1.1 RESEARCH BACKGROUND

Concrete is an extraordinary and key structural material in the human history. As written by Brunauer and Copeland [1], “Man consumes no material except water in such tremendous quantities”. It is no doubt that with the development of human civilisation, concrete will continue to be a dominant construction material in the future. It is obtained by mixing cementitious materials, water and aggregates (and sometimes admixtures) in required proportions. The popularity of the concrete is due to the fact that from the common ingredients, it is possible to tailor the properties of concrete to meet the demands of any particular situation. Although most of the structures are made of concrete, there are still some problems related to the utilisation of the material:

- Plain concrete possesses a very low tensile strength, limited ductility and little resistance to cracking. Internal microcracks are inherently present in the concrete and its poor tensile strength is due to the propagation of such microcracks, eventually leading to brittle fracture of the concrete.

- The self weight of the concrete structure is very high compared to the steel structure with the same load carrying capacity.

In the past, attempts have been made to impart improvement in tensile properties of concrete members by way of using conventional reinforced steel bars. Although this method provides tensile strength to the concrete members, they however, do not increase the inherent tensile strength of concrete itself. In plain concrete and similar brittle materials, structural cracks (micro-cracks) develop even before loading,
particularly due to drying shrinkage or other causes of volume change. The width of these initial cracks seldom exceeds a few microns, but their other two dimensions may be of higher magnitude. It has been recognised that the addition of small, closely spaced and uniformly dispersed fibres to concrete would act as crack arrester and would substantially improve its static and dynamic properties. This type of concrete is known as Fibre Reinforced Concrete. Although many fibres have been tried out in cement and concrete, not all of them can be effectively and economically used. Each type of fibre has its own characteristic properties and limitations.

The combination of two or more types of fibres (hybrid reinforcement) has been studied and applied with the objective of optimizing the overall system to achieve synergy, whereby the overall performance of the composite would exceed that induced by each of the fibres alone. This phenomenon is termed “synergy”. Banthia and Gupta [2] classified these synergies into three groups, depending on the mechanisms involved [2, 3]:

- Hybrids based on the fibre constitutive response, in which one fibre is stronger and stiffer and provides strength, while the other is more ductile and provides toughness at high strains [2].

- Hybrids based on fibre dimensions, where one fibre is very small and provides microcrack control at early stages of loading; the other fibre is larger, to provide a bridging mechanism across macrocracks.

- Hybrids based on fibre function, where one type of fibre provides strength or toughness in the hardened composite, while the second type provides fresh mix properties suitable for processing.

These concepts are based on adjusting fibres to the cracking mechanisms which control the composite at different stages of loading: (i) arrest and bridging macrocracks at early stages of loading to increase the cracking strength and obtain strain or deflection hardening and (ii) bridging of macrocracks which develop later on to
induce ductility into the composite. The fibres for these purposes could be either made from one material but with different geometries [4,5] (eg. Small steel microfibres for microcrack control and long macrosteel fibres for macrocrack bridging) or be composed of different materials, such as Polyvinyl alcohol (PVA) and Polyethlylene micro fibre for microcrack control and deformed steel fibres for macrocrack bridging [3].

1.2 IMPORTANCE OF HYBRID FIBRE REINFORCED CONCRETE

Rossi et al. [4] considered the crack evolution in an FRC composite in terms of three stages of crack formation: microcrack formation prior to peak load, coalescence of microcracks into one macrocrack at the peak load and thereafter propagation of a macrocrack. They suggested that in the first stage the steel fibres limit microcrack propagation and when the macrocracks form and propagate, the fibres bridge over them in an action which has similarity to that of conventional reinforcement. This effect of fibre action is addressed in two levels: the material (microcracking) and structure (macrocracking). At the material level, fibres can improve the strength and ductility of the concrete if a high percentage of fibres with a small diameter are used. At the structural level, fibres can improve the load bearing capacity and the ductility of the structures by using a low percentage of fibres long enough to allow for sufficient anchorage in order to transfer forces through large cracks. Based on this analysis the concept of hybrid reinforcement was proposed, in terms of large volume of short steel fibres to control microcracking and long fibres to control macrocracking, to induce ductility at the structural level. This was developed into a concept called multimodal fibre reinforced cement composite [5]. In most of these systems, the aspect ratio of the fibre is kept similar, about 50-200 and thus the length of the microfibres is usually in the range of 3-10mm, while the macrofibres are usually longer than 20mm. The small size of the microfibres enables denser packing of the cement particles around them, providing a potentially denser transition zone and higher interfacial bond.

Rossi [5] reported the development of a composite with about 40 MPa flexural strength reinforced with 5% volume of micro-steel fibres (0.25mm diameter and 5mm in length) and 2% volume of macrofibres (hooked 0.3mm (diameter and
25mm length) with a low w/c matrix of 0.56. Similar ranges of properties were reported by Katz et al. [6] in a study to optimize the reinforcing system for a deflection hardening composite. The fibre system which gave the optimum performance in terms of minimizing the fibre content and providing maximum mechanical performance (flexural strength and toughness) consisted of 1% volume of deformed steel macrofibres (30mm in length, 0.375mm diameter) and 4.9% volume of micro-steel fibres (6mm long, 0.16mm diameter).

