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Modelling, Simulation of Visco-Elastic Plastic Behaviour for Soft-Solids by CONE Indenters

Dr. Dharmendra C. KOTHARI[1], Prof. Paul F. LUCKHAM[2],

[1] Assistant Professor, Department of Chemical Engineering, College of Engineering & Technology, Babulgaon (Jh.), NH 6, District: - AKOLA, M.S, India,

[2] Professor of PARTICLE TECHNOLOGY GROUP, Department of Chemical Engineering & Technology, Prince Consort Road, London, United Kingdom, SW7 2BY,

ABSTRACT: Materials deforms in response to an externally applied stress. The deformation can be permanent or temporary. Permanent deformation stays after the removal of the applied stress, while temporary deformation disappears on the removal of the stress. Both temporary and permanent deformations can be functions of time or virtually independent of time. Processing and handling of intermediate or final products involving particulate materials dispersed in liquid media at high solids volume fraction means Soft-Solids, present major challenges in the chemical industry and in its allied sections, such as; Biochemical and Biotechnology apparently the drugs and Pharmaceuticals industries. In the development of new processes, manufactures are faced with growing diversity of equipment options and a limited technical basis for selection, of their complex flow behaviour and the influence of the wall boundary conditions. Pilot scale trials may be lengthy, expensive and has to rely on uncertain rules of modelling scale-up. Therefore the current strategy which is emerging world-wide is to employ computer simulation as a basis for optimising the design and operating parameters. Importantly, soft-solids exhibit complex bulk flow and interfacial properties; that leads to the requirement for accurate and reliable constitutive information to model their processing. To obtain useful experimental data, there is a need for a well characterised and reproducible material. The 'BEST' material will undergo sufficient plastic flow so as to be capable of being formed. Therefore a model paste Plasticine for Simulation and Terracotta for Modelling has been tested by CONE indenter over a wide range of strain rates. It was found that the terracotta exhibits a linear elastic behaviour at low stress levels and power law creeping behaviour at higher levels of stress. All the loading and relaxation tests at various strain-rates give the same material properties. This means that the model works reasonably well. The analysis of loading and relaxation is simple robust and easily provides a value of *E*, and the flow curve, this is also true for CONE indentation of soft-solids. The primary aim of this project was to attempt for developing and evaluating codes of the Finite Element Analysis (FEA) which are specifically designed for paste system. The finite element method has been shown to be viable computational tool for modelling pastes and the effects of the friction. However the practicality of the data method is very much dependent upon the accurate modelling of the paste behaviour. The predicted results, in some cases, show a reasonable agreement with those obtained experimentally.

KEYWORDS: Modelling, Simulation, Soft-Solids, Finite Element Analysis, Cone Indenters & Rheological Measurements.

I. INTRODUCTION

Soft-Solids generally exhibit elasto-viscoplastiv behaviour which is characterised by elastic deformation at low strains and rate dependent plastic flow when the yield criterion is satisfied. The behaviour of many soft-solids can be thought of as being somewhere between that of elastic and vicoplastic materials and should be termed as elasto-viscoplastic [1]. Figure [1] summaries these material responses on stress, strain and strain rate axes in briefly, the processing of soft-solids invariably involves relatively large strains and finite strain rates. The elementary requirement of the experimentation is for a stable model paste material, which is generally able to provide elasto-viscoplastic deformation (under large strain conditions) when the material is stretched, compressed or indented. Ideally, it should also be able to provide constant constitutive relationships between stress and strain with respect to other related material properties. Highly concentrated dispersions of solid particles dispersions in a viscous liquid medium are processed in a variety of

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industrial applications, such as food processing and ceramic manufacturing [2]. These materials normally exhibit a complex visco-elastic-plastic behaviour under the application of an applied stress, could be studied in details [3 & 4].

