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A laboratory study of freeze-thaw effects on hydraulic conductivity of kaolin-sand mixtures

Une étude en laboratoire des effets du gel-dégel sur la conductivité hydraulique des mélanges kaolin-sable

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ABSTRACT: Freeze-thaw effects on subgrade soils are of relevance to geotechnical and pavement engineering given the potential for increased road construction in colder regions due to climate change. The freezing and thawing cycles can result in changes to some soil parameters, therefore, for design processes, there is a need to characterize such progressive changes. This paper gives an overview of a laboratory experimental campaign on fine-grained soil and clay-sand mixture soil samples under multiple freezing and thawing cycles. The effects of freezing and thawing conditioning processes on the hydraulic and properties of tested soil samples were investigated. The experimental observations were used to develop transformation models for fine-grained soil and soil mixtures tested.

RÉSUMÉ: Les effets gel-dégel sur les sols de fondation sont importants pour l'ingénierie géotechniques et des chaussées, étant donné le potentiel d'augmentation du volume des routes dans les régions plus froides en raison du changement climatique. Les cycles de gel-dégel peuvent entraîner des modifications de certains paramètres du sol. Par conséquent, dans les processus de conception, il est nécessaire de caractériser ces changements progressifs. Cet article donne un aperçu d'une campagne expérimentale d'essais en laboratoire sur des échantillons de sol à grains fins et de mélanges argile-sable sous plusieurs cycles de gel et de dégel. Les effets d'application de ces cycles sur les propriétés de conductivité hydraulique des échantillons de sol testés ont été étudiés. Les observations expérimentales ont été utilisées pour développer des modèles de transformation pour les sols à grains fins et les mélanges de sols testés.

Keywords: Freeze-thaw effects; soil mixtures; hydraulic conductivity.

1 INTRODUCTION

Hydraulic conductivity (k) is used in many aspects of geotechnical engineering to understand the flow of fluids through soils and has been the subject of much geotechnical research (e.g. Chapuis, 2012). Freeze thaw effects have been reported in various studies showing some effect on intrinsic soil parameters (e.g. Benson and Othman, 1993; Othman and Benson, 1993; Feng et al. 2023).

For many geotechnical applications, including road construction, soils are found as a mixture comprising coarse and fine-grained materials and this can affect k values (e.g. Sivapullaiah et al. 2000). Various forms of empirical equations linking k to soil void ratio (e_s) (e.g. Nagaraj et al. 1993; Sivapullaiah et al. 2000; Vardanega et al. 2017; Feng and Vardanega, 2019) have been reported for fine-grained soils.

The important study of Sivapullaiah et al. (2000) compared k data for different percentages of Bentonite mixed with different sand and silt materials. Sivapullaiah et al. (2000) showed a log(k) versus e_s fitting for the datasets studied: in this paper this assumption will be tested for Kaolin-Leighton Buzzard Sand (K-LB) mixtures subjected to various numbers of freeze-thaw cycles (FTC). This paper will study the influence of FTC on the k function.

2 SAMPLE PREPARATION & TESTING

The kaolin sample preparation followed the procedure outlined in Feng (2022) and Feng et al. (2023). Reconstituted kaolin samples were prepared in a floating cylinder type consolidometer. The samples were then subjected to incrementally to the following vertical pressures, 30 kPa, 60 kPa, 120 kPa and 180 kPa. The first three pressures were continuously applied for 48 hours, and the final pressure for 120 hours. The samples were then allowed to swell for 48 hours after the consolidation phase. The extruded soil samples were sliced horizontally and then cut into oedometer samples of approximately 20mm in height and 75 mm in diameter. These samples had a pre-conditioned e_s of around 1.30. Further details on this testing are detailed in Feng (2022) and Feng et al. (2023).

In this paper, data from tests on Kaolin-sand mixtures are presented. The sand used in the mixtures was Leighton Buzzard Sand with: the sieve sizes through which ten percent (and fifty percent) of the material would pass are (D_{10}) of 1.28mm and (D_{50}) of 1.5mm respectively; coefficient of uniformity (C_U) of 1.26; coefficient of curvature (C_Z) of 0.97. The Kaolin-sand mixture samples were prepared using a moist tamping method to minimize the potential nonuniformity and inhomogeneity of the mixtures. The Kaolin was mixed with water, and then sand was added to form a mixture consisting of 50% kaolin and 50% sand (by mass) with an initial water content of 35%. The soil mixtures were then tamped in the oedometer cell to a pre-conditioned e_s of around 0.56.

