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Full Length Article

A multiphysics-viscoplastic cap model for simulating blast response of cemented tailings backfill

Gongda Lu, Mamadou Fall*, Liang Cui

Civil Engineering Department, University of Ottawa, Ottawa, ON, Canada

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ABSTRACT

Although a large number of previous researches have significantly contributed to the understanding of the quasi-static mechanical behavior of cemented tailings backfill, an evolutive porous medium used in underground mine cavities, very few efforts have been made to improve the knowledge on its response under sudden dynamic loading during the curing process. In fact, there is a great need for such information given that cemented backfill structures are often subjected to blast loadings due to mine exploitations. In this study, a coupled thermo-hydro-mechanical-chemical (THMC)-viscoplastic cap model is developed to describe the behavior of cementing mine backfill material under blast loading. A THMC model for cemented backfill is adopted to evaluate its behavior and evolution of its properties in curing processes with coupled thermal, hydraulic, mechanical and chemical factors. Then, the model is coupled to a Perzyna type of viscoplastic model with a modified smooth surface cap envelope and a variable bulk modulus, in order to reasonably capture the nonlinear and rate-dependent behaviors of the cemented tailings backfill under blast loading. All of the parameters required for the variable-modulus viscoplastic cap model were obtained by applying the THMC model to reproducing evolution of cemented paste backfill (CPB) properties in the curing process. Thus, the behavior of hydrating cemented backfill under high-rate impacts can be evaluated under any curing time of concern. The validation results of the proposed model indicate a good agreement between the experimental and the simulated results. The authors believe that the proposed model will contribute to a better understanding of the performance of hydrating cemented backfill under blasting, and also to practical risk management of backfill structures associated with such a dynamic condition.

1. Introduction

Cemented hydraulic and paste backfills represent two main types of cemented tailings backfill technologies in nowadays mining industry for tailings disposal and ground control. Due to the superior mechanical performance per unit of cement consumption, cemented paste backfill (CPB) has become increasingly popular (Landriault, 2001; Fall et al., 2010a,b). As a cementitious evolutive geotechnical material, CPB is a mixture of dewatered mine tailings (fine aggregates), binder additives (e.g. Portland cement, fly ash, slag), and water. Although the majority of research focus has been placed on the quasi-static mechanical behavior of CPB (Kesimal et al., 2005; Klein and Simon, 2006; Yilmaz et al., 2009; Abdul-Hussain and Fall, 2012; Ghirian and Fall, 2013, 2014), knowledge of its dynamic response is equally important, as field backfills are often subjected to dynamic excitations such as mining blasts, rockbursts, as well as earthquake loadings.

Unlike any other natural porous medium (natural soil, rock, etc.), cemented backfill has material properties that are very time-dependent, mainly due to the cement hydration process. Thus, its mechanical response will be significantly influenced by such a chemical process. To evaluate the response of hydrating CPB under blast loading, a coupled chemo-viscoplastic cap model has been developed (Lu and Fall, 2016) and validated against experiments on various types of cementitious materials. Specifically, in this model, a modified Perzyna viscoplastic formulation was employed to represent the rate-dependence in the behavior of cemented tailings backfill under blast loading. A modified smooth surface cap model was then developed to delineate the failure of the material, and can also control the material dilation and account for the hysteresis as well as full compaction effects. Then, the viscoplastic formulation

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* Corresponding author. Fax: +1 613 562 5173.
E-mail address: mfall@uottawa.ca (M. Fall).

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was further enhanced with a variable bulk modulus derived from a Mie–Gruneisen equation of state (EOS), in order to characterize the nonlinear hydrostatic behavior of cemented backfill subjected to high pressure. In the model, the material properties required for the viscoplastic cap model have been coupled with a chemical model, which captures and quantifies the degree of cement hydration. Thus, the behavior of hydrating cemented backfill under blast loading can be evaluated at any curing time of concern. However, the evolution of material properties of CPB is a function of not only the degree of cement hydration, but also all of the thermal (T), hydraulic (H), mechanical (M) and chemical (C) factors and their interactions to which the CPB is subjected during its curing (Ghirian and Fall, 2013, 2014) (Fig. 1). Thus, the coupled chemo-viscoplastic cap model proposed in Lu and Fall (2016) is not sufficient enough to capture the blast response of CPB when cured under the influence of complex thermo-hydro-mechanical-chemical (THMC) factors.

