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# MODELING THE RHEOLOGICAL PROPERTIES OF FRESH CONCRETE USING A 3D FINITE ELEMENT MODEL

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***Abstract:***

During the last thirty years, concrete has been industrially mutating from a soft granular medium to a proper non-Newtonian fluid. To benefit from the full potential of the modern fluid concretes such as Self-Compacting Concrete (SCC), prediction tools of the form filling taking into account the properties of the concrete, the shape and size of the structural element and the casting technique are needed. Development of a finite deformation elasto-plasticity model based on the multiplicative decomposition of the deformation gradient is presented. The presented model in this paper includes application of inelastic material properties are specified with the Drucker Prager hardening option.

*Keywords: Fresh concrete, Flow modeling, Finite element model.*

# MODELOVANJE REOLOŠKIH SVOJSTVA SVEŽEG BETONA PRIMENOM 3D KONAČNIH ELEMENATA

***Apstrakt:***

Tokom poslednjih trideset godina, definicija betona prelazi put od mekog granularnog medija u odgovarajući ne-Njutnov fluid. Da bi korist od punog potencijala modernih betona tečne konzistencije kao što je samougrađujući beton (SCC), potrebni su alati za predviđanje oblika punjenja, uzimajući u obzir svojstva betona, oblik i veličinu konstruktivnog elementa i tehniku ugradnje ugradnje. Predstavljen je prikaz elasto-plastičnog modela konačnih deformacija zasnovanog na multiplikativnoj dekompoziciji gradijenta deformacije. Model predstavljen u ovom radu uključuje primenu nelinearnih svojstava prema Drucker-Prager-ovom kriterijumu tečenja.

*Ključne reči: Svež beton, Modelovanje sleganja, Metod konačnih elemenata*

## 1. INTRODUCTION

Fresh concrete properties, especially workability, significantly affect transporting, placing, and compacting concrete. These properties have significant effects on the quality and cost of concrete construction. They also potentially determine certain hardened concrete properties, such as uniformity, strength and durability. One particularly important fresh concrete property is workability. Workability is defined as "the property of freshly mixed concrete or mortar that determines the ease with which it can be mixed, placed, consolidated, and finished to a homogenous condition". Concrete must have proper flowability, or rheology, in order to obtain desirable workability [1].

These all depend on the rheology of the material and a list of specific factors for consideration in these processes would include flow and frictional resistance against surfaces, adhesion, resistance to segregation, resistance to settlement and the formation of bleeding water, low water content to obtain high strength and durability, resistance to sagging under self weight on a wall or inclined surface, and low pressure on the temporary formwork erected to support a wall or other component [1].

Research has shown that a suitable range of rheology is helpful to prevent segregation [2]. The rheology study can also determine the design in pumped concrete. The fluidity of the vibrated concrete, determined from the rate of efflux from the pipe, is controlled by the peak velocity of the vibration and influenced by the rheology of the unvibrated concrete [3].

The rheology of concrete can be affected by different factors: mix proportions, characteristics of the cement, aggregate properties, amount and type of admixtures, time, temperature, and mixing condition. Among all these factors, aggregate properties are the most important because the aggregate normally occupies up to 70-80 percent of the total concrete volume of concrete. The flowability of concrete can be significantly changed by using different aggregates. The aggregate directly affects the flowability of concrete through interparticle forces (such as interlocking and friction of solid particles) and the movement of solid and liquid phases inside fresh concrete mixtures.

Several factors, such as size, type, gradation and texture of aggregates, also affect the properties of fresh concrete. The study of the effect of aggregate on concrete rheology is still very limited, and no efficient concrete rheology model considering the effect of aggregate had been developed so far [3].

## 2. FUNDAMENTALS OF CONCRETE RHEOLOGY

Rheology is the science of the deformation and flow of matter, and the emphasis on flow means that it is concerned with the relationships between stress, strain, rate of strain, and time. Concrete in its fresh state can be considered as a fluid and therefore the basic principles of rheology can be applied to this material [4].