The conditioning process was similar to the procedure described in the recent paper of Feng et al. (2023). In summary, samples were saturated with de-ionized water in the oedometer cell for 24 hours, then frozen at a temperature set at -20°C in a freezer. After 24 hours of freezing, the oedometer cells were then allowed to thaw with access to water in a bucket at room temperature (approximately 20°C) for 24 hours. After applying FTC, the specimens were placed in an oedometer cell and consolidated under vertical stresses of approximately 50 kPa, 110 kPa, 220 kPa, 440 kPa, and 110 kPa applied incrementally (following BSI 1990). The k values were found by the 'square root of time fitting method' (Taylor, 1948).

3 ANALYSIS RESULTS

3.1 Selection of empirical function

Figures 1 to 8 show the hydraulic conductivity (k) versus (e_s) data for both the pure kaolin data from Feng (2022) and Feng et al. (2023) and the new data for Kaolin-Leighton Buzzard (KL-B) sand mixtures fitted with various empirical functions. The statistical measures: number of data-points (n), coefficient of determination (R^2), standard error (SE) and p-value of the correlation (cf. Paradine and Rivett 1953) are also shown on the Figures 1 to 8.

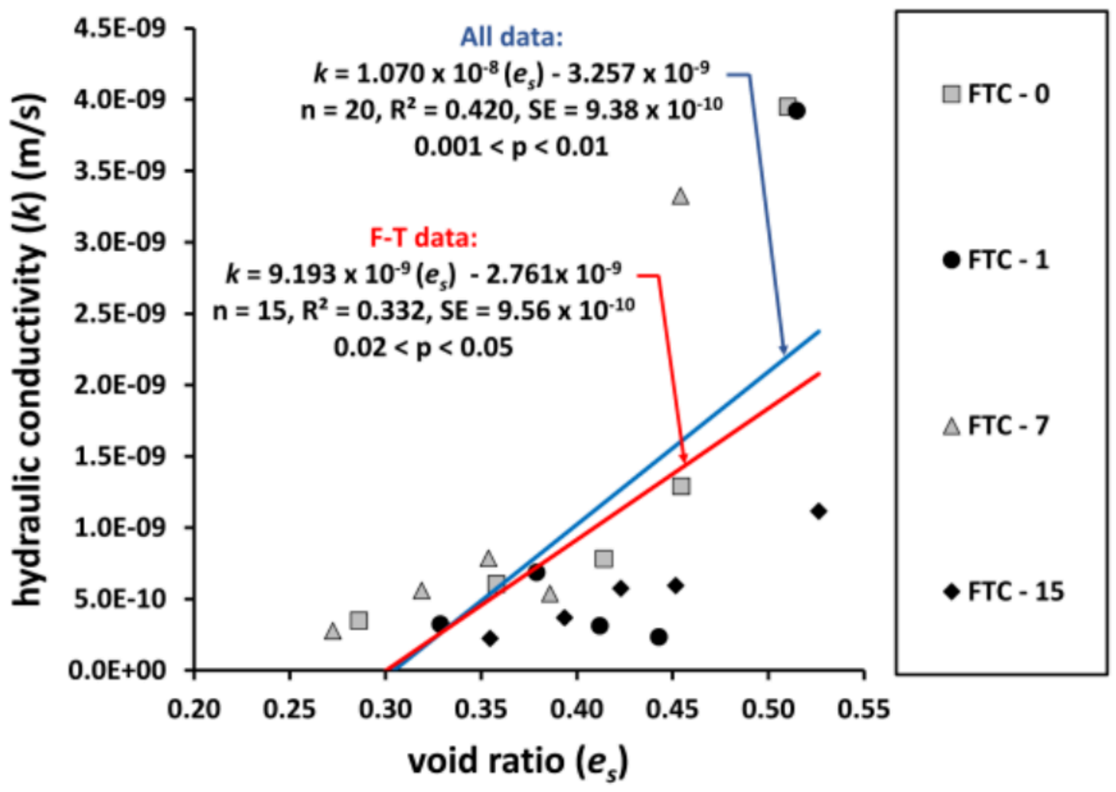

Figure 1. k versus e_s for the studied K-LB mixes.

