1. INTRODUCTION

1.1 General
Concrete is one of the most commonly used construction materials in the world due to the availability of ingredients, ability to take various forms and relatively low cost of production. It is, generally, produced by mixing cement, water, coarse and fine aggregates. Mineral and chemical admixtures are also being used nowadays. The properties of concrete such as strength, workability, cohesiveness and durability depend upon the properties of its constituents and their relative proportion in the mix. Concrete is, in general, categorized as ordinary, standard and high strength based on compressive strength at 28 days. It should have appropriate degree of workability such as very low, low, medium, high and very high based on placing conditions and also on mode of placing. Moreover, concrete need to sustain wide range of environmental exposure conditions and it should also be resistant to chemical attacks. Therefore the efforts are being made to make concrete durable. The quantity of the most expensive ingredient of concrete i.e. cement depend upon the strength, workability and durability requirements. However emission of carbon dioxide during the production of cement is hampering the image of concrete as a sustainable material. It is reported that the cement industry is responsible for about 6% of total CO\textsubscript{2} emissions. Therefore focus of research has now shifted towards reducing the cement content of the mix. It can be achieved by optimizing the contents of other ingredients of concrete so as to attain effective packing. Proper packing of coarse and fine aggregates, based on their characteristics, leave minimum voids and thereby reduce the quantity of binding material. Alternatively cement content can also be reduced by using cementitious materials such as fly ash, ground granulated blast furnace slag (GGBFS), silica fume, metakaolinoe etc.

1.2 Role of Aggregates in Concrete
Aggregates occupy maximum volume of concrete and they are relatively inexpensive components of concrete. Their characteristics such as size, grading, shape, surface texture, angularity etc. have major influence on workability, dimensional stability, strength and durability of concrete. Angular/crushed aggregates result in higher strength and excellent stability than rounded aggregates due to better mechanical interlocking. Flaky and elongated particles of aggregates are detrimental for the overall performance of concrete, therefore never recommended. The shape of aggregate particles depend mostly on geological formation of the rock, crushing technology and
reduction ratio. The reduction ratio is the ratio of size of material fed to the crusher and the size of aggregate particle derived after crushing. The effect of aggregate characteristics such as size, shape and grading is more pronounced in the case of high strength (HSC) and high performance concrete (HPC) due to very low values of water to cementitious material ratio. Attempts are continuously being made for the objective quantification of characteristics of aggregates. The methods used for this purpose can be broadly classified as Indirect and Direct methods and the same are discussed in the following sections.

1.2.1 Indirect Methods

The indirect methods for the evaluation of shape of aggregates are mostly based on determining voids in a given aggregate sample because for a given size, grading and compacting energy percentage voids vary with shape of aggregate particles. The methods proposed by various codes such as Index of Aggregate Particle Shape and Texture (IAPST) as per ASTM D3398 [19], Angularity number as per BS 812 Part-1[27] and IS-2386 part-I [72] are based on above principle. ASTM C1252-98 [16] provides a standard procedure for the quantification of percentage voids as a combined measure of size, shape, texture and grading of fine aggregate. The test is based on the principle that the rate of flow of aggregate particles through a standard cone with opening, is influenced by the fine aggregate characteristics and hence the percentage voids. Similar test but modified for coarse aggregate is provided by AASHTO TP-56 [9]. ASTM D5821 [20] suggested count of number of fractured faces of aggregate particles as a measure of angularity of coarse aggregate. Classification of aggregates in terms of its shape is also provided in IS 383 [70] based on visual inspection. However, these methods are laborious, time consuming and less accurate.

1.2.2 Direct Methods

Direct methods are based on manual and automated measurement of dimensions of aggregate particles in a sample. The method as per ASTM D4791 [21] is widely used for evaluating elongation and flatness ratio of the aggregates based on the three principal dimensions of the aggregate that is length (L), width (W), and height (H). The proportional caliper is also being used to measure these dimensions. Elongation Index (E) and Flakiness Index (F) is determined as the ratio of length to width and width to thickness respectively. The method is also provided by IS 2386-Part I[72] for evaluating these indices, based on the percentage of the total weight of the
material passing the appropriate length and thickness gauges and sieves. However, the test is not applicable for particle size smaller than 6.3mm.

The manual methods discussed above are tedious, labor intensive, time consuming and prone to human errors. Automated methods for shape characterization have been devised to overcome these problems. These methods can be mainly categorized into Tomographic, Laser Scanning and Digital Image Processing (DIP) based techniques. They provide relatively more accurate and easier way of measurement of aggregate characteristics. These methods are discussed broadly in the literature review.

1.3 High Strength Concrete (HSC)

Over the last decade, high strength concrete (HSC) has become widely used in the different construction field. This type of concrete is known by its improved mechanical properties and durability enhancement compared to normal strength concrete (NSC). Generally, it is considered that compressive strength is the major concrete characteristic required by structural design since both normal and high strength concrete are mainly designed to compressive forces.

To achieve high strength, it is necessary to use lowest possible water cement ratio with high cement content which invariably affects the workability of the mix and necessitates the use of special vibration techniques for proper compaction. It should be kept in mind that high cement content may liberate large heat of hydration causing rise in temperature which may affect setting and may result in excessive shrinkage. With respect to strength, we should note that the meaning of term 'high strength' has changed significantly over the years: at one time, 40MPa was considered as high; later on, 60MPa become viewed as high strength concrete.

