Nonlinear Rheological Modeling of Asphalt Using White-Metzner Model with Structural Parameter Variation Based Asphaltene Structural Build-up and Breakage

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Abstract:
Rheological behavior of asphalt is strongly affected by loading conditions, temperature and environment. One of the main challenges in understanding the rheology of asphalt is to relate the chemical constituents and the micro-structure of asphalt on one hand to its rheological behavior on the other hand. In this work, nonlinear rheological behaviour of asphalt was investigated using a structural rheological model. A first order kinetic equation to describe structural changes in asphalt has been incorporated with the nonlinear rheological model of White- Metzner. The resulting set of governing equations was solved numerically to describe the rheology of asphalts. Different modes of rheological testing and asphalts with different compositions were considered. An analysis and comparison of model behaviour with experimental data from the literature is carried out in both stress growth at constant shear rate and oscillatory shear modes. A strategy is proposed for the estimation and tuning of the model parameters based on available experimental data and literature. Qualitatively, the model can capture the rheological behaviour of non-Newtonian fluids such as asphalt under different modes of rheological testing. Quantitative analysis from this work shows that the model describes the rheological behaviour of asphalt for the temperature range of 20 – 60°C. It is demonstrated that a single set of equations tuned with the steady shear experimental data can be used to predict the nonlinear rheological behaviour of asphalts. In addition, it is shown that the model parameters can be related to the chemical composition of asphalts.

Zusammenfassung:
Das rheologische Verhalten von Asphalt ist stark von den Beanspruchungsbedingungen, der Temperatur und der Umwelt beeinflusst. Eines der größten Herausforderungen der Asphaltrheologie ist die Verknüpfung der chemischen Zusammensetzung und der Mikro-Struktur des Asphalts auf der einen Seite und sein rheologisches Verhalten auf der anderen Seite. Eine Gleichung erster Ordnung, welche die Veränderung der Struktur in Asphalt beschreibt, kann mit dem nicht linearen rheologischen Modell von White-Metzner verbunden werden. Die Gleichungssysteme wurden numerisch gelöst, um die Rheologie von Asphalt zu beschreiben. Asphalte unterschiedlicher Zusammensetzung wurden durch verschiedene rheologische Experimente charakterisiert. Analyse und Vergleich vom Modelverhalten mit den experimentellen Daten aus der Literatur wurden bezüglich Belastungsentwicklungen bei konstanter Schergeschwindigkeit und bei oszillierenden Scherarten durchgeführt. Eine Strategie zur Beurteilung und Verbesserung der Modelparameter basierend auf vorhandenen experimentellen Daten und Literaturwerten kann somit vorgeschlagen werden. Qualitativ kann das Model das rheologische Verhalten von nicht-Newtonschen Flüssigkeiten wie Asphalt bei unterschiedlichen Versuchsbedingungen erfassen. Quantitative Analysen von dieser Arbeit zeigen, dass das Model das rheologische Verhalten von Asphalt in einem Temperaturbereich von 20 – 60°C beschreibt. Es wurde gezeigt, dass ein einzelnes Gleichungssystem, das mit den konstanten Scherexperimenten abgestimmt wurde, zur Vorhersage von nicht linearen rheologischen Verhalten von Asphalt verwendet werden kann. Zusätzlich wurde gezeigt dass die Modelparameter in Beziehung zur chemischen Zusammensetzung des Asphalts gebracht werden kann.

Résumé:
Le comportement rhéologique de l'asphalte dépend fortement des conditions de son application, de la température et de l'environnement. L'un des principaux défis associé à la compréhension de la rhéologie de l'asphalte est de relier les constituants chimiques et la microstructure de l'asphalte à son comportement rhéologique. Dans ce travail, le comportement rhéologique non linéaire de l'asphalte a été étudié en utilisant un modèle structural. Une équation cinétique du premier ordre pour décrire les changements structuraux de l'asphalte a été incorporée au modèle rhéologique non linéaire de White-Metzner. L'ensemble d'équations résultant de cette approche a été résolu numériquement afin de décrire la rhéologie des asphaltes. Différents types de tests rhéologiques ont été considérés ainsi que différentes compositions d'asphaltes. Une analyse et une comparaison du comportement du modèle avec les données expérimentales trouvées dans la littérature ont été entreprises pour la montée en contrainte à vitesse de cisaillement constant et pour le test de cisaillement dynamique oscillatoire. Une stratégie basée sur les données expérimentales disponibles et sur la littérature est proposée pour une estimation et un contrôle des paramètres du modèle. Qualitativement, le modèle est capable de capturer le comportement rhéologique de fluides non Newtoniens tels que l'asphalte soumis à différents

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model incorporating structural parameter in the nonlinear White-Metzner model was considered. The model accounts for the effect of composition of asphalt on its rheological properties by considering the structural changes that occur with flow. From the qualitative analysis, it was observed that the model exhibits many important characteristics of a general non-Newtonian fluid, and hence the results obtained can be extended to other complex fluids with suitable modifications. The White-Metzner model, with structure dependent relaxation time and viscosity, does not have a linear viscoelastic limit. Hence, the results of the present model were only compared for qualitative trends in oscillatory testing. The experimental data from the literature on stress growth and normal stress difference in different grades of asphalt were compared with the model results. The variation of the parameters was observed to be consistent with the asphaltene contents of the asphalts. Cyclic shear tests with rest periods can also be modelled using the present model.

Overall, the model incorporates the effects of composition (structure), shear rate and temperature for explaining the complex rheological properties of asphalt, giving a qualitative approach of modelling rheology using microstructural methods. The results of the present model demonstrate that detailed nonlinear rheological experimental data on several asphalts and physico-chemical characterization of the same asphalts will lead to better quantitative predictive models and understanding of the nonlinear rheology of asphalt.

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