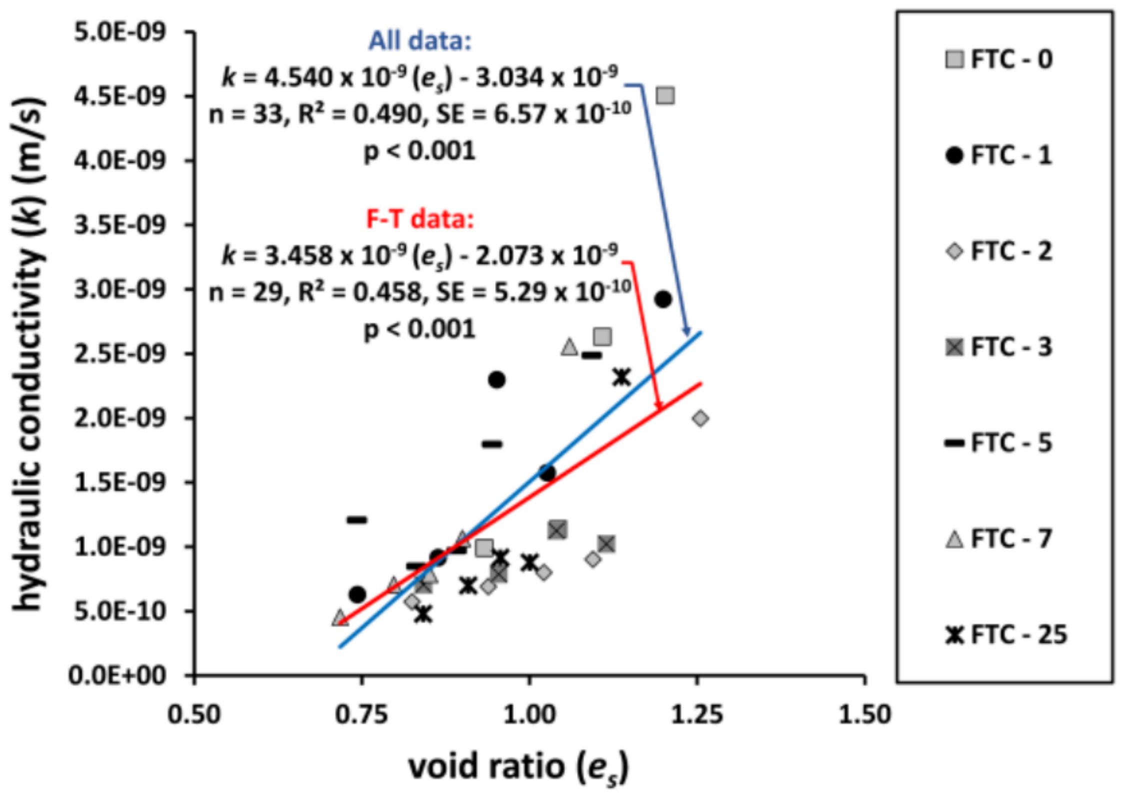

Figure 2. k versus e_s for the studied kaolin tests.