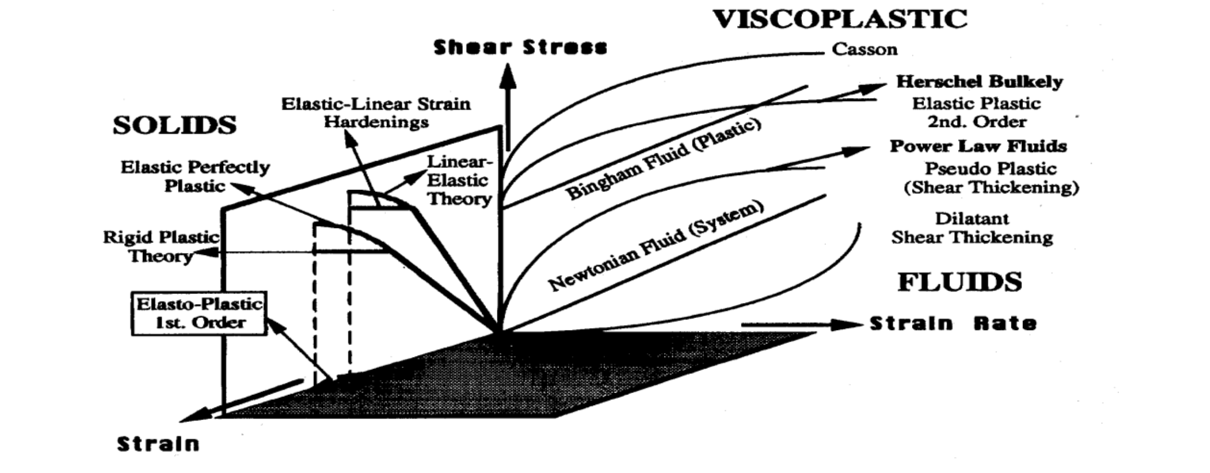

Figure [1] :- Rheological Flow and Deformations of SOLIDS to LIQUIDS.

II. MATERIALS & METHODS FOR SIMULATION

The hardness and yielding behaviour of food paste is an important mark of quality, affecting aspects such as eating quality, usage properties e.g. ease of cutting and spreading, handling properties during storage and further processing in connection with e.g. shape forming and extruding. All these phenomena have an outstanding resemblance to those well known for metals. Conventional indentation hardness tests involve the measurement of the size of a residual plastic impression in the specimen as a function of the indenter load. The hardness measured in this way is obviously related to the plastic flow stress of the material. hardness has been related to several other properties and attributes such as the yield stress and the Young's modulus. Considering the fact that different hardness measurements sense different properties of materials, viz. elastic, plastic and visco-elastic, hardnesses have been separated into these different classes.

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Deformation behaviour of soft solids and rocks are influenced by a number of factors, such as a the physical structure, porosity, density, stress history, loading characteristics, existence and moments of viscous like fluids in the pores and time-dependent or viscous effects in the solid skeleton and the pore fluids. In addition some features as faults, joints, seams, crushed zones, veins, fissures, folds, and other tectonic effects produce behaviour significantly different from that derived on the assumption of CONTINUOUS MASS. These factors render the stress-deformation behaviour highly complex and nonlinear. Thick rectangular blocks of terracotta with constant size of 150mm length, 70mm width and 35mm height were used as supplied for the tests. To prevent any drying or rheological changes, once the block of

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terracotta was un-wrapped, the experiments were carried out within a maximum of two hours and then the specimens were discarded and a new specimen from the same batch was used for further testing. This procedure was strictly followed throughout the experimentation. The principal device used was a standard universal testing machine (Instron 1122) of Instron Ltd. (High Wycombe, UK), equipped with a 50N transducer (bottom load cell) of accuracy $\pm 0.01\mathrm{N}$.

In a representative experiment the load cell output was zeroed with the sample on the platform and the indenter was brought very near the sample surface by moving the crosshead. Then the required indentation speed was set (normally, in the range 1 mm/min to 1000 mm/min), and the indenter was moved into the material at the prescribed speed. The displacement may be deduced from the speed and lapsed time data; however, a separate LVDT (linear variable displacement transducer) was used, as the displacement measurement is useful in the data analysis. In the second procedure, once the indenter reached the set depth (which was automatically controlled), the indenter was left within the specimen, for a relaxation time of 500 sec. In this work all of the experiments were displacement controlled. The Instron was reset at the beginning of every experiment to measure zero force when the tip of the indenter was out of the specimen [11]. The cone indentation hardness test is a non-destructive means of assessing several mechanical properties of solids and has important technological applications. However, in order to exploit the potential usefulness of the indentation test, it is necessary to have appropriate models of the contact mechanics and the means of quantifying the influence of the experimental variables. The experiments were carried out in order to obtain basic material properties with two protocols i.e. loading-unloading and loading-relaxation.

