Extrusion Criterion for Firm Cement-based Materials

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Abstract:
The stability of the flow induced by the extrusion forming process of a cement based material is largely influenced by the relative migration between the lubricating liquid phase and the granular skeleton. In the present work, we propose linking rheological concepts and soil mechanics (consolidation theory, Darcy's law) to reach a simple criterion which predicts the extrusion ability of a mortar. Extrusion tests on studied mortar are performed at different ram velocities for criterion validation.

Zusammenfassung:
Die Extrusionsprozessstabilität von zementbasierten Materialien ist in hohem Maß von der Partikelmigration zwischen der schmierenden flüssigen Phase und des Granulats bestimmt. In der vorgestellten Arbeit sind rheologische und bodenmechanische Ansätze verknüpft (Verdichtungstheorie, Darcys Gesetz), um ein einfaches Kriterium zur Beschreibung des Extrusionsprozesses von Mörtel vorzustellen. Zur Parametervalidierung sind Extrusionstests mit verschiedenen Vorschubgeschwindigkeiten des Extrusionsstempels durchgeführt worden.

Résumé:
La stabilité de l'écoulement du procédé de mise en forme par extrusion de matériaux à base cimentaire est largement influencée par la migration relative entre la phase liquide et le squelette granulaire. Dans ce travail, nous proposons de lier les concepts de rhéologie et de mécanique des sols (théorie de la consolidation, loi de Darcy) pour définir un critère simple qui prédit l'aptitude à l'extrusion d'un mortier. Des essais d'extrusion à différentes vitesses de piston sont ensuite réalisés pour valider le critère.

Key words: drainage, extrusion, filtration, mortar

1 INTRODUCTION TO TECHNICAL FIBRE SUSPENSIONS

Extrusion is a common forming process for a wide range of materials (food, polymer, clay, metal). For perfect and homogeneous plastic materials, the extrusion stress and the flow typology have been well described, as they are the subject of numerous studies [1–3]. For cement-based materials, extrusion could be a high productivity forming process which is expected to improve the mechanical properties of the formed material (limiting the water content and voids ratio in comparison with precast concretes) [4–6]. Mu et al. [4], Peled and Shah [5] or Zhou et al. [6] showed that the extrusion process is able to form hardened cement composites with higher mechanical properties than the traditional casting process. Those studies focused on cement-based pastes with admixtures, such as viscosity agents or plasticizers, reinforced with different types of fibres. Such engineered cement composites present optimized mechanical properties. But, the cost is very high and the forming of such a paste is often penalized by excessive fluidity of the mix. Cement-based materials behave as visco-plastic materials which are commonly modelled by a Bingham law as proposed by Roussel [7], De Larrard et al. [8] or Wallevick [9]. Such mixes are characterized by a value of yield stress higher than 1 kPa. For the extrusion of such materials, yield stress has to be high enough for the material to retain its shape when leaving the extruder as proposed by Toutou et al. [10, 11]. The common usable yield stress value is evaluated at 20 kPa. Consequently, there is not yet a common industrial-scale way to form coarse cement-based materials with an acceptable rate of admixture. As mentioned by Roussel

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Equations 9 and 10 are expected to correctly predict the evolution of yield stress during extrusion.

3.2 EXPERIMENTAL DEVICE AND TESTS

An axisymetrical ram extruder is used for tests. Ram (D = 43.3 mm) and die (d = 15 mm) present a circular cross section. For the present study, the die consists in an abrupt contraction (angle of the die entry equal to 90°). The sample mass is equal to 600 g. Tests are performed in the same geometry conditions as in reference [14]. In this work, authors highlight the evolution of material yield stress during extrusion. The author obtained a measurement grid of the local surface hardness of the paste. This measurement was shown to be proportional to the material yield stress.

The idea of this test is to compare those experimental yield stress values taken from Perrot [14] with computed value obtained with the modelling presented in Section 3.1. More precisely, we compare the evolution of the average yield stress in the 10 mm-layer located at the ram to the computed yield stress. The experimental average yield stress is obtained by averaging the yield stress values located at a distance of 5 mm from the ram. This averaged value is assumed to be representative of the mortar of the layer which is assumed to be homogeneous in the modelling. The two modelling developed in section 3.1 by Equations 9 and 10 are used in the given experimental conditions (i.e. with and without taking into account permeability evolution). A numerical convergence is obtained for a step of void ratio Δe of 10^{-4}. For higher value of Δe (i.e. 10^{-3}), the computation does not converge.

Figure 5 shows that the most influencing parameter to describe the yield stress evolution is the time of extrusion. One can see that for the two studied velocities, the material yield stress vs. the extrusion time can be plotted on a same curve. This is in correlation with the assumptions used: the material is not viscous and the top of the extruder can be considered as an oedometer. Experimental and analytical data are in quite good agreement with and without taking into account permeability evolution (Figure 5). It means that the permeability evolution has only little influence on yield stress variation (20 % of difference at 40 seconds). However, this is not negligible and taking the permeability evolution into account allows for better correlation of experimental data.

To find a parameter reflecting the consolidation effect on rheological behaviour, we decided here to consider the time required to double the initial yield stress in the mortar ($t_{K(t) = 2K(t = 0)}$). At rest, without any solicitations, this time is about 60 minutes, when regarding only aging effects (Figure 1). During the extrusion process, the time $t_{K(t) = 2K(t = 0)}$ in the studied layer (near the ram) is equal to 30 seconds (Figure 5). The evolution of the yield stress during extrusion is mostly affected by the consolidation process due to fluid migration. The aging effects are negligible for the duration of this test.

3.3 PROPOSED CRITERION

The proposed criterion consists of computing the ratio of the duration of extrusion (material length over ram velocity V) over the time needed to double the initial yield stress value (noted $t_{K(t) = 2K(t = 0)}$). Such a value can be easily computed using the previous rheological and hydromechanical analysis.

$$n_{ext} = \frac{t_{extrusion}}{t_{K(t)=2.K(t=0)}} \tag{11}$$

If the criterion ratio next tends to 0, the consolidation velocity is negligible compared to the extrusion velocity. As a result, the material remains homogeneous and extrusion continues. Inversely, if n_{ext} increases, consolidation has enough time to affect material rheology and thus extrusion load (Figure 6). In consequence, the smallest value of n_{ext} has to be searched and used. Such a value is a good index for the extrusion ability of the material as it directly conveys the ability of the material to remain homogeneous during extrusion. Note that the time required to finish the extrusion is not sufficient enough to explain the blockage only with the hardening phenomenon described in Figure 2.

4 CONCLUSION

The proposed approach and modelling enable one to define a criterion identifying multiphase flow during mortar extrusion. The kinetics of rheological evolution (yield stress increase) is identified and a non-dimensional number is defined as the ratio of the time of extrusion over the time needed to double the yield stress of the material in the ram area. This number predicts if the

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material will remain homogeneous and if the extrusion load will increase. The experimental data highlight the small effect of aging on the yield stress evolution of the mortar according to the yielding due to the consolidation effect.

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