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Improving the rheometry of rubberized bitumen: experimental and computation fluid dynamics studies

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HIGHLIGHTS

- Background on viscosity measurements and CFD studies on mixing complex fluids.
- Laboratory tests provide visual proves of enhanced mixing efficiency with DHI.
- CFD models validated the empirical calibration with single phase fluids.
- CFD simulations compared well with experimental results.
- CFD clarifies reasons behind the improved rheometry of complex fluids with DHI.

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ABSTRACT

Multi-phase materials are common in several fields of engineering and rheological measurements are intensively adopted for their development and quality control. Unfortunately, due to the complexity of these materials, accurate measurements can be challenging. This is the case of bitumen-rubber blends used in civil engineering as binders for several applications such as asphalt concrete for road pavements but recently also for roofing membranes. These materials can be considered as heterogeneous blends of fluid and particles with different densities. Due to this nature the two components tends to separate and this phenomenon can be enhanced with inappropriate design and mixing. This is the reason behind the need of efficient dispersion and distribution during their manufacturing and it also explains while real-time viscosity measurements could provide misleading results. To overcome this problem, in a previous research effort, a Dual Helical Impeller (DHI) for a Brookfield viscometer was specifically designed, calibrated and manufactured. The DHI showed to provide a more stable trend of measurements and these were identified as being "more realistic" when compared with those obtained with standard concentric cylinder testing geometries, over a wide range of viscosities. However, a fundamental understanding of the reasons behind this improvement is lacking and this paper aims at filling these gaps. Hence, in this study a tailored experimental programme resembling the bitumen-rubber system together with a bespoke Computational Fluid Dynamics (CFD) model are used to provide insights into DHI applicability to perform viscosity measurements with multiphase fluids as well as to validate its empirical calibration procedure. A qualitative comparison between the laboratory results and CFD simulations proved encouraging and this was enhanced with quantitative estimations of the mixing efficiency of both systems. The results proved that CFD model is capable of simulating these systems and the obtained simulations gave insights into the flow fields created by the DHI. It is now clear that DHI uses its inner screw to create a vertical dragging of particles within a fluid of lower density, while the outer screw transports the suspended particles down. This induced flow helps keeping the test sample less heterogeneous and this in turns allows recording more stable viscosity measurements.

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1. Introduction

Rheological properties and their measurement are of paramount importance for the development, performance and applications of products across a wide range of industries. More

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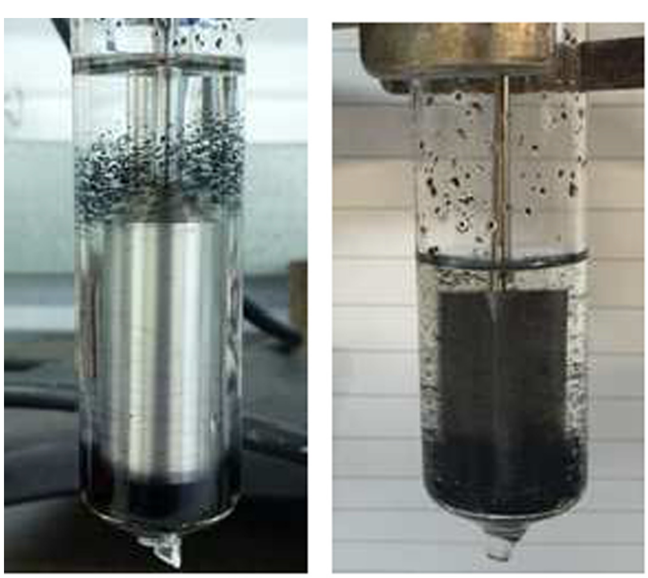
specifically, bitumen technologists are used to monitoring the high-temperature viscosity of these binders (in the range 100–200 °C) during manufacture, compaction and quality control [6]. Furthermore, the use of bituminous binders modified with polymers is a common practice used to enhance the performance of road pavements and roofing membranes. Nevertheless, measurements of their viscosity/rheology can be challenging due to the often heterogeneous structure of these complex systems, especially if these materials suffer from phase stratification within the time frame of typical viscosity measurements, as in the case of rubberized bitumen [7].