1.4 High-Performance Concrete (HPC)

Since all the high performance concretes (HPC) not only high strength concretes but also all-round high performance. To produce HPC it is generally essential to use chemical and mineral admixtures in addition to the ingredients, which are used for normal concrete. Neville [2] has pointed out that high-performance concrete has low water/cement ratio. However, there is a limit to the lowering of the water-cement ratio if ordinary Portland cement (OPC) cement is used. With only OPC used, the voids content tends to be quite large. To overcome this problem, supplementary cementitious materials finer than OPC, such as ultra-pulverized fly ash, silica fume can be added to fill the voids so as to improve the packing density of material. HPC
possess high workability, high strength, high modulus of elasticity, high density, high dimensional stability, low permeability and resistance to chemical attack.

1.5 Role of Mix Proportioning

The process of selecting suitable ingredients of concrete and determining their relative amounts with the objective of producing a concrete of required strength, durability and workability as economically as possible, is termed the concrete mix design. The proportioning of ingredients of concrete in two states namely the plastic and hardened states. In a plastic state, the concrete should be workable and free from segregation and bleeding. Segregation is the separation of coarse aggregate and bleeding is the separation of the cement paste from the main mass. The segregation and bleeding result lead to poor quality concrete. In hardened state, the concrete should be strong, durable and impermeable. Among the various properties of concrete, its compressive strength is considered to be most important and is taken as an index of its overall quality.

1.6 Methods of Concrete Mix Proportioning

Evolutions in concrete mix proportioning methods are taking place since long. Earlier it used to be considered as an art than a science[08]. Abram’s w/c ratio versus compressive strength law is a major breakthrough during the rationalization of mix proportioning process [10]. It facilitates the selection of w/c ratio for the required compressive strength of concrete. Lyse’s rule [92] for the selection of water content for desired workability and Glanville’s work [67,71] for arriving at optimum combination of fine and coarse aggregates for maximum workability were the key investigations in making concrete mix proportioning more scientific. These principles have been used in various forms in various methods used worldwide for mix proportioning such as DOE [24], ACI 211.1 and ACI 211.4 [11,12], IS 10262-1982 and 2009[67, 71] etc. These methods provide a step by step procedure to arrive at proportions of various ingredients for first trial mix based on material characteristics and design requirements. Corrective procedure is also provided in case the results of first trial mix deviate from desired properties. These methods are discussed in details in the next chapter. However, these methods lack in precision with respect to aggregate characteristics and packing behaviour. The aggregates are considered as either angular/crushed or rounded/uncrushed. These limitations motivated the researchers to investigate the possibilities of more refined methods for mix proportioning of concrete to achieve maximum
performance. Particle packing theories proposed by various researchers overcome these limitations to some extent.

1.6.1 Particle Packing Theories

The concept of particle packing involves the optimization of packing density of concrete by judiciously selecting the proportions of various ingredients. It can be achieved through minimization of voids. Particle packing theories proposed for this purpose account for material characteristics and their interaction. Particle packing models proposed by various researchers can be broadly categorized as (a) Analytical, (b) Continuous model and (c) Discrete Element Model. The fundamental assumption of the analytical model is that each class of particle will pack to its maximum density in the available volume. Continuous model assumes that all possible sizes are present in the particle distribution system and can be combined in such a manner that the overall particle size distribution is closest to the optimum. Discrete element models generate a virtual particle packing from a given particle size distribution using computer simulation. However, due to limitations in computational speed discrete element models are not considered suitable for concrete mixture optimization [136]. The various analytical models include Furnas[53,54], Toufar [143] and Modified Toufar [58], Dewar [37], the Linear Packing Density Model (LPDM)[140], the Compressible Packing Model (CPM)[33] and the Linear-Mixture Packing Model (LMPM) [1]. CPM is considered to be the most efficient model amongst all other models as it accounts for particle size distribution, method of compaction and particle packing in dry and wet state [136]. It is capable of computing packing density of an aggregate sample from the particle size distribution and the packing densities of each mono-sized particle class in the distribution. However, the particle shape is accounted based on packing density i.e indirectly.

1.7 Necessity of the Research

Existing methods of concrete mix proportioning and also particle packing theories are imprecise with reference to aggregate characteristics and their interaction. It makes the concrete mix proportion process highly trial intensive and may not even result in to optimum proportions. Quantification of aggregate characteristics closer to the reality and its incorporation in particle packing theories may further refine the process of concrete mix proportioning.
1.8 Objectives of the Study

The investigation is carried out to achieve following objectives,
To develop a digital image processing based system for the quantification of morphological properties of coarse aggregate particles
To study existing particle packing theories for mix proportioning of concrete and propose refined theory duly incorporating morphological properties of coarse aggregates.

1.9 Theme of the Research

To accomplish the objectives mentioned above, the study is divided into three phases as follows:
Phase I – Develop and calibrate digital image processing based aggregate measurement system for the quantification of morphological properties of coarse aggregates.
Phase II – Refine particle packing theory of concrete mix proportioning duly incorporating morphological properties of coarse aggregates.
Phase III – Experimental validation of proposed particle packing theory

1.10 Organization of Thesis

The thesis contains five chapters and three appendices. Introduction, necessity, objective and theme of the research are presented in Chapter 1. Chapter 2 presents elaborate view of relevant literature. It included the literature related to concrete mix proportioning methods, particle packing theories, aggregate characterization with and without digital image processing etc. Chapter 3, System Development, include development of setup for aggregate characterization using digital image processing, development of modified particle packing theory by incorporating aggregate characteristics. The results of investigation are discussed at length in Chapter 4. Chapter 5 contains conclusions, derived from the research work, and future scope of work. The list of references and the list of publications and patents are presented at the end.