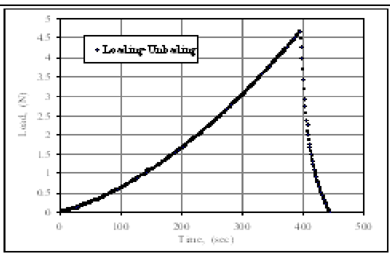

Figure [2]:- Lading-unloading.

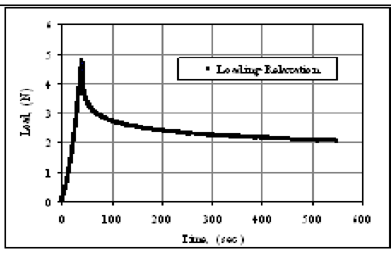

Figure [3]:- Loading-relaxation.

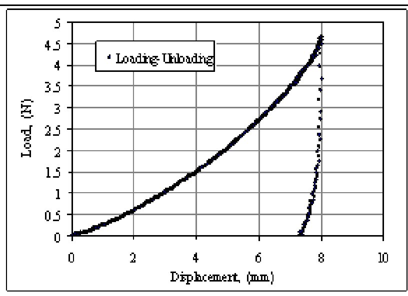

Figure [4]:- Lading-unloading.

The raw data were obtained in the form of time series of load, displacement and time. Typical examples are shown in Figure [2] where the total load (N) is plotted against the total time, (sec) for loading-unloading and Figure [3] for loading-relaxation for the cone indentation The load plotted against the displacement for the loading-unloading protocol shown in figure [4]. The preliminary raw load (*N*) vs time (*t*) curves show that the load is directly dependent upon the velocity of the indentation. Indentation is a comparatively simple and virtually non-destructive method of determining rheological properties of soft-solids surfaces by means of an cone indenter inducing a localized deformation. The dependence of the compliance curves, the hardness, the elastic modulus and the plasticity index upon the imposed penetration depth, the applied normal load and the deformation rate are described.

The combination of Spring-Dashpot and combinations of the classical linear laws of Hooke and Newton are based on the simple three-element Maxwell model, for experimental interpretation of this model [5], the material is considered to be nonlinear viscoelastic, so that if the indentation occurred very slowly, the material response would be given by a non-linear viscous relationship, $\sigma = F(\dot{\gamma})$ between the local stress and strain rate. However, as long as the material itself is homogeneous, it might be expected that the average applied stress is related to some average or nominal strain rate $\dot{\gamma}$ by a relationship;

$$\sigma = C_P F(\dot{\gamma}) \tag{1}$$

Where F is the non-linear viscous material function and C_P is the plastic constraint factor. The constraint factor may vary with cone angle and with the wall friction condition, but for a given combination of materials it should be approximately constant. In the general case, the strain and strain rate will have both elastic and plastic contributions, in

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different proportions throughout the material. In this simple model, the deformation is characterised entirely by the penetration depth *H*, which is therefore regarded as having elastic and plastic components:

$$H = H_E + H_P \tag{2}$$

Therefore, the elastic strain and the plastic strain rate are given by: $\varepsilon = H_E / a$ (3)

$$\dot{\gamma} = \dot{H}_P / a \tag{4}$$

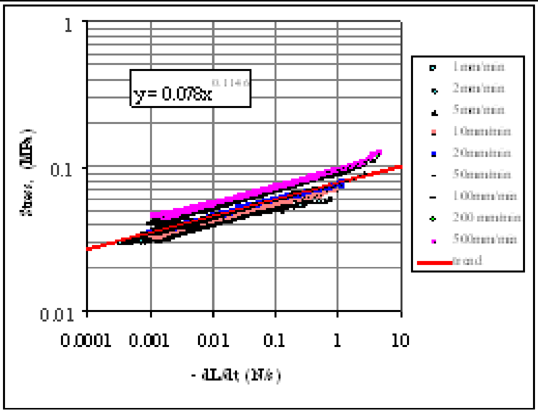

Figure [5]:- Stress vs Change.

