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Review Article

Mesoscale Modelling of Concrete: Need of Including Rheological Parameters

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Concrete is a highly complex and heterogeneous material which limits the characterization prediction reliability of the concrete by experimental investigations. To obtain a deeper knowledge about the behavior of the concrete, better understanding of mesoscale constituents of the concrete need to be analyzed. Interaction of different constituents and their parameters manipulating the microstructure is not strictly considered for computing macroscopic performance of the concrete. For realistic simulation of macroscopic performance of concrete, those disregarded parameters need to be examined and included for computational analysis, since mechanical behavior and characterization of concrete are highly influenced by mesoscopic structural arrangement of the concrete ingredients. Characterization of different components of the concrete is made by finite element meshing the individual component with desired approach to vitalize effective computational analysis. This paper reviews different mesoscale modelling approaches and recommends the need and inclusion of rheological parameters in mesoscale models.

Keywords: **Mesoscale Constituents; Concrete; Finite Element Meshing; Computational Analysis; Rheological Parameters**

Introduction

Mesoscopic level numerical and analytical analyses are influenced by several parameters. Basically, mesoscopic level classification of concrete divides concrete into mortar mix as the main constituent and the aggregate particles ranging to different sizes embedded in the mortar mix. Some researchers have further classified concrete as a multi-scale composite heterogeneous material in mesoscopic level which conglomerates after chemical reactions to form a homogeneous material at macroscopic level. Aggregate parameters which influence the macroscopic properties are shape, size and aggregates distribution within the mortar mix. Different researchers considered different assumptions for mesoscopic modelling of concrete depending upon the scale of measurement of the concrete from nanometers to millimeters. Numerical modelling of hydration of concrete requires nanoscale measurement and modelling, while micro-mechanical analysis requires scale of measurement varying from few millimeters to micro scale.

Numerical modelling deals with the finite element characterization of each and individual constituent of the concrete. Modelling of large volume of concrete constituents requires enormous amount of time and computational effort. In order to reduce the effort required in modelling more complex mesoscopic structure, localized classification and modelling are introduced with reliable macro-micro approach. In macro-micro approach for modelling the concrete, partial discretization of the concrete to behave as homogeneous material and specific localized microscopic behavior are induced in order to account for the mesoscopic level of variation in the properties.

Later, unit cell approach of computation was introduced by (Vander Sluis *et al*., 2000). Classification of local microstructural field and their corresponding physical properties can be easily obtained by the unit cell approach. The two-dimensional random packing was also developed by

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(Wittmann *et al.*, 1993). Due to the computational limitations, real internal mesoscale arrangement of the concrete was not obtained resulting in the under-utilized model development. For generating the actual cement hydration process in the concrete, a special type of arrangement HYDROSTRUC Model was used. Application of digital images developed by the randomly packed spherical aggregate model (Bentz *et al.*, 1992). In order to investigate the effect of variation in the shape and the size of the aggregate particles on micromechanical behavior, sequential packing of various shaped aggregates were considered. But the investigation of the above process was restricted due to the equipment's limited image resolution.

Extensive development of mesoscale structure by considering only spherical shaped aggregate with mono and poly-dispersion lagged the realistic explanation of modelling. Several authors have further contributed for the growth of mesoscale modelling of the concrete. Two-dimensional random sequential packing of elliptical aggregate was considered by employing perram contact function to study the influence of Interfacial Transition Zone (ITZs). Shape influence of the elliptical aggregates on the packing volume was studied by (Xu *et al.*, 2012). Based on the packing volume obtained with respect to the elliptical shape of the aggregate, algorithm was devised for better dislocation of the aggregates inside the concrete. Further enhanced the influence of the shape of the aggregate by using convex polygonal shaped aggregates under random sequential packing model has been further enhanced (Wang *et al.*, 1993). Above packing models were limited to the two-dimensional packing of non-spherical aggregates while random sequential packing of ellipsoidal particles has also been presented (Xu and Chen, 2012). Several other aggregate packing models were established and used for the mesoscopic analysis, where basis of the established models were based on the assumption that the aggregate shapes are spherical. Those models established on the presumption that shape of the aggregate are sphere are the particle suspension model (Mori and Tanigawa, 1992), the µic model, the HADES model (Stroven *et al.*, 2006), the discrete element model (DEM) (Stroven *et al.*, 2009), the molecular dynamic model (MDM) (Thomas and Jörg, 2015) and the integrated spherical particle kinetics model and advanced integrated kinetics model (XIPKM) basically used for modelling of hydration process and microstructural evolution (Le *et al.*, 2013).