Marcovic et al. [7, 8] evaluated a composite with a similar matrix, of 0.20 w/c ratio, using hybrid reinforcement of micro-steel fibres [0.16-0.2mm diameter and 6-13mm length] and hooked macrofibres of [0.5-0.71mm diameter and 40-60mm length]. Optimum properties of 45 MPa flexural strength and 48,550 J/m² fracture energy were obtained with a hybrid of 2% volume of micro-fibres and 1% volume of macrofibres. The small diameter and the length of the microfibre provided a system with sufficiently small spacing to control microcracking at early stages of loading, while at advanced stages, when bigger cracks develop, they were less efficient and the macrofibres took the role of crack bridging [9]. The effectiveness of the hooked macrofibres in such composites was estimated by evaluating the relative number of fibres in which the failure of the fibre was accompanied by deformation of the hook; deformation of the hook maximizes the pull-out resistance and therefore such failure mode is indicative of an ‘active’ fibre. Fibres which only slip were considered as only partially active [8]. When the reinforcement was with hooked fibres only, 15% of the fibres were fully active; in the hybrid composite the effectiveness increased and 32% of the fibres were fully active [7]. One may consider this effect as an additional benefit of hybridization in such systems, which can provide synergistic influence. This is consistent with the observations of Shannag et al. [10] showing an increase in the fibre-matrix bond in systems reinforced with microsteel fibres of 0.19mm diameter and length of 6, 12 and 18mm; the increase in bond was observed in both conventional and Densified Small Particle systems (DSP) matrices, but was much more significant DSP matrix and the for the longer fibres. The systems described earlier, used as a hybrid steel fibre system, consisting of micro and macro fibres. Systems in which the smaller fibre in the hybrid reinforcement was a microfibre were reported in several studies [11-13].
The microfibres were in most cases of a different composition than the macrofibre (usually steel). The microfibres evaluated were alumina [11], carbon [11,12], PVA [12,13], ultra high density polyethylene [12,13] and steel [12].

The matrix used Mobasher et al. [11] was 0.3 w/b ratio, with the macrofibre being polypropylene and the microfibres alumina and carbon. Reinforcement with 8% polypropylene gave higher strength and toughness, but was not efficient in stabilizing cracks, as been by developments of relatively large crack opening displacements at early stages of loading. Replacing of 4% of the polypropylene with microfibres provided much greater stability at the microcracking stage, although the composite was less effective in its load bearing capacity at greater crack opening. The combination of 1% of carbon, PVA, Polyethylene (PE) and steel microfibres, with 2% of twisted steel fibre (Torex) [12], resulted in a marked improvement of the load bearing capacity of the composite at small deflections as well as in large ones (pre and post-crack loads). The enhanced performance in these zones was higher with the PVA (40 µm), PE (38 µm) and carbon (9 µm) than with the steel (50 µm) and the smaller PVA fibre (15 µm). With these combinations tensile and flexural strength of about 8 MPa and about 30 MPa, respectively were reported [12] with a hybrid of 1% microfibre and 2% macrofibres. It was suggested that the enhanced performance due to the presence of the microfibres is the result of their influence on the mechanical properties of the matrix (microcrack control) and bonding of the macrofibre [3].

The nature of cracking of such systems with steel macrofibres (1% volume) and polyethylene (PE) and PVA microfibres (1% volume) was reported in [13,14] for a 0.40 – 0.50 w/c ratio matrix. The performance obtained with PE was somewhat better, exhibiting higher tensile strength (4 MPa), and a better post-cracking behavior, showing some strain hardening. This was accompanied by more multiple cracking in the PE composite with cracks which are much better distributed and less localized than in the PVA [13]. In a further study of the cracking in the PE hybrid composite [14] it was shown that microcracks of about 1 -15 µm are present before loading; the process of multiple cracking as a function of increased stress was characterized. These
characteristics highlight the advantage of such composites for structures where a high level of durability performance is required [3].

1.3 HIGH PERFORMANCE CONCRETE

It is mistaken to bestow that supplementary cementitious materials were used in the concrete only because of their availability and just for economical considerations. These materials present some unique desirable properties which cannot be met by using OPC only (15). For producing high performance concrete (HPC), it is well recognised that the use of supplementary cementitious materials (SCMs), such as silica fume (SF), ground granulated glass blast-furnace slag (GGBS), metakaoline, rice husk ash (RHA) and fly ash (FA) either individually or in combinations are necessary. The concept of HPC has definitely evolved with time. Initially it was equated to high strength concrete (HSC), which certainly has some merit, but it does not show a complete and true picture. There is a need to consider other properties of the concrete as well which sometimes, may even take priority over the strength criterion. Various authors proposed different definitions for HPC. According to Forster [16], “High Performance Concrete is a concrete: made with appropriate materials, combined according to a selected mix design; properly mixed, transported, placed, consolidated and cured so that the resulting concrete will give an excellent performance in the structure in which it is placed, in the environment to which it is exposed and with the loads to which it will be subjected for its design”.