The simplest fluid is one that obeys Newton's law of viscous flow, which can be described as:

$$\tau = \eta \cdot \dot{\gamma} \quad (1)$$

In this equation $\tau$ is the shear stress (Pa), $\eta$ is the coefficient of viscosity (Pa·s), and $\dot{\gamma}$ is the rate of shear (shear rate) or the velocity gradient (s-1). The flow behavior of any fluid requires the measurement of the relationship between shear stress and shear strain rate of the material, which is normally called the flow curve. As shown in Figure 1, the Newton liquid described in Equation 1 can be represented with a plot of the shear rate versus the shear stress that has a straight line passing through the origin, with a slope of $\eta$.

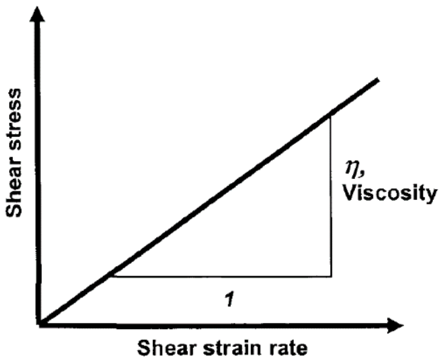


*Figure 1. The Newton model*

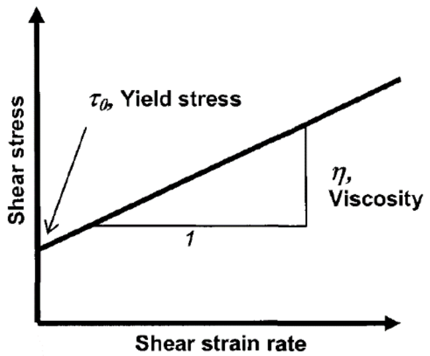


*Figure 2. Bingham model*

For a very diluted suspension of solids in a liquid, there is no interparticle force; and the effect of small increases in the amount of suspended solid is merely to increase the coefficient of viscosity. Nevertheless, concrete has to be considered as a very concentrated suspension, in which the volume ratio of solids-to-water would be as high as around 4.5:1.

For such concentrated materials, there are forces acting between the particles. This does not merely change the viscosity, but actually changes the type of flow. The Bingham model, as seen in Figure 2, concrete has a yield stress, which indicate the minimum stress to start a flow of a material. The material obeys Bingham model and can be written as:

$$\tau = \tau_0 + \eta \cdot \dot{\gamma} \qquad (1)$$

In this equation $\tau_0$ is the yield stress (Pa) and $\eta$ is the plastic viscosity (Pa·s).

Both parameters should be used in order to fully describe the rheology of the materials that obeys Bingham's model, because some materials may have the same viscosity but different yield stresses or the same yield stress but different viscosities.

Another important parameter of rheology is thixotrophy. A thixotropic fluid undergoes a decrease in viscosity with time, while it is subjected to constant shearing. The shear rate was first increased to a certain value, then immediately decreased to the starting point. This "hysteresis loop", the area between the up and down curves is caused by the decrease in the fluid's viscosity with increasing time of shearing resulting from the material's structural breakdown. Generally, the larger the "hysteresis loop" area, the higher degree that the material structure is broken down [1]. Some thixotropic fluids, if allowed to stand undisturbed for a while, can regain their initial viscosity, while others can not. This behavior is due to interparticle attraction and weak bonds.

Newtonian liquid has a constant viscosity. A Bingham material needs to overcome the yield stress to initial flow, and its plastic viscosity is also constant. In a shear thickening material, viscosity increases continuously with shear rate, while viscosity decreases continuously with shear rate. In the material having shear thinning with yield stress, viscosity decreases with shear rate once the yield stress has been exceeded.

## 3. A FINITE DEFORMATION ELASTO-PLASTIC DRUCKER-PRAGER MODEL

Example in this paper illustrates the use of the extended Drucker-Prager plasticity model for a problem involving finite deformation. Software Abaqus provides three different yield criteria of the Drucker-Prager class. In all three the yield function is dependent on both the confining pressure and the deviatoric stress in the material. The simplest is a straight line in the meridional (p–q) plane. The other yield criteria are a hyperbolic surface and a general exponential surface in the meridional plane.