Different shapes of the aggregates have different effects on the physical properties. Earlier works on incorporating shapes of the aggregates in modelling of concrete were done by introducing harmonic shape functions by (Garboczi, 2002). The Voronoi tessellation a mathematical approach for creating random points in the space based on which the complex shaped aggregate particles were created (Xu and Chen, 2013). Distribution of the aggregates in concrete is regarded as essential for the volumetric stability and better resilience. For the attainment of the better stability, grading of the aggregates is considered a priori.

Grading of the aggregate was done by Fuller's curve. Several authors have used Fuller's curve for the geometrical modelling of the concrete. Higher the density, higher the strength of the concrete which recognizes the need of grading of the aggregates. This advocacy of high density theory lead to the development of the gradation curve with parabolic fashioned gradation. Nevertheless, it is found that the grading of the aggregate conferring to the maximum density theory leads to the harsh and unworkable mix. Further, several gradation curves with little modifications were given by several authors according to the practical consideration of the aggregates to be used and for minimizing or optimizing the need of different volumetric constituent of the concrete.

Mesoscale simulation and modelling were primarily done for the assessment of microscopic behavior of the concrete to get an insight knowledge about the morphological characterization and macroscopic behavioral pattern of the concrete. Different tools have been used for discretizing the concrete on elemental basis (Wang *et al.*, 1999; Wittmann *et al.*, 1992; Eckardt *et al.*, 2003; Huet, 1993; Kwan *et al.*, 1999) who have utilized aligned mesh approach for discretization of concrete in mesoscopic level. Aligned approach has been widely used for meshing in two-dimensional cases for aggregate particles and mortar mix. Introduction of Interfacial Transition Zone (ITZ) which accounted for analysis of the micro-crack initiation required different kinds of discretization approach. Wang *et* *al*. (1993) developed advancing front approach for mesh generation and used Goodman type elements for the ITZ layer. Bond between aggregate and mortar was considered as rigid (Eckardt *et al*., 2003). Random aggregate structure was meshed using the projection method (van Mier *et al*., 2002). Cubic meshes have also been introduced (Zohdi and Wriggers, 2001). This was an unaligned approach for the better capture of discontinuities in the constituent's geometry. The hanging node concept was introduced by (Lhnert, 2004), in which geometries of the inclusions and the cohesive zone were meshed with better refinement in the model.

Multi-phase microstructural analysis can be structured hierarchically based on the requisite and necessity of the complex parameter extraction namely macroscale, mesoscale, microscale and nanoscale, since the complex extraction parameters at different scales of the concrete model entail different approaches of fundamental model scale.

Influence of Grading of Aggregate in Mesoscale Model

Distribution of size of the aggregate referred as gradingis considered as one among the priori for the mesoscopic modelling of the concrete. Maximum density of packing can be achieved by picking up the right distribution of aggregates. Choosing the right grading of the aggregate leads to the filling up of the voids created by the higher sized particles in the selected distribution range. Several other properties of the concrete are affected by the chosen range of aggregate size distribution. Shape and size of the particles chosen in a particular distribution range also play a vital role in achieving greater closeness in packing of the concrete. Strength attained by the concrete does not depend directly on the type of grading. In the first instance, type of grading does affect the workability of the concrete. The amount of work required for full compaction should be reasonable for a concrete mix to achieve a given strength with prescribed grading of aggregates and water to cement ratio. In order to attain required strength, with reasonable compaction, the mix should be satisfactorily workable.