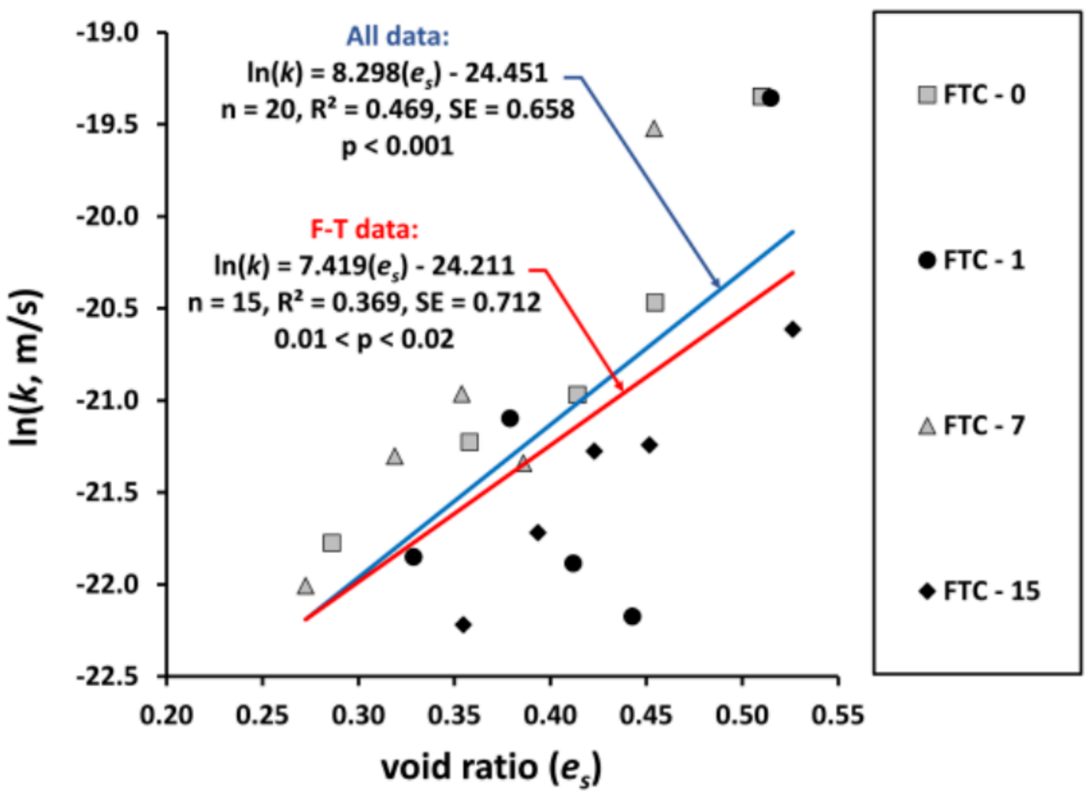

Figure 3. ln(k) versus e_s for the studied K-LB mixes.

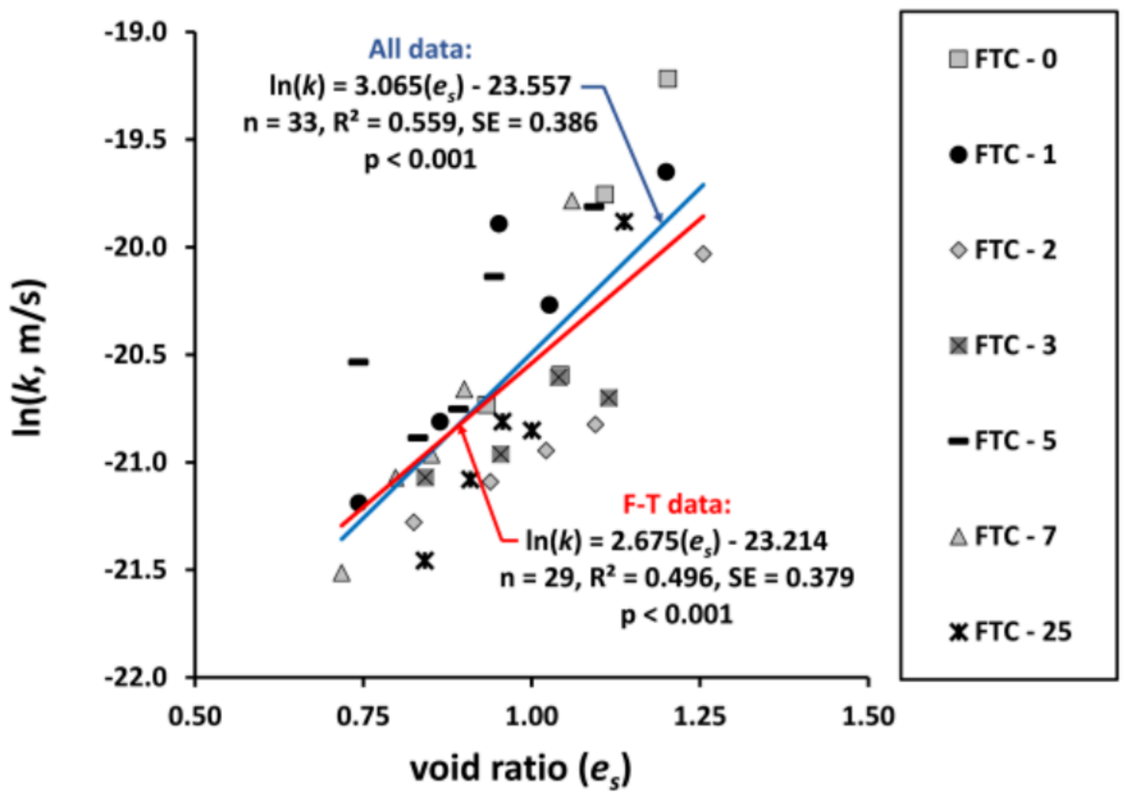

Figure 4. ln(k) versus e_s for the studied kaolin tests.

