The Particle-Matrix model: limitations and further improvements needed

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ABSTRACT

According to the Particle-Matrix Model (PMM) philosophy, the workability of concrete depends on the properties of two phases and the volumetric ratio between them: the fluid matrix phase (≤ 0.125 mm) and the solid particle phase (> 0.125 mm). The model has been successfully applied to predict concrete workability for different types of concrete, but has also indicated that some potential cases exist when its application is limited. The paper presents recent studies on improving the method by analysing how the PMM one-point flow parameter λ_Q can be expressed by rheological models (Bingham and Herschel-Bulkley).

Key words: Rheology, matrix, FlowCyl, yield stress, plastic viscosity.

1. INTRODUCTION AND BACKGROUND

1.1. The Particle-Matrix Model (PMM)

To simplify the practical modelling of the effect of different concrete part materials on concrete workability, Ernst Mørtsell developed a material model called the Particle-Matrix Model (PMM) as a part of his doctoral thesis at the Norwegian University of Science and Technology in 1996 [1]. According to the PMM philosophy, the workability of concrete depends on the properties of two phases: the fluid matrix phase (≤ 0.125 mm) and the solid particle phase (> 0.125 mm), *i.e.* a liquid phase (matrix) and a friction material (particles):

- The lubricating concrete **matrix phase** is defined as consisting of all fluids (water, admixtures, *etc.*) and particles (binder, filler, fines from the aggregate, etc.) ≤ 0.125 mm. This definition was chosen to acknowledge that very small particles will mainly affect properties of the fluid matrix phase due to their surface properties whereas gravity plays a small role when the particles are dispersed in a fluid. It is therefore natural to let the small particles and entrained air by definition belong to the matrix;

- The **particle phase** dispersed in the lubricating matrix is defined as all the particles in concrete > 0.125 mm, which are in general the aggregate particles. The effect of these particles on concrete flow is mainly governed by density, shape and size distribution.

In practice, the PMM approach is based on a single-parameter characterisation of each phase, *i.e.* the flow resistance ratio of the matrix and the air voids modulus of the particles:

- The **flow resistance ratio** (λ_Q) is a one-point workability parameter determined in the FlowCyl test, which is a simple flow viscometer – a modification of the Marsh Cone test apparatus (see in [1] and [2] for details);
- The **air voids modulus** (H_m) is based on the air voids space ratio of the fine (0.125-4 mm) and coarse (> 4 mm) portions of the particle system. Details on the determination of this parameter can be found in [1] and [2].

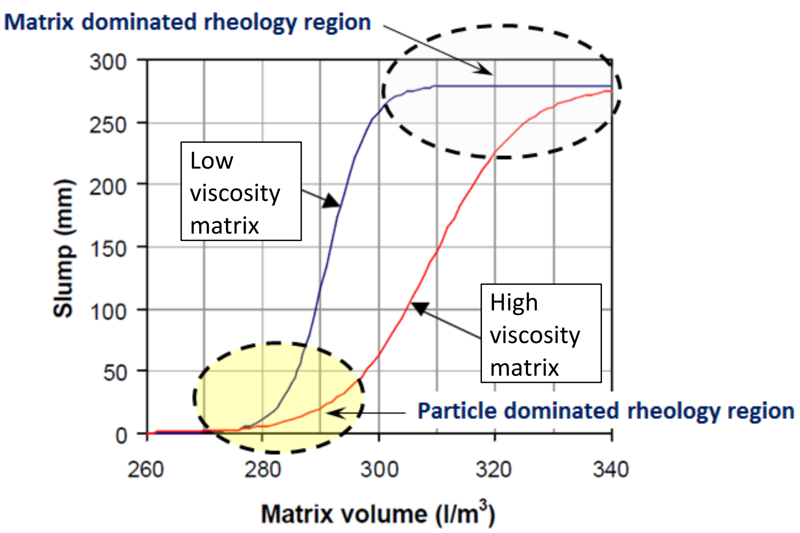

Figure 1: Slump value as a function of matrix volume for two concretes based on the same particle system, but different matrix compositions [3].

Mørtsell [1] demonstrated that, when the properties of the two phases are determined in this simple way, the workability of the concrete depends on these properties and the volume ratio between them. The workability of the concrete as characterised by the slump and flow measure (or another rheological parameter) is then finally expressed as a function of the flow resistance ratio of the matrix, the air voids modulus of the particle phase, and the volume fraction of the matrix. Mørtsell [1] chose the hyperbolic tangent (tanh) function as a basis for his workability function, which then resembles an “S-shape” in matrix volume vs. slump (also slump-flow, yield stress or any other workability parameter) coordinates (Figure 1). The syntax and use of these functions are described in detail in [1] and [2].

1.2. Current recognised limitations of the PMM

Ernst Mørtsell showed in his doctoral thesis [1] that the PMM is applicable for conventional (vibrated) normal-weight Norwegian concrete mixes with consistencies of up to about 250 mm of slump, based on natural sand and matrices with relatively low fines content. Later, Smeplass [2] demonstrated that the PMM is also applicable to light-weight aggregate concrete (LWAC) based on natural sand and coarse lightweight aggregates, *i.e.* no modifications are required to handle the reduced density of the LWAC.