As major part of concrete consists of aggregate, this requirement is due to the fact that in first instance aggregate is economic to be used and higher the density of the concrete greater is the strength which can be achieved by packing greater amount of solid particles inside the concrete. Based on packing, Fuller has devised a grading curve to achieve maximum density. Accordingly, the curve has combination of a part parabolic and straight line. However, grading the aggregates according to maximum density curve leads to somewhat unworkable mix. Workability can be enhanced by having little excess paste required for filling the voids created by the sand and excess of mortar for filling voids created by the coarse aggregate. Segregation and workability play hand in hand in such situations during sequential filling up of voids from higher level to lower level. Former and latter tend to have partially opposite relationship to one another, as workability deals with easiness of the available particles to rearrange within and fill the voids created by subsequently higher to lower sized particles. Segregation tells about the easiness of smaller particles to spread out through such voids created during packing of the smaller sized particle within the larger sized particles.So, for a proper workable and rich mix, proper grading is of deep concern.

Maximum Aggregate Size

For a given water to cement ratio, a concrete mix to achieve given strength requires optimum maximum size of aggregate (Nichols, 1982). Concrete to attain certain strength requires certain fixed water/cement ratio. On the other hand, considering the amount of water required for cement paste to cover all the particles in the mix is determined by the size of the aggregate. As the size of the aggregate increases, surface area decreases resulting in the reduced water requirement. The above statement is confirmed by such a way that specific surface is inversely proportional to the particle size. Specific surface is the ratio of surface area to that of volume of the particle considered. But the above relationship between the specific surface area and the size of the particle is valid for maximum size of 38.1 mm, above which unfavorable effect takes place resulting in reduced bond area pertaining to higher stresses at interface while larger sized particles introduce discontinuities especially in rich mixes. Based on the richness of the mix chosen, different higher particle sizes of the aggregates can be used, for example use of 150 micrometer (or 6 inches) aggregate is advantageous in lean concrete mix with 165 kg of cement per cubic meter (Higginson *et al*., 1963). However, for structural concrete, usage of aggregates size more than 25 mm or 40 mm is not advantageous. Practical considerations which are governed by code provisions restrict the usage of higher sized aggregates in order to enhance and emphasize the structural limitations.

Based on the surface area of the aggregate (Edwards, 1918) has devised mix design and recommended the use of such mix design worldwide. But the mix design based on surface area had its major drawbacks such as calculation of specific surface is a difficult mathematical approach, since it involves variables of numerous aggregate particles shape. One more reason for the decline of this recommendation is due to breakdown of this mathematical procedure for particles below 150 µm (Glanville *et al*., 1947). Tests conducted on concrete with the mix design based on the specific surface resulted in lower strength of the concrete, the reason behind this was not clear but the increase in the fineness of the sand decreased the density of the concrete lowering the strength of the concrete (Newman and Teychenne, 1954). Experiments on changing gradations with smaller alteration in fine aggregate content showed similar variation in slump value exposing that there is a direct connection between the surface area of the aggregate and workability of the concrete (Hobbs, 1994). Workability in turn disturbs cement and water requirements, controls segregation, bleeding etc. which in turn controls the properties of fresh concrete and perpetual hardened concrete such as shrinkage, strength, and durability.

Considering different hierarchy of the mesoscale modelling of the concrete,several works were proposed from nanoscale modelling for predicting complex chemical process to macroscale models for extracting complex real word problems. Still, in the process of meso-level models considering the above parameters which basically affects the workability parameter that could really have greater influence on several properties of both fresh concrete and hardened concrete. The possibility of including physical parameters which affect workability of the concrete, during transformation of zones from fresh concrete to hardened concrete, need to be considered for obtaining a more realistic numerical modelling and for mesoscale level concrete modelling.