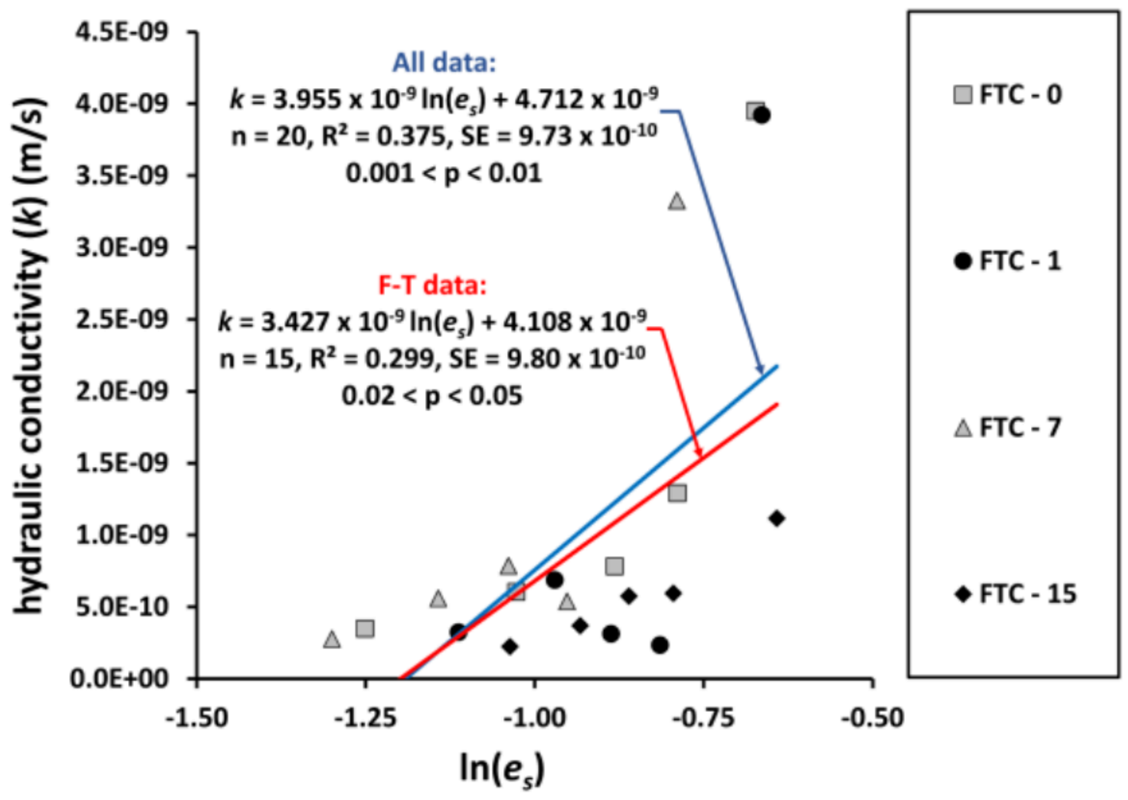

Figure 5. k versus ln(e_s) for the studied K-LB mixes.