Smeplass and Mørtsell [6] investigated the applicability of the PMM to self-compacting concrete (SCC). Their study included both high-strength SCC based on high-strength ordinary Portland cement (OPC) without additional fillers and low-strength SCC based on regular OPC with substantial filler additions. The hypothesis for the study was that the PMM would work even better with the matrix-dominated SCC mixes, and that the workability of the SCC mixes tested would be a unique function of the flow resistance ratio of the matrix and the volume of the matrix according to the PMM. However, the results revealed that, to achieve a slump-flow measurement of approx. 650 mm, the necessary matrix volume was 40-80 l/m^3 lower for the mixes based on the high-strength OPC than for the regular OPC mixes, when all other parameters (including λ_Q values) were comparable. In other words, the researchers did not find a simple correlation between the flow resistance ratio of the matrix (λ_Q) and the workability of the SCC. Smeplass and Mørtsell [6] proposed that the problem was in the measuring device used for the characterisation of the matrix, *i.e.* the FlowCyl. They suggested that the problem with the FlowCyl was that it gives only a single value, whereas the matrix is at least a two-parameter fluid that needs to be more fundamentally described with a yield value (τ_0) and plastic viscosity (μ).

2. USING FLOW-CYL AS ONE-PARAMETER CHARACTERISATION OF MATRIX RHEOLOGY: RECENT FINDINGS

The reviewed previous research in Subsection 1.2 above raises a very important question: why the FlowCyl test on matrices does not reflect the differences in concrete workability for all types of concrete, even when the particle phase is kept constant? Recently, two new studies with the goal of answering this question have been conducted by Cepuritis, et al. [5] and [6]. The studies [5], [6] included development of a numerical model of the FlowCyl, as well as a series of simulations of the FlowCyl test aimed at analysing the effect of the yield shear stress (according to the Bingham and Herschel-Bulkley (H-B) material models) on the flow resistance ratio λ_Q. The numerical results were found to be in good agreement with experimental results on rheology measurements of approx. 100 cement pastes including crushed aggregate fines (≤ 125 µm).

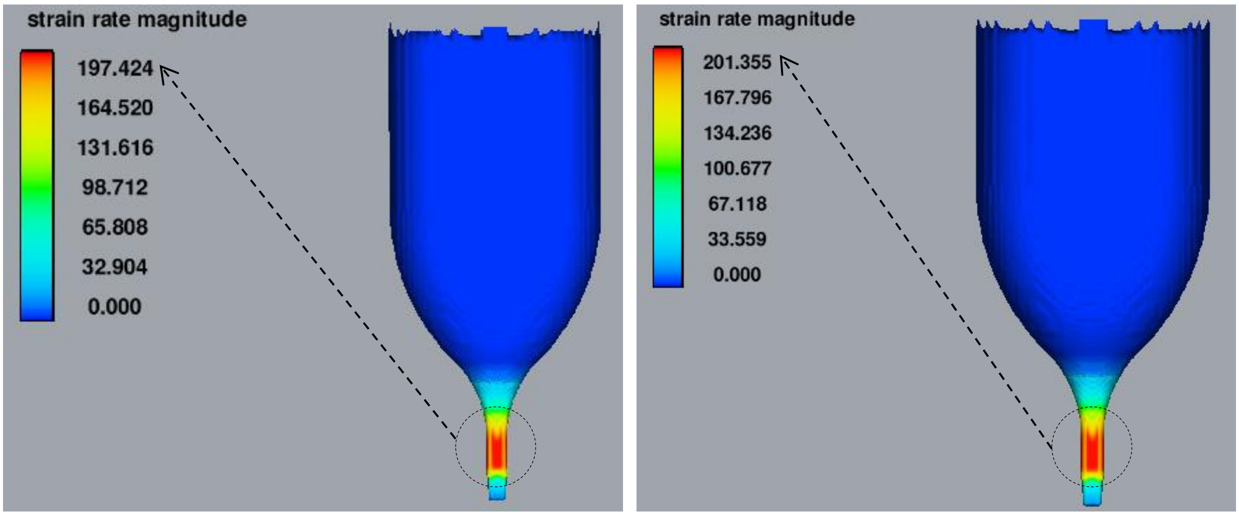

Figure 2: A figure of the shear rate magnitude in the FlowCyl for a cement paste after 25 seconds: left) Bingham material model right) H-B model [5].

Results of the investigation in [5] and [6] have revealed that that the plastic viscosity dominates the flow resistance ratio. The reason for the dominance is owed to the fact that the cement paste experiences high shear rates (approx. 200 1/s) at the outlet, see Figure 2, which is a region of the FlowCyl that has a great influence on the flow rate and thereby the flow resistance ratio.

3. CONCLUDING REMARKS: FURTHER IMPROVEMENTS NEEDED

As a result of the findings reported in Section 2, one can state that the flow resistance ratio can be used as a one parameter characterization of the matrix rheology, when utilized to predict the flow behaviour of concrete, such as in the PPM model, as long as the shear rates that the cement paste undergoes during the concrete flow are high. Moreover, the PMM shall only work when comparing mixes with similar yield stress of the matrix phase, as the yield stress of the matrix is not represented by the flow resistance ratio value. In more practical terms this would mean that PMM should probably work fine when the dosage of the superplasticiser (SP) is relatively high and the yield stress of the matrix phase has been reduced to be negligible. PMM should also work when comparing mixes where the yield stress of the matrices is the same, which would then imply similar dosages of the SP and use of binders/ fines ≤ 0.125 mm that have similar interaction with the SP molecules.

The further proposed improvements for the PMM, based on the discussion presented here, would imply finding a way so that the flow-resistance ratio also includes a contribution from the yield stress of the matrix. There are two directions for this chosen in a work in the MiKS (Mikroproporsjonering med Knust Sand (Norwegian for Micro-proportioning with Crushed Sand)) project currently in progress at NTNU. These are: supplementing the flow resistance ratio value with a mini-cone spread measurement to capture the yield-stress effect or changing the geometry of the FlowCyl so that the mass flux out of the FlowCyl and thereby the flow resistance ratio measurement would also include a contribution of the yield-stress of the matrix.

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