Influence of Geometrical and Surface Characteristics on Mesoscale Model

Geometrical characteristics of the three-dimensional particles are challenging to designate especially in numerical modelling. Although several authors have idealized aggregate as a rounded spherical particle, the primary physical property that governs the degree of packing of aggregate is the relative measure of the sharpness of the aggregate. Based on (BS EN 933-4: 2008), particle size classification is given by rounded, irregular, flaky, angular, elongated and flaky, and elongated. As the percentage of the rounded aggregate in the proportion increases, a corresponding decrease in the voids of the aggregate is noted (Shergold, 1953). An additional physical property associated to the shape of coarse aggregate is surface area to volume ratio termed as sphericity. Aggregates with high sphericity demands increased amount of water for given concrete mix to achieve required workability.

Characterizing the aggregates based on above classification, equidimensional particles are preferred since the particles which set out from such classification lead to anisotropic packing due to larger surface area of such aggregates. Some example of aggregates which depart from such normal equi-dimensional classification are elongated and flaky aggregates. Type of parent rock from which the aggregate originates plays a partial role in the above two important physical properties. Parent rock properties like grain size, pore characteristics and hardness highly determines the surface texture and hardness of the surface. Meanwhile, the former and the latter govern the bonding effect of aggregates to the cement paste.

Bond strength of the concrete is a highly influenced property because of the transformation of zone from highly inert aggregate to hydrated cement paste. Bond strength essentially depends upon the interlocking between hydrated cement paste and aggregate. Surface texture and roughness of the latter have significant influence on the interlocking developed in the concrete. Crack propagation is highly influenced by the strength of the parent rock, surface texture and the shape of the aggregate particles instead of the strength of the mortar mix itself (Regan *et al*., 2005). Geometrical forms and surface textures are two important characteristics that greatly influence the development of adhesive forces.

In numerical modelling, several authors have understood the need and the influence of geometrics and surface texture of the aggregates on the early and later development of strength in concrete. Influence of the geometrics of the aggregate was incorporated in two-dimensional modelling by assuming aggregate as polygonal and circular shape. For crack propagation study (Zaitsev and Wittmann, 1981) modified prescribed elongation ratio for the randomly developed polygonal aggregate (Wang *et al*., 1999) incorporated relative sharpness to the corners and edges of the particles. For three-dimensional particle generation, mostly aggregate was considered as spherical particle (Bazant *et al*., 1990; Guidoum and Navi, 1993; Schlangen and van Mier, 1992; Schorn and Rode, 1991). X-ray tomography images was used to generate concrete aggregate particles based on spherical harmonic functions (Garbozi, 2002). Numerous aggregate shapes were randomly created by means of ellipsoidal functions and used (Hfner *et al*., 2003; Leite *et al*., 2004; Zohdi, 2001). Surface texture was not taken separately as there are no standard procedures available for measuring the surface texture. Still, some authors (Wright 1955; Czarnecka and Gillott, 1977; Ozal, 1978) have proposed some approaches for the texture classification which lags the capability of defining the wide range of aggregate shapes and textures.

Recent works in modelling geometry and surface texture have contributed lot to the incorporation of shape change of the aggregates in the concrete resulting in the improved physical property fusion in the mesoscale stage. This can be used for the improved behavior and pattern detection of the concrete response with respect to different physical properties. But still during the standard concrete casting in laboratories and placing process of concrete requires an external energy given for compaction purpose. This external energy required during placing process reorients the aggregate particles achieving maximum density. A study envisages that using spherical particle as a single sized particle during packing process can attain a density range of 0.52-0.74 for most loose and most dense packing by applying compaction energy.

Influence of Distribution of Aggregate on Mesoscale Model

Structure and arrangement of the aggregate give the layout of the mortar mix. This generated structure consists of randomly distributed aggregate particles with the remaining spaces of voids to be filled by the mortar mix. Distribution of the aggregates during placing of the concrete in construction practices is a process which requires handling care during mixing process so that aggregates mix well and during placing process increased workability with reduced segregation can be achieved with minimum external work, i.e., compaction. So, the distribution of the aggregates during placing process extremely depends upon the workability of the concrete mixture. Distribution of the aggregates in concrete is a random process in mesoscale modelling for achieving maximum packing. Several kinds of optimized packing models are utilized for distribution of aggregates. The list of processes proposed and adopted for the arrangement of the aggregates inside the concrete determines the type and level of model required. Spatial distribution of the aggregate plays an important role in realistic simulation of mesoscale structure of the concrete. Numerous approaches and techniques are developed and extensively used by several authors. Some of the methods developed and their extensive usage are enumerated in Table 1.