Moreover, according to Henrych (1979), dry and water-bearing loose materials have distinct behaviors under blast loading. This difference in water content is represented by the maximum volumetric plastic strain (parameter W) in the cap model, which is a measure of the volumetric gas content of the material (Chen and Baladi, 1985). Therefore, W should be a variant in the cement hydration process as the interstitial water is gradually consumed. The same applies to the material density (ρ_0, used in the Mie–Gruneisen EOS) if drainage or evaporation occurs. In contrast, W and ρ_0 have been assumed to be constant in this prototype of the chemo-viscoplastic cap model for cemented tailings backfill (Lu and Fall, 2016). This simplification was appropriate because the CPB samples in Lu and Fall (2016) had been only cured at the early ages, and the volumetric gas contents and densities of those samples should be almost constant according to the analogous experiment in Ghirian and Fall (2013). However, this will not be the case if CPB samples are cured for a longer period of time, and the volumetric gas content and density of CPB would significantly deviate from younger samples at a more mature stage (Ghirian and Fall, 2013). Furthermore, matric suction develops as cement hydration takes place. Most models for porous media (including CPB) under blast loading have neglected the influence of suction. However, this is important for soft cementitious materials such as CPB, as the cement hydration process can generate up to hundreds of kPa of suction (Ghirian and Fall, 2013) due to self-desiccation, which is very large scale compared to both the static and dynamic strengths of CPB which are usually less than 1 MPa and 3 MPa, respectively (Klein and Simon, 2006; Huang et al., 2011; Ghirian and Fall, 2014). Thus, in order to recapture the mechanical response of more mature cemented backfill under blast loading, a chemical model alone would not be sufficient to quantify all of the incorporated (time-evolutive) parameters in the viscoplastic cap model, and a model that can further reproduce the hydraulic process during cement hydration is needed. The same also applies to the thermal and mechanical factors, and they will also affect the evolution of the material properties including W and ρ_0 of CPB. A detailed description on the coupling mechanisms of multiphysics processes that occur during the curing of cemented backfill is presented in Section 2.

Therefore, to describe these multiphysics processes, the coupled THMC model for cemented backfill developed by Cui and Fall (2015) is adopted. By using this THMC model, the evolution of parameters required in the prototype viscoplastic cap model can be obtained with more rational considerations of the influence of the environment and intrinsic ingredients of the backfill itself. Noticeably, there has been no shortage of models for cement-based materials in which at least two components of coupled THMC processes are considered. However, their mechanical components have been developed only to capture the creep (e.g. Cervera et al., 1999a,b; Sercombe et al., 2000; Gawin et al., 2006a,b; Li et al., 2015), shrinkage (Ulm and Coussy, 1995; Gawin et al., 2006a,b; Pichler et al., 2007; Li et al., 2015), cracking (e.g. Zhang et al., 2013; Li et al., 2015), or uniaxial/triaxial compression (e.g. Cui and Fall, 2015) behaviors of cement-based materials under quasi-static conditions, and they cannot evaluate the response of an evolutive cement-based material under transient blast loading. In the remainder of the paper, considerations for the coupled THMC processes and the modeling approach of the present model are briefly outlined. Then, formulations of the coupled THMC model for recapturing the variation of CPB properties are presented, and it is coupled with a viscoplastic cap model to characterize the response of CPB during blast loading. Finally, the developed model is validated against laboratory experiments.

2. Considerations for coupled THMC processes in cemented backfill

The performance of cemented backfill is significantly influenced by complex coupled multiphysics, including thermal (T), hydraulic (H), mechanical (M) and chemical (C) processes (Ghirian and Fall, 2013, 2014). Their interplays are conceptually illustrated in Fig. 1. Therefore, the heat transfer, liquid flow, gas migration, skeleton deformation, binder hydration processes and their mutual coupling effects are taken into account, and their roles in the curing process are elucidated as follows (Dutt et al., 2012; Cui and Fall, 2015; Maheshwar et al., 2015; Verma et al., 2015, 2016; Gautam et al., 2016).

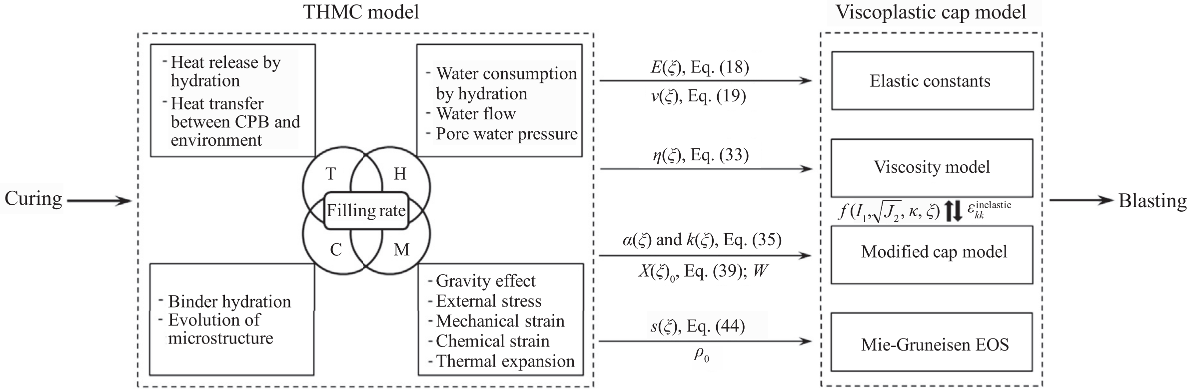

Fig. 1. Component interactions and parameter update in the coupled THMC-viscoplastic cap model (modified from Cui and Fall (2015) and Lu and Fall (2016), where CPB properties $E(\xi)$ and $\nu(\xi)$ stand for the elastic modulus and Poisson's ratio, respectively; $\eta(\xi)$ is the fluidity parameter; $\alpha(\xi)$ and $k(\xi)$ are the Drucker–Prager parameters; $X(\xi)_0$ denotes the initial vertex of the cap yield surface; W indicates the maximum inelastic volumetric strain allowed; ρ_0 is the density; and $s(\xi)$ represents the slope of the shock velocity against the particle velocity curve).