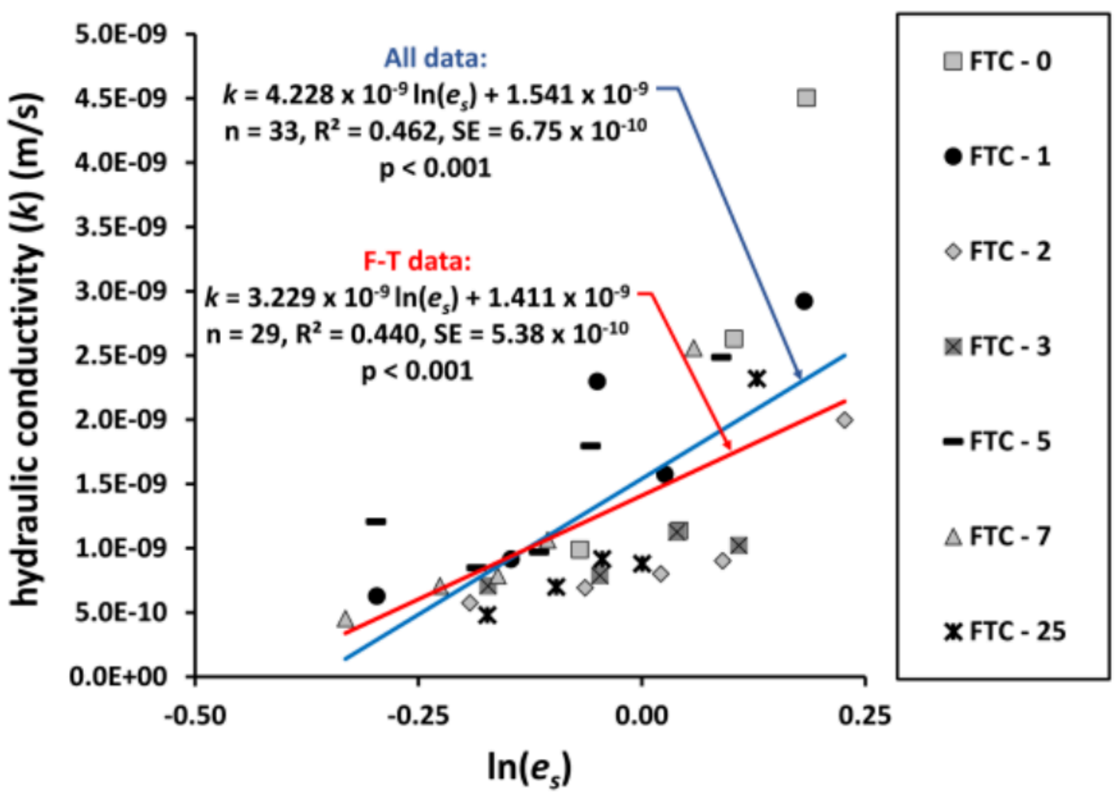

Figure 6. k versus ln(e_s) for the studied kaolin tests.