In all the above models, enumerated by different researchers, concrete is modelled as a homogeneous material in which the arrangement of the aggregates is made by some distribution patterns and then created

Table 1: Approaches developed and adopted for spatial distribution of the aggregate

S.No.	Approaches Developed and Adopted	Authors
1.	Take and Place Process	Bazant *et al*., 1990; Schlangen and van Meir, 1992; Wittmann *et al*., 1993 and Wang, 1996
2.	Divide and Fill method	De Schutterand Taerwe, 1993
3.	Stochastic Heuristic Algorithm	Leite *et al*., 2004
4.	Random Particle Drop Method	van Mier and van Vliet, 2003
5.	Distinct Element Method	Cundall and Strack, 1979

voids are filled with mortar mix. During practical casting or placing process of concrete, strength attained by the concrete depends upon the degree of compaction, i.e., the workability of the mix. Degree of compaction, density ratio can be related to the strength of the concrete strength ratio (Glanville *et al.*, 1947). Degree of compaction determines the presence of voids in the concrete, as the presence of voids in the concrete greatly decreases the strength of the concrete which is also confirmed by Feret's expression relating the volume of water and air present in the hardened concrete with the strength of the concrete.

As for any kind of mix to achieve a maximum density, to minimize the sum of volumes of air bubbles and water space in the mix depending upon the type of compaction method will have an optimum water content. Optimum water content varies with respect to the grading of the concrete, since the surface area of the aggregates plays supreme role. Similarly, the water to cement ratio should also be taken care of. So, it is obvious that the aggregate grading which can produce good workability for a given water to cement ratio cannot produce the same workability for another value of the ratio. Also, for producing good workable mix based on the above basis, coarse to fine aggregate ratio is fixed for a given water to cement ratio.

Influence of Aggregate Characteristics on Workability of Concrete

Characteristics of aggregates such as surface texture, shape of the aggregate and grading have influence on the workability of the concrete distressing major physical properties of fresh as well as hardened concrete as proved by (Quiroga, 2003). Image analysis on examining the influence of morphological characteristics of aggregates on concrete found that the effect won't be much influential on compressive strength and elastic modulus of concrete (Leon and Ramirez, 2010). Workability produced by rounded aggregate will be better when compared to the workability produced by flat, elongated, rough and angular aggregates for the same water content. For the aggregates other than round shaped, percentage of voids produced will be higher and those aggregates have higher surface area requiring large quantity of cement paste for producing required adhesion.

Need of Including Rheological Parameters in Mesoscale Model

As indicated earlier, consolidation, flowability, and workability which are also referred as rheological parameters or flow properties of the concrete determines the spreading of the concrete in its fresh state. Spreading of the concrete during placing process determines several parameters of the concrete which influences the concrete strength and durability. Formation of honeycomb, air voids and defects in the concrete is mainly due to the ineffective consideration of the rheological parameters which highly influences the fresh concrete properties like workability which in turn influences the later part of the concrete strength during development stage. The characteristic parameters used for manifestation of this rheology for the real-world applications are plastic viscosity and yield stress. While the later is due the internal friction between different compositions in the concrete and the former is due to the movement of water between the particles due to viscous dissipation. Ratio between the solid volume to that of the packing density of the granular material controls the plastic viscosity while the yield stress is controlled by accumulated different granular materials in the concrete mix proportion influenced mainly by size and the roughness of the granular materials.

