INTRODUCTION
CHAPTER 1
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1.1 General

Plain concrete is a brittle material and the inclusion of randomly oriented, discrete and discontinuous fibers in it improves many of its engineering properties. Since the advent of fiber reinforcing of concrete in the 1940's, a great deal of testing has been conducted on the various fibrous materials to determine the actual characteristics and advantages for each product. By using different fibers at appropriate fiber contents, it is possible to achieve the required performance in terms of strength, durability and aesthetics.

The cement concrete is the most widely used construction material in the construction industry. It is also versatile, economical and in severe environments, the service life of some concrete structures is prematurely shortened, resulting in costly repairs. Unfortunately, concrete's low tensile strength and brittle characteristics make it prone to cracking. The inclusion of fibers provides an energy absorbing capacity that can maintain the structural integrity of concrete during fracture. In fiber reinforced concrete, cracks are restrained from propagation, decreasing the concrete's rate of deterioration.

Fibers may be grouped into two categories those with low modulus of elasticity and high elongation properties, and those with high modulus
of elasticity. Synthetic, organic fibers, such as nylon and polypropylene, belong to the first category, whereas steel, glass, asbestos and carbon fibers belong to the second category. Use of both types of fibers does not lead to any significant increase in strength, but does improve toughness of material and resistance to impact and impulsive loading.

Fiber reinforced Cement or Concrete (FRC) is now being used in a wide variety of applications. Applications in which fibers are used principally to augment the integrity of the matrix materials are more common than applications in which they are required to act as one of the primary structural load—carrying component.

Applications of FRC in new construction and repair include dams, bridge decks, mines, tunnels, canals, reservoir linings, security and utility vaults, caissons, piles and pile caps, modular panels including tilt up and sheet, breakwaters, mine crib blocks, machine bases, pipes, and non—structural flatwork, such as for highways, airports, composite decks, pavements, overlays, residential slabs, and industrial floors.

Concrete structures may be subjected to impact or impulsive loads during service life and may also have to be designed to resist impact or impulsive loading. Examples of these include defense shelters, ammunition bunkers, firing ranges and protection works (tunnels, structures to shield mountain roads against falling rock sheds, structures in the sea or in rivers to protect bridge piers against impact etc.,) This category includes nuclear power plants, containment structures for
hazardous substances or chemicals, gas tanks, grain or fertilizer silos, oil platforms, etc. Struck and Voggenriter (1975) compiled some major examples of impact loading on concrete structures in the area of Civil and Structural Engineering.

1.2 Literature Review

Kolsky (1949) developed a split Hopkinson bar test, which enables determination of stress – strain responses in compression and tension at high strain rates. The specimen located between two long bars, namely the incident and transmitter bars is held in this way to generate either a tensile or compressive stress pulse through the specimen. The stress pulse is generated at the free end of the incident bar by an impacting bullet or an explosive charge.

Numerous constitutive relations possessing varying levels of sophistication have been developed for concrete. They are commonly divided into six categories:

1) Elasticity based models (Nilson 1968)  
2) Standard elastoplasticity based models (Chen and Chen 1975, Buyukozturk 1979, Hsieh et al. 1982)  
3) Bounding surface models (Fardis et al. 1983)  
4) Endochronic models (Bazant and Bhat 1976)
5) Damage theory models employing scaler and vector (Krajcinivic and Fonseka 1981, Costin 1985) and tensor damage parameters (Dragon and Mroz 1979, Ortiz 1985)

6) Hybrid formulations

Shah and Key (1972) investigated the impact resistance of ferrocement plates using pendulums.

Krenchel (1974), Johnston (1974) used Charpy impact test to evaluate impact performance in terms of energy absorption capacity of steel fiber reinforced concrete relative to unreinforced matrix. Tests by simple drop weights swinging pendulums and explosives can be used to ascertain the relative merits of the different composites. But theses tests do not yield basic materials characteristics, which can be used for design.

Berriaud et al. (1978), Degen (1980), Sliter (1980), Chang (1981), Haldar and Miller (1982), Haldar and Hamiah (1984), Williams (1994) were discussed the hard missile impact. But these may not be suitable for low velocity projectile impact especially when the deformation undergone by the target is considerable.

Paul and Pama (1978), ACI SP – 61 (1979), ACI Committee 549 (1997) discussed the application of ferrocement and its properties such as strength, toughness, water – tightness, durability, and environmental stability.
Maurice and Douglas (1979) presented improved energy absorption under impact loading for plain mortars with wire meshes and steel fibers. They observed that the steel wire fibers assist in distributing cracks and use can be made of much heavier meshes. Due to this, high strength materials can be obtained and the flexural properties can be predicted.

Nimityongskul et al. (1980) reported the response of ferrocement boat hulls subjected to impact.

