Cold Regions Science and Technology 108 (2014) 10–17

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Predicting the phase composition curve in frozen soils using index properties: A physico-empirical approach

Zhen Liu [a,*], Xiong Yu [b,**]

[a] Department of Civil and Environmental Engineering, Michigan Technological University, United States
[b] Department of Civil Engineering, Case Western Reserve University, United States

ARTICLE INFO

Article history:
Received 13 October 2013
Accepted 8 September 2014
Available online 16 September 2014

Keywords:
Phase composition curve
Frozen soils
Physico-empirical approach
Prediction
Unfrozen water content
Index properties

ABSTRACT

The relationship between unfrozen water content and temperature in frozen soils, which is referred to as the phase composition curve (PCC), is a fundamental relationship in cold regions engineering. In a previous study, the authors succeeded in developing a physical description and a physically-based equation for the PCC, which overcomes the limitations of the existing empirical approaches. Here, the authors propose a physico-empirical approach to predict the parameters in this equation to facilitate the calculation of the PCC in practice. An accurate prediction of the PCC will only need simple soil index properties and one measured data point for constraint. In this approach, the four parameters in the PCC equation are first calculated from soil index properties using accepted formulas. Two selected parameters are then adjusted by a curve fitting process using the measured data point. A criterion was suggested for obtaining the best point. This new approach was implemented using a computer program to automate the process. Validations with data from several soils indicated that the approach offers consistent and accurate predictions of PCCs when used with Zapata's model for plastic soils and with the Mechanistic–Empirical Pavement Design Guide (MEPDG) model for non-plastic soils. This study thus bridges an important gap between the theory and application of PCCs.

1. Introduction

The relationship between unfrozen water content and temperature in frozen soils has been repeatedly confirmed since its first observation in the early 20th century (Buckingham, 1907). In geotechnical engineering, this relationship was extensively studied in terms of phase composition curves (PCCs) in 1960s (Koopmans and Miller, 1966; Williams, 1964). A typical outcome is the considerable number of data published in the First International Permafrost Conference in 1966 (Anderson and Tice, 1972). This relationship has been recognized as fundamental in cold regions engineering due to its essential role as a constitutive relationship between two fundamental quantities in frozen soils, i.e., unfrozen water content and temperature (Anderson and Morgenstern, 1973). The relationship thus links the degree of phase transition to the sub-freezing temperature. As a result, many important parameters in cold regions engineering practice, such as the segregation potential for frost heave (Konrad, 2001), resilient modulus (Bigl and Berg, 1994), and strength (Agergaard and Ingeman-Nielsen, 2012; Akagawa and Nishisato, 2009), can be calculated using PCCs.

Meanwhile, the relationship has also been studied indirectly by soil scientists to obtain the Soil Freezing Characteristic Curve (SFCC), which can be related to the PCC via the Clapeyron equation. The SFCC is the relationship between unfrozen water content and suction in frozen soils. Due to the similar energy relationships in thermal and drying processes (Liu and Yu, 2013; Schofield, 1935), the SFCC is essentially analogous to the Soil Water Characteristic Curve (SWCC) in unsaturated soils. A considerable amount of experimental work has been conducted to explore this similarity (Gardner, 1919; Koopmans and Miller, 1966). Based on this similarity, numerous methods have been suggested for obtaining SWCCs by measuring PCCs (Bittelli et al., 2003; Croney and Coleman, 1961; Schofield, 1935; Spaans and Baker, 1996). Within these studies, the two components of PCC, temperature and unfrozen water content, were usually measured using a thermometer and a liquid water measurement method (e.g., time domain reflectometry, nuclear magnetic resonance, and transmission line), respectively. In more recent studies, PCCs have been measured to obtain other properties of frozen soils, such as the hydraulic conductivity (Arenson et al., 2008; Azmatch et al., 2012).

Despite its long research history and essential role, this relationship has not been studied and applied as intensively as the SWCC in unsaturated soils. One possible reason is that a physical understanding of this relationship had long been absent until recently. As a result, empirical equations were usually used to formulate the PCC. Anderson and Tice (1972) found that the unfrozen water contents of most frozen soils

* Corresponding author. Tel./fax: +1 906 487 1826.
** Corresponding author. Tel.: +1 216 368 6247; fax: +1 216 368 5229.
E-mail addresses: zhenl@mtu.edu (Z. Liu), xxy21@case.edu (X. Yu).

http://dx.doi.org/10.1016/j.coldregions.2014.09.003
0165-232X/

can be conveniently expressed as a function of temperature by a simple power curve. Dillon and Andersland (1966) proposed a prediction equation by incorporating the specific surface area, the Atterberg limits, temperature, the clay mineral type, and a defined activity ratio for soils. Similarly, Anderson and Tice (1972) suggested an equation based on a regression analysis of phase composition data for various soils. This equation predicted that water content was a function of the specific surface area and temperature. All of these equations are empirical and thus can hardly guarantee satisfactory predictions under various conditions. This situation caused the nature of the PCC to remain obscured and the relevant research to seriously lag behind.