Rheological parameters of the materials can be modelled by two distinct formations linearly by Bingham Model and non-linearly by Herschel-Bulkley Model. Recent trends in the study and the development of the rheological parameters are introduced after the insufficiency and substantially varying results obtained for fresh concrete using different tests. One of the pioneers in concrete rheology proposed (Tattersall, 1991) and applied Bingham model for modelling and characterizing fresh concrete flow. The proposed form was given by Equation (1).

$$\tau = \tau_0 + \mu\dot{\gamma} \tag{1}$$

where, τ is the shear stress applied to the material, is the shear strain rate, τ_0 is the yield stress and μ is plastic viscosity. Flow properties of the material are characterized by plastic viscosity and yield stress. Rheological parameters are highly influenced by composition of the concrete and process followed during placing. In order to represent the flow behavior of the concrete more precisely non-linear relationship of concrete was given by Herschel-Bulkley model (de Larrard *et al.*, 1998) as represented by Equation (2).

(2)

where, τ is the shear stress applied to the material,

is the shear strain rate, , *a* and *b* are new parameters describing the rheological behavior of the concrete. So, the inclusion of such parameters during testing and modelling might increase the reliability of the meso-level mode. Computational models developed and analyzed using such parameters can validate the exact experimental results and further extension of these models can be used for computing the variation of the quality of concreting during placing processes. Determination of the above parameters for linking it with practical usage is still under study due to unavailability of standard procedure for the measurement and correlation of characterization parameters such as yield stress and plastic viscosity.

$$\tau'_0 = \tau'_0 + \mu\dot{\gamma}^b$$

Past Works in Modelling Concrete Rheology

Flow behavior of cementitious materials have been studied (Tattersall and Banfill, 1983) based on composition and several influential characteristics, concrete can behave as a Bingham material, shear thinning material (if viscosity decreases with shear rate on stress exceeding yield stress), or shear thickening material (if viscosity increases with shear rate). Various equations relating shear stress and shear strains were obtained by curve fittings based on the measurements obtained for different cement based materials.

Substantially varying test approaches for classifying concrete samples based on rheological properties exists. Some of them are slump test, flow time test, compacting factor test, workability test etc. led to the introduction of complete flow characterization of fresh concrete by mixer (Tattersalland Banfill, 1983). These proposed approaches related Bingham parameters (yield stress and viscosity) with concrete's flow behavior. Subsequently different approaches relating concrete material properties to Bingham parameters have been conducted. In concise this empirical and semi-empirical model can be summarized as: Empirical model (Ouchietal, 1999), Volume faction model (Powers, 1968), Gap and aggregates spacing theory (Denis *et al*., 2002; Bui *et al*., 2002b), Two-phase theory (Kurokawa *et al.*, 1996), Maximum packing density model (de Larrard, 1999), and Excess paste theory (Kennedy, 1940; Oh *et al*., 1999; Su *et al*., 2001). In all the above theories and models, finite element approaches were implemented for simulating fresh concrete deformation (Mori and Tanigawa, 1992).

Two-phase theory was utilized by Kurokawa and co-workers, they considered expressing yield stress and viscosity as a summation parameter, sum of yield stress and viscosity contributed by individual constituent of the concrete in its fresh state (coarse aggregate and mortar) (Kurokawa *et al*., 1996), Similarly, the law of plastic viscosity for two-phase composite material modelling has been used (Topcu and Kocataskin, 1995). The excess paste theory, (Kennedy, 1940), states that additional paste is required in addition to the paste that fills up the voids created by aggregates to maintain the flow, when thickness of the excess paste increases gradual reduction in rheological parameters are found (Oh *et al*., 1999). Based on the energy conservation concept, the fresh concrete flow model concluded that the summation of shear stresses produced by individual phases in concrete is the overall shear stress responsible for shear stress transfer mechanism of fresh concrete (Pimanmas and Ozawa, 1996). However, a major drawback of the above approach was that the consideration was not given to the gap and aggregate spacing. Reviews made from previous research works show that friction between aggregate particles, volume fraction of solid particles, inter-particle distance, paste property were all considered as important parameters influencing rheological models. Still in order to establish and to govern the durability of the hardened concrete integration of different dimensional scales of concrete modelling is crucial to extend the service life of concrete structures.