Ramakrishnan et al. (1980) compared the relative improvement in impact resistance of different fiber concrete specimen. A large variation in the number of blows required to initiate visible first cracking was observed and the results on ultimate failure did not show such a wide variation. This empirical method has been slowly replaced by more sophisticated instrumented methods that generate much more useful information.

Gokoz and Naaman (1981) experimentally studied the effect of loading rate or strain rate on the pull out response of fibers in cement mortar by using a specially designed test set up. Three types of fibers namely steel, glass and polypropylene were used. It was reported that the energy absorbing capability of steel fiber and glass fiber reinforced composites does not seem to be very sensitive to the loading rate. This was probably because the energy was mostly absorbed by the pullout of the fibers, which depends on friction.
Radomski (1981) used a rotating impact machine, generally for investigating metal specimens, to conduct tests on fiber reinforced cement concretes. The scatter observed in the qualitative results was attributed to heterogeneity of the material.

Rao et al. (1981) carried out tests to determine the ability of ferrocement slabs to resist impact.

Schrader (1981) developed simple portable and practical test setup to perform input resistance of concrete mixes. The numbers of input blows delivered by a drop hammer are accumulated until the first visible crack occurs and until the test specimen is forced to separate by continued impact. With this he included other material properties such as toughness, strain capacity, and fatigue performance.

Suaris and Shah (1981) conducted instrumented impact tests using projectiles and drop weights. They presented the basic mechanical properties of fiber reinforced concrete subjected to impact load.

Hughes and Beeby (1982) pointed out that a concrete structure might be designed to withstand the expected maximum impact loads or stresses using static load design methods. The static load approach is commonly adopted, as structural designers are more accustomed to such design methods. However as the structural response at higher modes of vibration are different from the static response, a different design approach for impact loading is needed.
Hughes and Speirs (1982) carried out a theoretical study of the beam impact problem and obtained good correlation with data obtained from instrumented drop weight impact testing. The use of beam vibration theory in conjunction with Hertz's contact law led to an integral equation for the contact force. The importance of two parameters, the mass ratio and pulse ratio, was recognized.

Knab and Clifton (1982) conducted repeated impact tests by drop-weight on reinforced concrete slabs and measured the cumulative damage in terms of crater depth and ultrasonic pulse velocity across the impacted region.


Naaman (1983,1984), Rostasy and Hartwick (1985) concluded that high strain rate of fiber composites indicate higher energy absorption under direct compression and in flexure.

Gopalaratnam et al. (1984) modified the Charpy test by instrumenting the striking tup and used it for studying impact behaviour of steel and glass fiber reinforced cement composites. Concrete exhibited increased flexural strength of about 60% when the strain rate was increased from $10^{-6}$/sec to 0.3 sec. At higher rates of loading a decrease in the amount of micro-cracking was observed.
Hughes (1984) dealt with local damage to reinforced concrete barriers due to hard missile impact. Formulae for penetration scabbing, spalling and a dimensional analysis of the impact problem are presented.

Grabowski (1985) conducted drop weight impact tests and Charpy impact tests on ferrocement slabs.

Ito et al. (1985) studied impact resistance and residual strength of prestressed concrete beams using a compressed air – gun facility. The natural frequency before and after impact was related to the rigidity before and after impact.

Gopalaratnam and Shah (1986) conducted the impact test using modified instrumented Charpy test and compared with instrumented drop weight result. They discussed the strain rate on the flexural behavior of the reinforced matrix and three different fiber reinforced concrete mixers. Relative improvements in performance due to the addition of fibers as observed in the instrumented tests were compared with those from the conventional impact tests. The comparison showed that static flexural toughness tests may be used to approximately estimate the performance of Fiber Reinforced Concrete.

Malvern et al. (1986) studied the high strain rate behaviour of cement composite in compression using the split Hopkinsion bar test.
Mindess et al. (1986, 1989), Banthia et al. (1987, 1989) carried out extensive impact studies on plain concrete, fiber reinforced concrete and conventionally reinforced concrete beams using an instrumented drop–weight impact test machine capable of dropping a 345 kg mass hammer from heights of up to 3 m. The study included normal strength and high strength concrete using hooked–end steel and fibrillated polypropylene fibers at different loading rates. Inertial contribution to recorded tup load at high loading rates was established. At increased loading rates, higher maximum load and inertial load were observed. A method of analysis to account for inertial correction to recorded tup load was developed. Fiber reinforced concrete is a better material than plain concrete in dynamic situations because of its ductility and increased impact resistance. It was stronger and more energy absorbent under impact than under static loading. Steel fibers seemed to perform much better than the polypropylene fibers. In general, it was found FRC was stress–rate sensitive and that the properties of concrete under the high stress rate associated with impact loading could not be predicted from conventional static tests.

Reinhardt et al. (1986) studied the high strain rate behaviour of cement composite in uniaxial tension using the split Hopkinson bar test.