The mineral materials, when used in HPC, can enhance either or both the physical and durability properties of concrete. Concretes with these cementitious materials are used extensively throughout the world. Some of the major users are power, gas, oil and nuclear industries. The applications of such concretes are increasing with the passage of time due to their excellent performance, low influence on energy utilisation and environment friendliness [17]. Combining the properties of hybrid fibres and HPC, the concrete can be termed as High Performance Hybrid Fibre Reinforced Concrete (HyFRC). These concretes are designed in a systematic way, such that they can perform well during production, construction and for the entire life of the structure.
1.4 RESEARCH SIGNIFICANCE / LIMITATIONS

With the production of high strength concrete, enhanced material properties such as increased compressive and tensile strength and elastic modulus can be achieved. However, high strength concrete is known to manifest a more brittle behavior than normal strength concrete, representing a significant limitation for its wide range application in innovative structural design. When shear stresses are involved, in addition to the low toughness (brittle) characteristics, a relatively low shear strength behavior may be observed also for concrete with high compressive strength. Shear failure can be sudden and catastrophic. This is especially true for critical sections where, due to construction restraints, little or no reinforcing steel may be placed. For a broader use of high strength concrete in innovative structural solutions, there is a need for the development of a fundamental understanding of the shear behavior of this material.

HyFRC should be designed so as to perform with adequate workability, high tensile strength, sufficient toughness and adequate shear strength. Utilizing the concept of hybridization, a concrete with superior properties are very much necessary. Mechanical properties of concrete can be improved at lower fibre contents, where fibres are used in combination rather than reinforcement with a single type of fibre. Limiting the high aspect ratio fibre content, without compromising the ductility and the strength of the concrete, problems associated with workability can be eliminated. Results obtained from this study are expected to contribute to the efforts made to characterize the mechanical properties of HyFRC such as compression, elastic modulus, direct shear, flexure and direct tension. The different types of fibres used in this study are micro fibres (steel and polyethylene) and macro fibre (hooked steel). The combination of these micro and macro fibres in suitable combination may give desired properties.

1.5 SCOPE OF THE RESEARCH

Keeping research significance in mind, it was decided to develop high performance hybrid fibre reinforced concrete, and then to characterize and quantify the benefits obtained by the concept of hybridization. To improve the mechanical properties
of HyFRC such as compressive strength, elastic modulus using ASTM C 469, direct shear using notched cylindrical specimens, flexural strength using four point load test and direct tension using dog-bone shaped specimen is studied. Hence, the scope of work for this research is limited to fulfill the objectives is presented below.

1.6 OBJECTIVES OF THE RESEARCH

The objective of the investigation is to study the mechanical properties of HyFRC. More specifically the research has the following objectives.

i. To develop a mix design for high performance Hybrid Fibre Reinforced Concrete (HyFRC) for three different grades of concrete viz. M60, M80 and M100 and to characterize their compressive strength and elastic modulus.

ii. To establish a three dimensional analytical model to study the direct shear strength using notched cylindrical specimen subjected to compression and to validate with experimental investigation.

iii. Flexural properties of HyFRC on beam specimens in bending tests under four point loading were determined and quantify the toughness values using ASTM and JSCE method. In addition, stiffness, ductility and energy absorption capacity were also quantified.

iv. Tension tests on HyFRC dog bone shape specimen were conducted to quantify the tensile strength, toughness characteristics, ductility and energy absorption capacity.

v. To develop a correlation between compressive strength with other mechanical properties such as elastic modulus, direct shear, flexure and direct tension.
1.7 OUTLINE OF THE THESIS

This thesis is structured as nine chapters. Chapter 1 delineates the research background, significance, scope and objectives of the research work. In Chapter 2, a detailed literature review is carried out on the performance of high performance concrete (HPC) in specialized concreting applications. The use of mono fibres as well as hybrid fibres (containing two different types of fibres) in HPC to improve concrete performance is also studied in detail. In Chapter 3, details of the materials used for concreting such as cement, sand, fine aggregate, superplasticizer and the mix proportions are provided. The various metallic and non-metallic fibre materials used, their physical and mechanical properties and their proportions in the concrete mixtures are presented. This is followed by a description of the experimental methods and standards adopted for the various tests conducted on fresh and hardened concrete. In Chapter 4, the compressive strength of plain concrete and HyFRC is studied. The elastic modulus of the various concrete and the toughness ratio is also computed. Chapter 5 provides the analytical results of shear strength of concrete and it is compared with experimental values. In Chapter 6, experimental results of the evaluation of flexural strength and toughness using two different methods ASTM and JSCE are discussed. Chapter 7 presents the results of the direct tensile strength obtained experimentally and the various factors such as ductility is also discussed. The Chapter 8, gives the correlation between compressive strength and other strength parameters such as elastic modulus, flexural strength, shear strength and direct tensile strength. Lastly, the specific conclusions drawn from the entire study are given in Chapter 9, together with recommendations for further research.