Factors Influencing Concrete Rheology

Rheology of concrete is affected by the constituents of the concrete itself, manufacturing and testing conditions, and the properties of the materials used. Logically considering, the influential factors can be grouped into three categories: properties of matrix material, dispersing solid particles and other factors. Large amount of previous studies has been done on the effect of influential factors on rheological parameters. Some of influential factors and their effect on concrete rheology are discussed below. Water to cement ratio is one of the important factor governing rheological parameter of the concrete, as the water content increases yield stress and viscosity of the cement paste decreases (Jones and Taylor, 1977; Banfill, 1994). The influence of concentration of different solids and specific surface area of cement pastes has been studied (Vom Berg, 1979). This study describes, as concentration of solids and fineness of cement increases which has an intense control over attractive and repulsive forces between particles increasing yield stress and plastic viscosity of cement paste. With respect to type of coarse aggregate used, both yield stress and plastic viscosity increased as coarse aggregate volume fraction increased (Geiker *et al*., 2002a). Further, yield stress and viscosity are affected differently on using coarse aggregates with different physical properties such as aspect ratio, angularity, surface texture etc. lower rheological parameters were reported for rounded and smaller coarse aggregates. Influence of other factors such as porosity and density of aggregates, effect of supplementary cementitious materials (Celik and Marar, 1996), and the effect of super-plasticizer (Ho *et al*., 2002) was also reported.

A Brief Review and Further Requirements: Flow-Behavior of Cement-Based Material

In order to bring a compromise between fluidity and stability of fresh concrete numerous numerical models are proposed by different researchers (Dolado and van Breugel, 2011). Rheological properties defining the evolution and their consequences are time variant demanding reversible evolution. This reversible time variant evolution behavior of the fresh concrete is mainly attributed due to the inherent nature of cementitious material causing thixotropic variations. Thixotropic actions lead to manipulation of yield stress and plastic viscosity building an internal structure on course of time (Otsubo *et al*., 1980; Banfill and Saunders, 1981; Lapasin *et al*., 1979; Geiker *et al*., 2002; Roussel, 2005; Wallevik, 2009; Billberg, 2005; Jarny *et al*., 2005; Assaad *et al*., 2003; Roussel, 2006). This thixotropic manipulation of cementitious material led to development of kinetic models. These kinetic models are physical contact models defining the rate of reaction of cement grains at different dimensional scales leading to the development of various sophisticated mechanical properties (Jennings, 2008). These mechanical properties govern the durability of the concrete structures and play a vital role in the service life of concrete structures. Each kinetic model augmenting different integrated properties, particle kinetic models focuses on reacting grains dissolution process describing the formation of pore structure and microstructure related material properties, hybrid kinetic models explicitly allows influence of chemical composition in addition to the particle size distribution of the cement, although this model disregards formation of contacts between inter-particle and their influence on rate of reaction. Integrated kinetic model is a computer based model explicitly prototypes the reaction rates and their interdependencies (van Breugel, 1991; van Breugel, 1996). The above models which describe the modelling at microscopic level determining microstructural elemental properties are called as fundamental models except particle kinetics model, since the basic principle of inter-particle contact formation is explicitly disregarded in this model (Garboczi and Bentz, 1992). Most of the models mentioned above are analytical models which can be used extensively for describing observed phenomenon. Although the models required for predicting, simulating and researching are typically numerical models which might deal with aggregate and matrix interface properties.

