K = 1.65.

S = 5.3 for M25 mix and good degree of control

f_t = 25 + 1.65 x 5.3

f_t = 33.75 N/ mm^2

(ii) Selection of Water – cement Ratio

The water cement ratio for this stipulated target mean strength is chosen using Table A-2 and Fig. A-1.

The water – cement ratio chosen is 0.55

(iii) Selection of water and cement content

For coarse aggregate of maximum size of 20 mm, uncrushed fine aggregate and high workability the water content is determined from Table A-3 as:

$$w = \frac{2}{3} w_f + \frac{1}{3} w_c$$

$$w = \frac{2}{3} \times (195) + \frac{1}{3} \times (195)$$

w = 195 kg/m^3

Now cement content = 195/ 0.55 =354.5

This cement content is within the permissible amount of cement (290 – 550 kg/m^3), hence O. K.

(iv) Determination of Total Aggregate Content

For the relative density of combined aggregate as 2.61, the wet density of concrete as obtained from Fig. A-2 is 2360 kg/m^3.

Thus, total aggregate amount / m^3

= 2360 – (Weight of cement + Weight of water)

= 2360 – (355 + 195)

= 1810 kg/m^3

(v) Determination of Proportion of Fine Aggregates

For fine aggregates confirming to grading Zone III, water cement ratio 0.55 and high workability (slump 60-180 mm, Vee-Bee 0-3 seconds), the proportion of fine aggregates as found from Fig. A-3 is 32% of total aggregate.

Now Total Aggregate = 1810 kg/m^3

F. A. = 0.36 x 1810 = 651.6 $\approx$ 652 kg/m^3

C. A. = 0.64 x 1810 = 1158.4 $\approx$ 1159 kg/m^3

Thus the mix proportion is:

TABLE A1: Mix Proportion

Mix	**Water (kg/m^3)**	**Cement (kg/m^3)**	**Sand (kg/m^3)**	**Coarse aggregate (kg/m^3)**
M25	195	355	652	1159
	0.549	1	1.84	3.26

TABLE A2: APPROXIMATE COMPRESSIVE STRENGTH OF CONCRETE MIXES WITH WATER – CEMENT RATIO OF 0.5

Type of cement	**Type of Coarse aggregate**	Compressive strength, MPa **Age (days)**			
		3	7	28	91
Ordinary or sulphate – resisting Portland cement	Uncrushed	18	27	40	48
	Crushed	23	33	47	55
Rapid – hardening Portland cement	Uncrushed	25	34	46	53
	Crushed	30	40	53	60

TABLE A3: APPROXIMATE FREE WATER CONTENT REQUIRED TO GIVE VARIOUS LEVELS OF WORKABILITY

		DESCRIPTION	EXTREMELY		VERY LOW	LOW
		MEDIUM		HIGH		
		Low				
Level of workability	Slump, mm	0	0 – 10	10 – 30	30 – 60	60 – 180
	Vee – Bee, s	>20	20-12	12-6	6-3	3-0
	Compact- Ing factor	0.65- 0.75	0.75- 0.85	0.85- 0.90	0.90- 0.93	>0.93
Maximum Size Of aggregate, mm	**Type of aggregate***		**Water content, kg/m^3**			
10	Uncrushed		- 150	180	205	225
	Crushed		- 180	205	230	250
20	Uncrushed		- 135	160	180	195
	Crushed		- 170	190	210	225
40	Uncrushed		- 115	140	160	175
	Crushed		- 155	175	190	205

- When the coarse and fine aggregates used are of different types, the water content is estimated by the following expression :

$$w = \frac{2}{3} w_f + \frac{1}{3} w_c$$

Where w_f = Water content appropriate to the type of fine aggregate.

W_c = Water content appropriate to the type of coarse aggregate.