Reinhardt (1986), Kormeling et al. (1987) studied on the behaviour of plain concrete at high strain rates under uniaxial tension.
ACI Committee 544 (1987, 1988b) proposed a repeated drop – weight testing apparatus for testing FRC materials. In this test, a 4.5kg (101b.) steel ball is dropped repeatedly from a height of 457 mm (18 in.) onto a standard concrete disc type specimen. The concrete specimens are 63.4 mm (2.5 in.) thick with a diameter of 152 mm (6 in.). The steel ball is dropped successively, and the number of blows required to cause the first visible crack on the impact surface and ultimate failure of the disc specimen are recorded.

Desnoyers et al. (1987) used the finite element analysis package ADINA (Automatic Dynamic Incremental Nonlinear Analysis) to simulate the impact behaviour of corroding steel reinforced concrete beams subjected to accelerated corrosion in seawater. The load values predicted by ADINA package were considerably larger than the experimental load values.

John and Shah (1987) used the modified Charpy impact test for fracture mechanics investigation on the effect of impact loading. Instrumented impact testing gives a better understanding of the impact process and provides quantitative data that may be helpful in design.

Barr and Bouamrata (1988) developed a repeated drop – weight impact apparatus to evaluate the impact resistance of polypropylene fiber reinforced concrete notched beam samples. Effect of mass, drop height; notch depth and span length were studied. The number of impacts to
cause first crack and failure were significantly higher for concrete reinforced with fibers.

Barr and Bouamrata (1988) developed drop weight impact test apparatus and presented the results for polypropylene fiber reinforced concrete. Two drop heights 0.5m & 1.0 m. were adopted and five impacting masses (1.0kg, 1.5kg, 2.0kg, 3.0kg, 4.0kg) were investigated together with the effect of span length.

Paramasivam et al. (1988) carried out a number of experiments on the performance of ferrocement systems. The success of ferrocement has been attributed to the ready availability of its component materials. The low level technology needed for its construction and the relatively low cost of the final products, has made it possible to widely use it in the construction industry.

Shirai et al. (1990) examined the improvement in the flexural behaviour and impact resistance of ferrocement using polymers.

Yan and Mindess (1990) studied the effect on bond of reinforcing bars and steel fibers on the bond behaviour of reinforcement in reinforced concrete under impact loading. Significant improvement in the bond behaviour under impact loading was observed when steel fibers were incorporated in concrete while polypropylene fibers have a much smaller effect.
Toutlemonde et al. (1993) tested concrete slabs with a shock tube and found larger structures to reach high strain rates within a non-homogeneous stress field.

Banthia et al. (1994) constructed two simple impact machines, one with 100 Joules capacity and the other with 1000 Joules capacity for testing fiber reinforced mortars and concrete. During the test, the applied load, acceleration and velocity were measured such that with a proper analysis scheme, the raw data can be analyzed to obtain fundamental properties under impact loading. They tested various fiber-reinforced mortars and concrete and the results were reported.

Gambarova and Schumm (1994) also carried out drop weight impact testing to study the strength and collapse mechanism of slabs reinforced with polyacrylonitrile (PAN) fibers and reported marked increase in the punching strength with increasing fiber content. Based on some assumption with regards to the failure pattern of slabs (number and depth of radial cracks, shape of the directrix of the shear cone, etc) the specific fracture energy, which is a fundamental property, was computed from the total dissipated energy. It was found that the fiber content can markedly modify the strength and the collapse mechanism with no major variation in the total energy dissipated during the cracking process.

Toutlemonde et al. (1995) tested a series of concrete slabs in order to analyze the effect of free water, porosity of cement paste and reinforcement on their dynamic strength. The increase in failure load
under a dynamic versus a quasi static rate of loading was attributed to the presence of evaporable water inside the concrete pores. Rapid loading may favour a shear mechanism, which may lead to failure prior to the quasi static bending mechanism.

Banthia et al. (1996) constructed an impact test set up to conduct uniaxial tensile tests and used it to generate impact data for normal strength, medium strength and high strength fiber reinforced concrete, for use in design. Steel fibers with various geometrical shapes were used in their investigation.

Nemkumar Banthia et al (1996) presented the need for a standardized technique of testing concrete under impact. They constructed a simple impact machine capable of conducting impact test on concrete in uniaxial tension. Impact data for normal strength, medium strength, high strength and fiber reinforced concrete was presented. It was demonstrated that the machine was capable of generating rational data for various concretes.

Ruel and Lilia (1996) concluded that ferrocement may be cast in various shapes and forms even without the use of formwork and are aesthetically very appealing. The structural concept of ferrocement has been shown to possess excellent mechanical properties in terms of crack control, impact resistance and toughness which are achieved by close spacing and uniform dispersion of reinforcement within the matrix.
Manolis et al. (1997) investigated both simply supported and on grade slab specimen, reinforced with different volumes of fibrillated polypropylene fibers, to gauge the influence of fibers on the impact resistance and natural frequency of slabs.