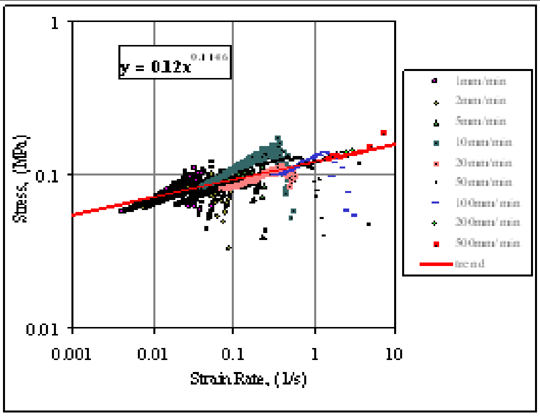

Figure [6] Stress vs. Strain rate.

Where the (dot) on $\dot{H}_P$ indicates a time derivative. The (mean) stress is simply the load divided by the nominal contact area, $\sigma = L/A$. Therefore from equation (2), the elastic strain is: $\varepsilon = \dfrac{\sigma}{C_E E} = \dfrac{L}{A C_E E}$ (5)

and from equations (4) and (5), the elastic displacement is: $H_E = a\varepsilon = \dfrac{a\,L}{AC_E E}$ (6)

from (3) & (6), the plastic part of the displacement is: $H_P = H - H_E = H - \dfrac{a\,L}{AC_E E}$ (7)

Furthermore, from equations (1) and (5) in terms of applied force; $\dfrac{L}{A} = C_P\,F\left(\dfrac{\dot{H}_P}{a}\right)$ .... (8)

so that by combining (7) and (8) the main working equation is obtained that relates the experimentally determined quantities;

$$\frac{L}{A} = C_P F\left(\frac{1}{a}\frac{d}{dt}\left[H - \frac{a\,L}{AC_E E}\right]\right) \tag{9}$$

The plasticity indexλ, characterises the relative importance of the elastic component of deformation. For the cone geometry, the contact area *A*, is simply given by $A = \pi\, a^2$. Furthermore, if piling up or sinking in of the free surface of the specimen is neglected, the contact radius is given by $a = H\tan\alpha$. In interpreting experimental data, the effect of piling up or sinking in will be swept into the constraint factors C_E and C_P. Then equation (9) is replaced by;

$$\frac{L}{\pi(H\tan\alpha)^2} = C_P F\left(\frac{1}{H\tan\alpha}\left\{\dot{H} - \frac{1}{\pi\tan\alpha\, C_E E}\frac{d}{dt}\left[\frac{L}{H}\right]\right\}\right) \tag{10}$$

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This is the general equation for cone indentation. Specific loading protocols are now considered for this geometry. When the material is loaded at constant speed, $\dot{H} = V$, and for small plasticity index, (10) reduces to;

$$\frac{L}{\pi\left(V\left(t-t_0\right)\tan\alpha\right)^2} \approx C_P F\left(\frac{1}{\left(t-t_0\right)\tan\alpha}\right) \tag{11}$$

where t_0 is the time at which the experiment starts. Thus the loading curve may be analysed to obtain an approximate form of the viscoplastic constitutive function *F*. Now the displacement is fixed, and (10) gives;

$$\frac{L}{\pi(V\tan\alpha)^2} = C_P F\left(\frac{\dot{L}}{\pi(H\tan\alpha)^2 C_E E}\right) \tag{12}$$