In a recent study (Liu and Yu, 2013), the authors succeeded in presenting a physical description for the PCC in frozen soils and, for the first time, obtaining a closed-form physically-based equation for this relationship. The proposed prediction equation was proven to yield excellent fitting results for both PCCs measured by the authors (Fig. 1a) and published data for a variety of soils (Fig. 1b), in a large temperature range (Fig. 1c), and in both freezing and thawing processes (Fig. 1d). In spite of these achievements in advancing the PCC research, one more issue still needs to be addressed to facilitate the application of the PCC in engineering practice: how to predict the PCC using soil properties that can be easily obtained, such as the index properties? To address this knowledge gap, this paper presents a physico-empirical approach to predict PCCs using soil index properties. This method can accurately predict the PCC with only one measured data point. The effort overcomes an important barrier for the application of PCCs due to demanding experimental work, and further develops the theoretical framework into a reliable research and engineering tool.

2. Physico-empirical prediction approach

The physical mechanisms necessary for developing the physico-empirical approach, which were described in detail by Liu and Yu (2013), are briefly introduced here. The existence of the PCC is attributed to two physical mechanisms. The first mechanism is the SFCC (Koopmans and Miller, 1966; Liu et al., 2013; Spaans and Baker, 1996), which establishes a relationship between the suction and unfrozen water content in frozen soils. This relation can be expressed as follows,

$$\psi = \psi(S) \tag{1}$$

where ψ is the soil suction and S is the saturation. S is equivalent to the unfrozen water content in a freezing/thawing process. The second mechanism is described by the Clapeyron equation. This equation predicts that the freezing point of pore water will decrease to somewhat below the freezing point of bulk water due to the presence of suction:

$$T = T_0 \exp\left(\frac{\psi}{-\rho_w L}\right) \tag{2}$$

where T_0 is the freezing point of bulk water (273.15 K), ρ_w is the water density (10^3 kg/m^3), and L is the latent heat of water fusion (3.34×10^5 J/kg). Eq. (2) was obtained based on the original equation (Hansson, 2005; Kay and Groenevelt, 1974) by assuming that the ice pressure is zero, which is more a rule than an exception when ice lenses are absent.

A prediction equation can be obtained based on the aforementioned physical mechanisms. In the previous study (Liu and Yu, 2013), the

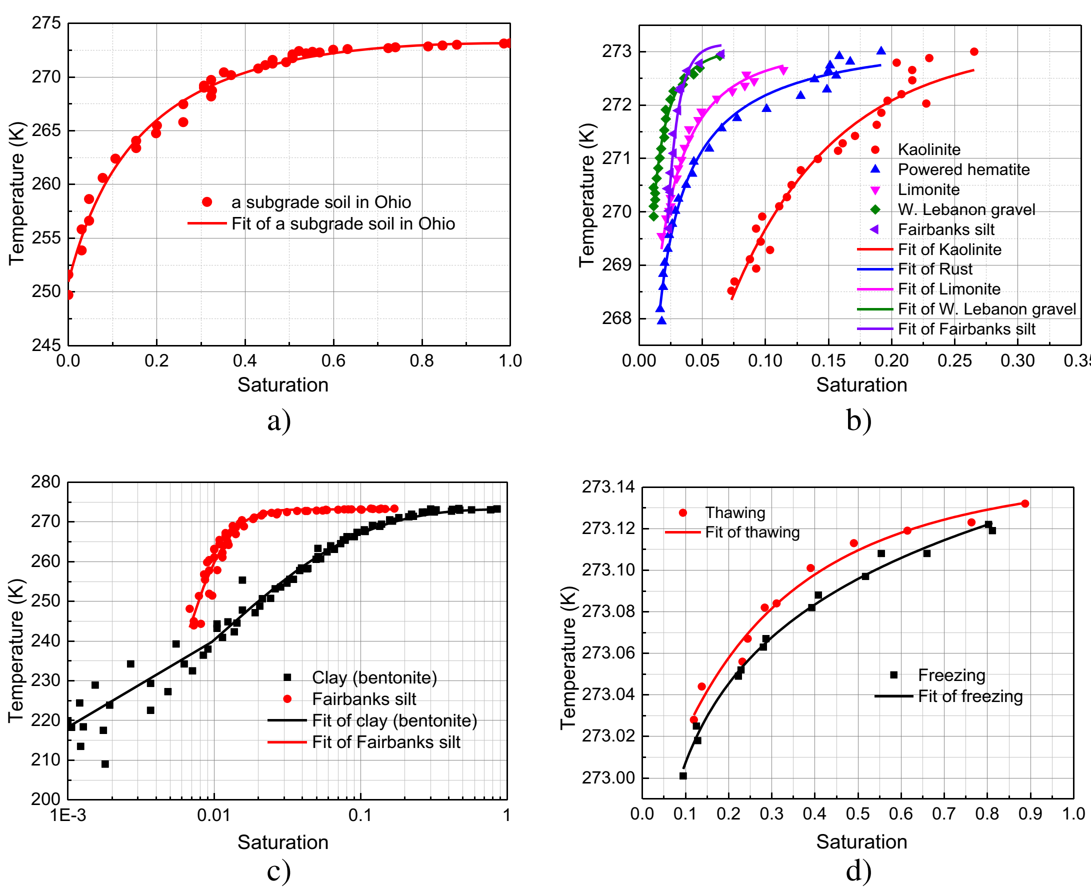

Fig. 1. Validations of the physics-based equation for PCC on various types of soils: a) experimental measured data by the authors; b) published data in literature; c) data in large temperature range; d) freezing and thawing processes (Liu and Yu, 2013).