In this example, material parameters of fresh concrete shown in the literature were applied for the linear Drucker-Prager model are examined by simulating a concrete slump test. The slump test is a standardized procedure performed on fresh, wet concrete to determine its consistency and ability to flow. The test consists of filling a conical mold with concrete to a specified height. The mold is then removed, and the concrete is allowed to deform under its own weight. The reduction in height of the concrete cone, referred to as the "slump," is an indication of the consistency and strength of the concrete. This example is a simulation of such a test. A finite element analysis of this problem has been published by Famiglietti [5].

No specific system of units is used in this example for the dimensions, the material parameters, or the loads. The units are assumed to be consistent. A standard, conical mold is used when performing a slump test on concrete. The cone is 0.3 units high. The radius at the base of the cone is 0.2, and the radius at the top is 0.1.

The mesh used in the example is shown in Figure 3. First-order CPE4 elements are used. A Young's modulus of 2.25 and a Poisson's ratio of 0.125 define the elastic response of the concrete. A density of 0.1 is used as specified in [5].

It is assumed that the inelastic behavior is governed by the cohesion or shear strength and by the friction angle of the material. A cohesion of 0.0011547 and friction angle of 20° is used. Perfect plasticity is assumed. Since these parameters are provided for a Mohr-Coulomb plasticity model, they must be converted to linear Drucker-Prager parameters. Plane strain deformation and an associated plastic flow rule, where the dilation angle is equal to the material friction angle , are assumed for the purpose of this conversion.

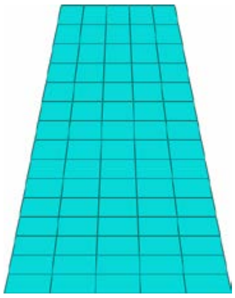

*Figure 3. Undeformed mesh (CPE4 elements)*

The inelastic material properties are specified with the *DRUCKER PRAGER option and the *DRUCKER PRAGER HARDENING option.

The loading is a gravity load, 0.981, applied to the entire model. The load is increased linearly from zero at the beginning of the step to its maximum value at the end of the step. The load is ramped up using the *AMPLITUDE, DEFINITION=SMOOTH STEP option. This amplitude definition provides a smooth loading rate, which is desirable in quasi-static or steady-state simulations.

The base of the concrete cone is held fixed in the vertical direction but is free to move in the radial direction. Friction between the concrete and the support is not considered. Since finite strains and large displacements must be accounted for, the NLGEOM parameter is specified on the *STEP option. The models with the hyperbolic and exponential yield criteria use the default values for the *CONTROLS option. However, for the linear Drucker Prager model the *CONTROLS, PARAMETER=FIELD option is used to override the automatic calculation of the average forces to decrease the computational time required for the analysis. The convergence criteria is set to 1%, and the average force is set to 5.0 × 10–5.

The maximum time increment is limited in the models such that no more than 2.0% of the total load is applied in any given increment. This is done so that the point of initial yield and the shape of the inelastic response are captured accurately during the analyses.

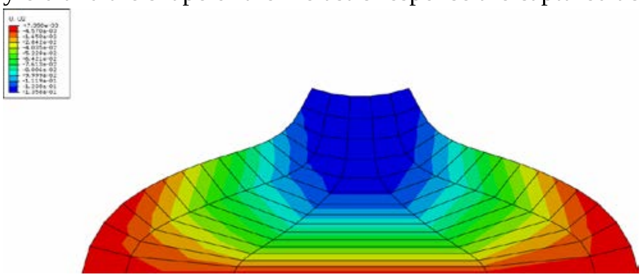

*Figure 4. Deformed mesh (deformed "concrete slump")*

## 4. CONCLUSION

Rheological model has been shown that it can predict the plastic viscosity and yield stress of fresh concrete and model were developed for predicting the mortar and concrete rheological properties as well as for evaluating the factors that influence mortar and concrete rheological behavior.

This paper has presented a finite-strain elasto-plastic Drucker-Prager model based upon the multiplicative decomposition of the deformation gradient. The equations have been developed within a framework using a spectral decomposition approach found in literature. Solution of an example problem (the concrete slump test), has been performed to illustrate implementation of finite deformation elasto-plastic Drucker-Prager model.

ACKNOWLEDGEMENTS

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