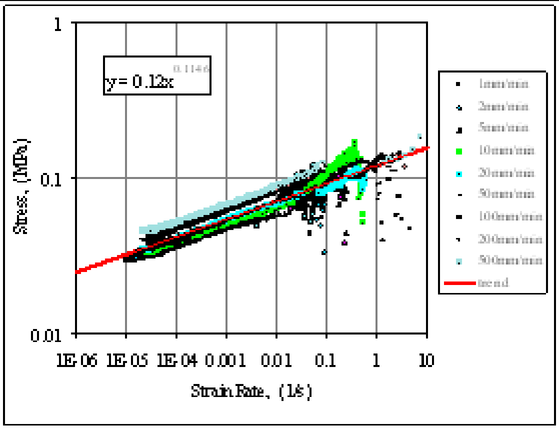

Figure [7]:- Stress Vs Strain Rate, (Combined).

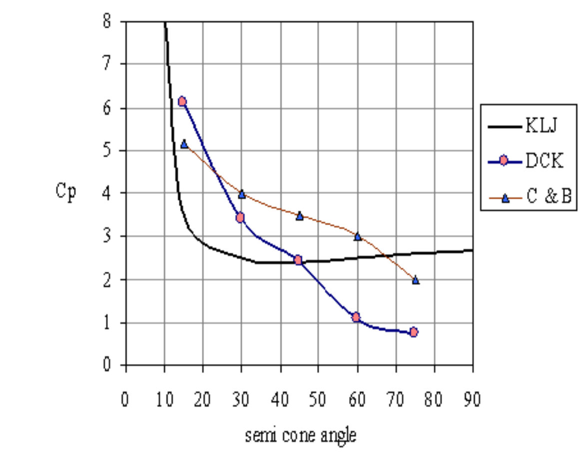

Figure [8]:- Comparison between the constraint factor *C* as a function of cone semi angle α details [3, 12, 13 & 14].

The data were analysed using equations (11) for loading data as displayed in Figure [5] and (12) for relaxation data as displayed in Figure [6]. First, the time dependent response was characterised by examining the relaxation behaviour from which the general shape of the function *F* can be obtained. For the terracotta material F was found to follow a power-law relationship. According to equations (11) and (12), the plots of mean indentation pressure against strain rate for different speeds should collapse to a single master curve, where 'strain rate' is defined as the argument of the function F, apparently, it does as it displayed in Figure [7]. Figure [8] shows the Comparison between the present research and Dugdale (1954) [12] Johnson (1970) [13] and Hill (1992)[14] work on the constraint factor *C* as a function of cone semi angle α at room temperature with comparison to Kothari (1999) [3].

III. EXPERIMENTAL RESULTS FOR MODELLING

A continuum material is a material for which the densities of mass, momentum, and energy exist in the mathematical sense, the mechanics of such a material is continuum mechanics. Crisfield & Shastri, [6 & 7], deals with the main ideas of geometric non-linearity, provides a framework for a non-linear finite element computer programs that displays most of the main features of more sophisticated programs. The details study of the commercial finite element packages used in this research (ABAQUS, USA [8]; ELFEN, Rockfield Software Limited, UK [9]; LUSAS, FEA Limited, U.K, [10].) to describe the isothermal indentation of the CONE. Exemplar based in finite element technique is used for boundary elements of element regions, which takes structure synthesis and texture synthesis together. The finite element analysis is done in such a manner, that it fills the damaged region or holes in an element, with surrounding colour and texture.