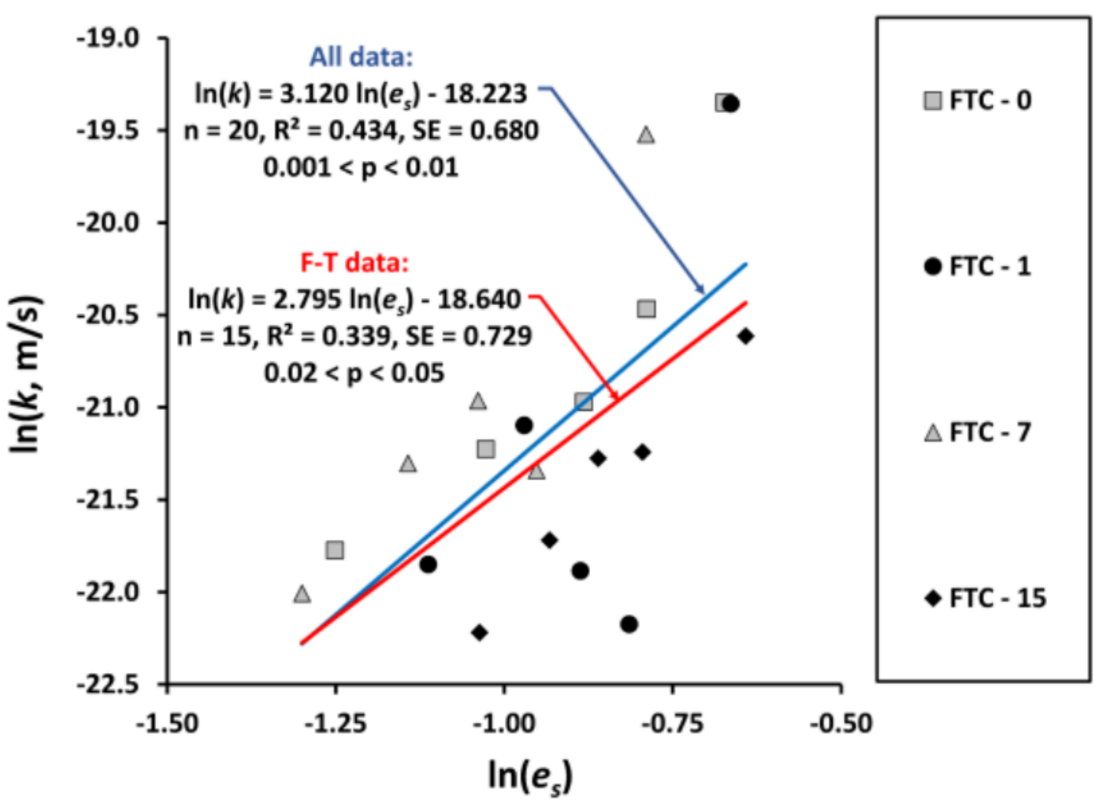

Figure 7. ln(k) versus ln(e_s) for the studied K-LB mixes.

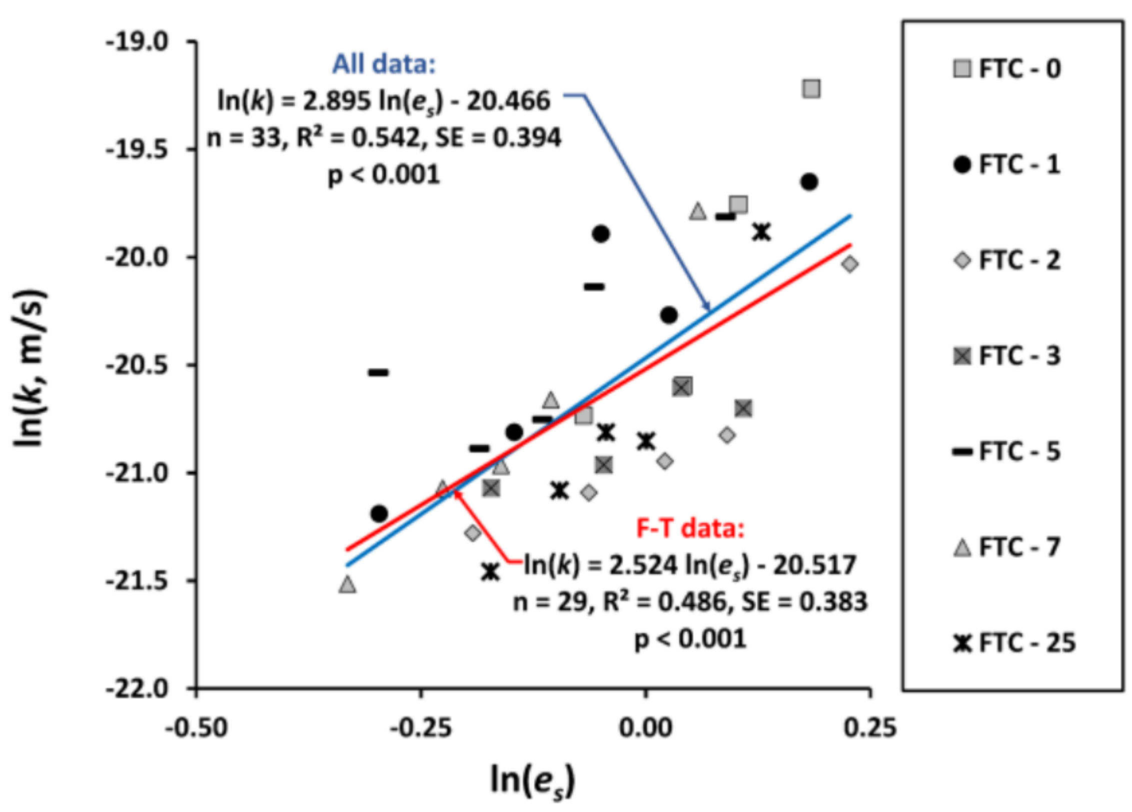

Figure 8. ln(k) versus ln(e_s) for the studied kaolin tests.