Considering length scale characteristics it was suggested that simulation levels, i.e., multi-scale system with three different levels viz., the micro-, meso- and macro-level (Witmann, 2008). This new perspective of modelling from macro to micro-level, sometimes even to nano-scale that is responsible for durability and cohesion of structures made of cementitious materials were proposed by researchers like van Damme, Pellenq, Scrivener, Kalinichev, etc. Shrinkage of these modelling levels from higher to lower levels, i.e., fine tuning can be used to foresee the next source of improvements in order to comprehend and endeavor the crucial role of nano-scale hydrates and colloidal porosity on molecular modelling (Pellenq *et al*., 2008). Atomistic simulations are used to perform simulations at this scale, especially equipped for modelling crystalline phases of cementitious material (Manzano *et al*., 2008). Still higher scale needs are recommended for description and simulation of C-S-H gel formulation. Since the above models are fundamental for inter-particle contact formation that in turn articulates rheological parameters such as yield stress and viscosity manipulating the thixotropic nature of the concrete during its earlier age to mobilize the balance between stability and fluidity. Influence of particle size distribution and composition of supplementary cementitious materials has also been incorporated (Maruyama *et al*., 2008). Recently, information upscaling has been made by HydratiCa (Bullard, 2008; Bullard, 2010; Bullard *et al*., 2010) a code which addresses four parallel individual chemical reactions that involves dissolution, growth, diffusion, complexation and nucleation of hydration process when cement comes in contact with water. Time dependent behavior of early stage concrete evolution was modelled by Scheiner, this time dependent evolutionary model consists of a cementitious micro viscoelastic continuum (Scheiner and Hellmich, 2008), where cementitious continuum response as a function of viscoelastic hydrates, the elastic properties of cement, water and aggregates. A multi-scale engineering model has been proposed (Asamoto *et al*., 2008) and used by DUCOM (Ishida *et al*., 2001) is a time variant deformation model for cementitious solidifying material.

In meso-scale several researchers have provided valuable additions in incorporating workability of fresh concrete pastes during concrete flow simulation (Roussel *et al*., 2007; Mori and Tanigawa, 1992; Shyshko and Mechtcherine, 2008; Shyshko and Mechtcherine, 2010; Lu and Wang, 2010). Categorization of concrete flow simulation are based on modelling referring to the constituents in the model developed. Based on the above categorization, three main divisions are described in literature, i.e., discrete particle flow numerical simulation, single fluid simulation and modelling of particle suspension in fluid. Mori and Tanigawa used visco-plastic finite element method (VFEM) and the visco-plastic divided element method (VDEM) for simulating fresh concrete flow (Mori and Tanigawa, 1992). The Discrete particle model was used, which considers yield stress and re-structuration rate that evolves with respect to time, where structuration rate evolves with the help of previous flow history (Roussel *et al*., 2007). Although classical slump model was successfully simulated using above model, a complete classification for fresh concrete rheological prediction was not established adequately (Shyshko and Mechtcherine, 2008, 2010). For gaining complete rheological prediction above model needed further vital data about pore water properties and surface properties of the powders. The attractive and repulsive forces between particles were governed by chemical reactions defined by intrinsic properties of the materials used for modelling (Lu and Wang, 2010). However, there is a need for evolution of this multi-dimensional, multi-scale versatile model from nano scale to meso-scale in order to understand and simulate to accomplish and improve the reliability and quality of fresh concrete for better transportation, placing and compaction to potentially improve durability of concrete structures.

Conclusions

Even the scope of modelling mainly depends upon the level of analysis need and the type of parameters to be arrived from analysis. Different researchers have used different methods for meso-level model of concrete. Each model has its own kind of advents in testing, analysis, and experimental validations. Idealizations of concrete in each level created several models extending from nanoscale idealization for examining the chemical reactions to macroscale idealization for loading and stress analysis. This paper discussed about some of the features and parameters considered by many authors in hierarchical level of concrete models. Some of the shortcomings in the existing models and the need of inclusion of rheological parameters can bring the model to reality in terms of considering the bond strength developed after the morphological transformation of concrete from fresh state to hardened concrete. The existing models describe the overlapping of mortar mix with randomly generated aggregate for filling the voids generated by different grading of the aggregates used. In practice, the placing of the concrete requires good consistency and workability of the mix in order to increase the strength and durability of the structure. Since consistency and workability variations can determine the percentage of defects/ voids, and/or honeycombs in the structure. In order to include the above parameters, rheological characterization of concrete using Bingham Model and Herschel – Bulkley model can be used. Addition of these flow behavioral approaches with multi-dimensional, multi-scale versatile model from nano scale to meso-scale can enhance actual rheological characterization to bring the relationship between plastic viscosity and yield stress for better modelling and arrival of parameters from different analyses for enhancement of its practical applicability.

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