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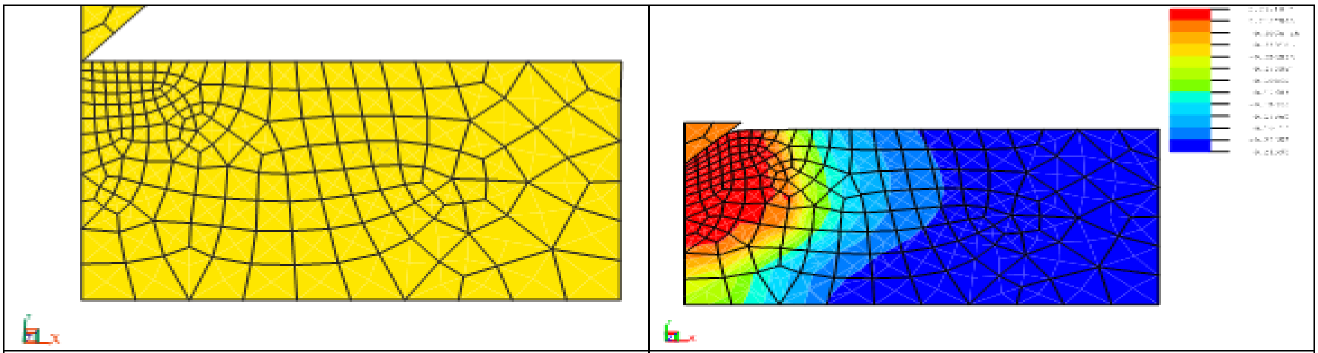
The algorithm automatically generates mask image without user interaction that contains only elements regions to be filled with various colours as the load as shown [9].



The initial mesh of the cone indentation.	Final results for the deformed mesh.

Figure [9]:- Deformed mesh with contours the results obtained from ELFEN Software.

IV. CONCLUSION

Indentation hardness measurements have been carried out over a wide range of strain rates and cone angles. The material properties were thereby characterised in terms of elastic and viscous parameters. The range of indentation speeds used covers nearly three decades, but by analysing the stress-relaxation phase the range of shear rates was extended to almost six decades, and an estimate of the elastic modulus was obtained. A distinct procedure was used to interpret the experiments, in which the material is regarded as incompressible, so its elastic behaviour is characterised by the Young's modulus *E*. The viscoplastic behaviour was allowed to take an arbitrary form, but the data are well represented by a power law, with index *n*, and consistency factor *k*. The model is based on incorporating the elastic and viscous elements in series, together with some simple geometrical relations.

Visco-elastic behaviour is found in soft-solids, which respond to an applied stress by both recoverable and permanent deformations, which are time dependent. Macroscopic continuum models are used to describe the Visco-elastic behaviour of soft solids. During the relaxation process, the energy loss during a cycle was maximum at different velocities of loading. Indentation hardness measurements have been carried out over a wide range of strain rates and cone angles. The material properties were thereby characterised in terms of elastic and viscous parameters. The range of indentation speeds used covers nearly three decades, but by analysing the stress-relaxation phase the range of shear rates was extended to almost six decades, and an estimate of the elastic modulus was obtained. A distinct procedure was used to interpret the experiments, in which the material is regarded as incompressible, so its elastic behaviour is characterised by the Young's modulus *E*. The Visco-plastic behaviour was allowed to take an arbitrary form, but the data are well represented by a power law, with index *n*, and consistency factor *k*. The model is based on incorporating the elastic and viscous elements in series, together with some simple geometrical relations. It may be concluded that good first order, and indeed in some cases highly accurate, estimates of the mechanical properties of soft-solids may be abstracted from indentation measurements even at rather small levels of indentation. In order to characterise different materials or to validate the model for another material, we may get reasonable material properties in qualitative form.

V. ACKNOWLEDGMENT

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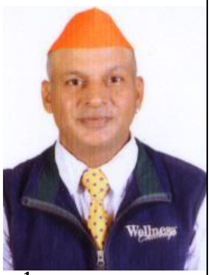 [1]**Asst. PROF. Dharmendra C. KOTHARI**	Qualified to PhD, MSc in Chemical Science, Engineering & Technology with 10 years experience in Research & Development, 5 years in Teaching & 10 years of International Industrial experience. Achieved to maintain good staff relations particularly in respect to working environment, health & safety, minimising waste and ensuring quality standards. Published various technical and non-technical articles at different CONGRESS. Extensively travelled around world.	 [2] PROF **Paul F. LUCKHAM**	Professor of Particle Technology PhD in Physical Chemistry, University of Bristol (1980). My principle area of research is the interactions between particle and another particle or surface is then determined. The bulk properties of the system include rheology and more recently structural determination using various scattering techniques. Like to play SQUASH regularly at Imperial College SQUASH indoor ground.