Figures 1 and 2 show a linear fitting to the K-LB mixtures and the pure kaolin tests series. The linear fittings considering only samples with FT conditioning give similar trends as the combined datasets albeit with consistently lower R^2 values. The correlations shown on Figures 1 and 2 have $R^2 = 0.420$ ($0.001 < p < 0.01$) (K-LB) and $R^2 = 0.490$ ($p < 0.001$) (Kaolin). Figures 3 and 4 show a semi-log fitting to the K-LB mixtures (ln(k) vs. e_s) and the pure kaolin tests series. The correlations shown on Figures 3 and 4 have $R^2 = 0.469$ ($p < 0.001$) (K-LB) and $R^2 = 0.559$ ($p < 0.001$) (Kaolin). Figures 5 and 6 also show a semi-log fitting to the K-LB mixtures (k vs. ln(e_s)) and the pure kaolin tests series. The correlations shown on Figures 5 and 6 have $R^2 = 0.375$ ($0.001 < p < 0.01$) (K-LB) and $R^2 = 0.462$ ($p < 0.001$) (Kaolin). Figures 7 and 8 present a log-log fitting to the K-LB mixtures (ln(k) vs. ln(e_s)) and the pure kaolin tests series. The correlations shown on Figures 7 and 8 have $R^2 = 0.434$ ($0.001 < p < 0.01$) (K-LB) and $R^2 = 0.542$ ($p < 0.001$) (Kaolin).

3.2 ln(k) – e_s equation

The best fitting was obtained for both kaolin and kaolin-sand data sets (see Figures 1 to 8) was the ln(k) versus (e_s) fitting of the form shown as Eq. (1) (see also Sivapullaiah et al. 2000) which can be rearranged to Eq. (2):

$$\ln(k) = \alpha(e_s) - \beta \quad (1)$$

$$k = e^{-\beta} e^{\alpha e_s} \quad (2)$$

where α and β are fitting parameters. For the K-LB data series (Figure 3):

$$\ln(k) = 8.298(e_s) - 24.451 \quad (3)$$

[$n = 20$, $R^2 = 0.469$, $SE = 0.658$, $p < 0.001$]

For Eq. 3 the R^2 value indicates that 46.9% of the variation in ln(k) can be explained by e_s (cf. Montgomery et al. 2004, p.273). Eq. 3 can further be rearranged to the following format:

$$k = 2.405 \times 10^{-11} e^{8.298 e_s} \quad (4)$$

For the kaolin data series (Figure 4):

$$\ln(k) = 3.065(e_s) - 23.557 \quad (5)$$

[$n = 33$, $R^2 = 0.559$, $SE = 0.386$, $p < 0.001$]

For Eq. 5 the R^2 value quoted means that 55.9% of the variation in ln(k) can be explained by e_s. Eq. 5 can be rearranged to:

$$k = 5.879 \times 10^{-11} e^{3.065 e_s} \quad (6)$$

3.3 Freeze-thaw effect

Table 1 shows the fitted α values for Kaolin samples with 0% and 50% sand after various numbers of FTC. The α parameter increases consistently with the addition of sand. A decrease in α is seen when comparing the 'All data' to the 'FTC samples' dataset. The small sizes of single FTC value datasets (e.g. 1 FTC, 2 FTC etc) are not sufficient to establish if the α values are influenced by the number of FTC.

Table 1. α-values for data series from this study.

Mixture	**0% Sand**		**50% Sand**	
	α	n	α	n
All data	3.065	33	8.298	20
FTC samples	2.675	29	7.418	15
0 FTC	5.973	4	10.14	5
1 FTC	3.348	5	10.86	5
2 FTC	2.820	5		
3 FTC	1.641	4		
5 FTC	2.657	5		
7 FTC	5.006	5	12.21	5
15 FTC			9.022	5
25 FTC	5.137	5		

4 SUMMARY AND CONCLUSIONS

This paper has presented some new k data of Kaolin-sand mixtures. The new data has been compared with k tests on kaolin reported in Feng et al. (2023). A semi-log function was found to be the best fit to the data studied in this paper. The α value increases considerably with the addition of 50% sand to kaolin, compared to the tests on pure kaolin. However, the effect of the number of FTC was not detected in this study.

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Data availability: the new experimental data are available from the first author upon reasonable request.

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