A common instrument used to perform these measurements is the rotational viscometer, typically by means of the coaxial cylinder testing geometry. This setup consists of a static outer cylindrical vessel into which is poured the test fluid and a concentric cylinder (spindle) which is inserted and then rotated at a given angular velocity so that the applied torque can be measured. A standard cylindrical spindle that can be used in the Brookfield viscometer is shown in Fig. 1(a). This arrangement, however, is incapable of providing reliable viscosity measurements of multiphase systems containing suspended particles with a density different to that of the continuous phase [19]. In fact, when standard cylindrical spindles are used to measure viscosity of fluids with suspended solid particles, if the two phases have very different densities the higher density component will tend to settle to the bottom during the measurement rendering the data acquired of very little use.

These type of scenarios are encountered in many type of complex systems such as: chocolate, plastic, rubber, ceramics, food, cosmetics, detergents, paints, glazings, lubricants, inks, adhesives and sealants [12,13,17,20,27]. Rotational viscometers (Brookfield in this case) are provided with supplementary spindle designs that help in some of these cases. For instance, a vane spindle allows performing measurements with paste-like materials, gels, and fluids where suspended solids migrate away from the measurement surface of standard spindles. Furthermore, the Brookfield Helipath Stand is designed to slowly lower or raise a Brookfield T-bar spindle so that it describes a helical path through the test sample. Nevertheless, these accessories are not designed to minimize the heterogeneity of multiphase blends, especially when that sample has the tendency to stratify due to phase density differences.



(a) (b)

Fig. 1. Visualisation of the phase separation during viscosity measurements of suspensions for (a) the SC4-27 spindle and (b) a vane spindle.

Fig. 1(b) shows the inefficiency of the vane spindle when used for viscosity measurements of suspensions. In an effort to improve the rheometry of these scenarios by overcoming sample's phase separation issues, Lo Presti et al. [19] successfully designed, manufactured and tested a prototype of a Dual Helical Impeller (DHI) for Brookfield Rotational Viscometers (Fig. 2, right). Experimental studies were carried out to evaluate whether the DHI is able to improve the degree of homogenisation of high viscous fluids in order to obtain more realistic viscosity measurements of a blend of fluid with suspended particles. In comparison to the Brookfield standard, cylindrical geometry (spindle SC4-27), the DHI always predicted a different "apparent" viscosity (see Section 1.1 for definition). This result was explained by the capability of the DHI to create what have been likened to convective flows as opposed to the axisymmetric swirling flow induced by the standard SC4-27 spindle.

Rubberised bitumen is a complex system of the type described above, where the bitumen is the fluid matrix and the particles are the swollen tyre rubber crumbs. These two components have a moderate difference in densities and for this reason the phase separation could not possibly occur within standard rotational viscosity measurements at 135 °C. However if long equilibrium times are required, rather than high percentage of modifier, higher testing temperatures and high spindle speeds, the phase separation issue is very likely to occur, especially for a wet process-high viscosity binder. Furthermore, this issue is particularly relevant within the product development of rubberised binder with rotational viscometer used as a mixing device offering a continuous monitoring of the viscosity [7,26]. In fact, in this scenario the processing is made at high rotational speed and at a temperature where the bitumen viscosity is quite low (180 °C) and rubber particles are not swollen yet and tend to agglomerate in layers, mainly at the bottom of the tube. The DHI presented above was developed [19] specifically to solve this type of issue within low-shear development of rubberised bitumen. This research showed that carrying out measurements of rubberised bitumen with the DHI at 135 °C reduces the initial effort needed to accelerate a bitumen-rubber blend from a stationary position and provide more stable viscosity readings. This allowed the authors to declare that this type of measurements were "more realistic" (Fig. 3). However, despite these satisfying results, the mechanisms behind the enhanced mixing efficiency provided by the DHI and the actual level of enhancement were not clear and this present study aims to clarify.

In order to provide the reader with further information for the interpretation of the presented results and conclusions, the following sections will provide a background on measuring viscosity by means of a rotational viscometer and a brief review on the use of CFD for modelling mixing of complex fluids.

1.1. Background – Measuring viscosity by means of a rotational viscometer

For the rheological measurement of materials by means of a rotational viscometer with a coaxial cylindrical geometry, there is a theoretical basis for the calculation of the viscosity. Consider a cylinder of radius R_s and length, L_s, rotating at an angular velocity, ω, inside a stationary cylinder of radius, R_c. The shear rate at the surface of the spindle, $\dot{\gamma}$, is

$$\dot{\gamma} = \frac{2\omega R_c^2}{R_c^2 - R_s^2}, \tag{1}$$

and the shear stress, τ, is

$$\tau = \frac{T}{2\pi R_s^2 L}, \tag{2}$$