Yankelevsky (1997) proposed an analytical approach for projectile penetration and perforation of concrete targets and comparison of results with empirical formulae and test data were made.

ACI committee 544 (re approved 1999) outlines the revised procedure for the measurement of properties of fiber reinforced concrete. It suggests the procedure for preparation of specimen and new methods for testing impact strength, toughness energy and workability.

Basheerkhan et al (1999) investigated fiber concrete slabs subjected to low velocity projectile impact. The main variables of the study were type of fiber and volume fraction of fiber. The types of fiber chosen were polyolefin, polyvinyl alcohol and steel. The volume fractions of fiber examined were 0%, 1% and 2%. The tests were carried out by dropping 43kg projectile from a height of 4m, by means of instrumented impact test facility. They concluded that the hooked end steel fiber concrete slab has better cracking and energy absorption characteristics than the slab reinforced with other items.

Banthia and Bindigannavile (2002) described the response of plain and fiber reinforced concrete to impact loading through a multi pronged
investigation using instrumented drop weight impact tests. The study involved understanding the influence of machine specific parameters such as hammer mass and drop-height, specimen specific parameters such as specimen geometry and size and, several material related parameters including the type of fiber reinforcement. Among the fibers investigated, particular attempt was made at comparing steel and polymeric fibers under varying rates of load application. It was found that machine parameters such as the hammer mass and drop height greatly influence the apparent resistance of concrete to impact and its apparent sensitivity to stress rate. This paper discusses the relevance of these data in designing structures under impact and blast loading and identifies areas of further research.

1.3 Scope and Objectives

Numerous data on fiber reinforced cement concrete and concrete cylinder specimens under high rate compressive loading, high rate tensile loading and beam specimens under high rate flexural loading, both quantitative and qualitative are available in the literature. With the increased usage of fiber reinforced concrete in construction, different types of fibers are available in the market. Different categories of fibers exhibit a wide range of mechanical properties. In general, inclusion of fibers in concrete was found beneficial in improving fracture energy absorption in addition to improved resistance to scabbing, spalling and crack formation. It is, thus, essential to quantify the improved impact
resistance of concrete reinforced with various types of fibers. Research on fiber reinforced concrete slabs, of a quantitative nature, has been very limited partly owing to the difficulties with data acquisition and analyses. Analytical analysis of FRC subjected to impact loading had received less attention, the reason being attributed, largely, to the inadequacy of reliable material data. Very few laboratories are equipped with facilities to conduct reliable impact testing.

In the present study, the impact behaviour of fiber reinforced concrete and ferrocement slabs were investigated using a drop weight impact test facility developed at our Institute. The study would provide more insight on the behaviour of fiber reinforced composite slabs under impact loading situations and on the applicability of analytical technique in predicting the impact response of slabs.

The main objectives include:

- To fabricate impact testing frame and instrumentation for the
  (a) Application of impact load by constant mass from various heights.
  (b) Application of impact load by variable mass from constant height.

- To evaluate the energy absorption capacity of fiber reinforced concrete slabs containing different types of fibers under static and impact loading. The fibers under study include Glass, Polypropylene, and Steel fibers.
➢ To study the influence of the slab properties with different volume fractions of the above fibers under impact load.

➢ To predict the impact response of fiber reinforced concrete slabs based on analytical study by using ANSYS software.

➢ To predict the impact response of fiber reinforced ferrocement slabs based on the analytical study by using ANSYS software.

➢ To study the responses like energy, deflection, crack pattern etc.,

➢ To study the behaviour of ferrocement slabs with different types of fibers subjected to drop weight impact and static loads.

➢ To compare the analytical and experimental results

1.4 Organisation of the Thesis

In chapter 1, a general introduction and review is given on the impact testing and performance of fiber reinforced concrete composites. The objectives and scope of the present study are also defined.

In chapter 2, the theory of impact loads is clearly explained. This includes common engineering problems due to impact, effects of impact and different types of impact loads with mode shapes.
In chapter 3, the different materials used for impact and static test in this thesis are elaborately discussed. This includes concrete, mortar and fibers.

The response of fiber reinforced concrete slabs and ferrocement slabs with different volume fractions to static loading under experimental study are explained in chapter 4.

An experimental programme is performed to study the effects of volume fraction of fibers at the point of impact on fiber reinforced concrete slabs. These details are explained in chapter 5.

In chapter 6, experimental study on the response of fiber reinforced ferrocement slabs to impact loading is outlined with different volume fractions of different fibers.

Chapter 7 focuses on the theoretical modeling of impact loading. It is performed by ANSYS software.

Chapter 8 concludes on the main findings of the study and also points out on further work that is necessary for follow up.