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Assessment of the effect of fines content on frost susceptibility via simple frost heave testing and SP determination

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Abstract. The Segregation Potential (SP) is one of the most widely used predictors of frost heave in cold regions. Laboratory step-freezing tests determining a representative SP at the onset of the formation of the last ice lens (near the thermal steady state condition) can predict susceptibility to frost heave. Previous work has proposed empirical semi-log fitting for determination of the representative SP and applied it to several fine-grained soils, but considering only frost-susceptible soils. The presence of fines in coarse-grained soil affects frost susceptibility. Therefore, it is required to evaluate the applicability of the empirical semi-log fitting for both frost-susceptible and non-frost-susceptible soils with fines content. This paper reports laboratory frost heave tests for fines contents of 5%-70%. The frost susceptibility of soil mixtures composed of sand and silt was classified by the representative SP, and the suitability of the empirical semi-log fitting method was assessed. Combining semi-log fitting with simple laboratory frost heave testing using a temperature-controllable cell is shown to be suitable for both frost-susceptible and non-frost-susceptible soils. In addition, initially non-frost-susceptible soil became frost susceptible at a 10%-20% weight fraction of fines. This threshold fines content matched well with transitions in the engineering characteristics of both the unfrozen and frozen soil mixtures.

Keywords: fines content, frost heave, frost susceptibility, segregation potential, semi-log fitting method, simple laboratory frost heave testing

1. Introduction

A soil's fines content greatly influences its mechanics and geotechnical engineering (Shariati *et al*. 2019, 2020, Dai *et al*. 2019, Jin *et al*. 2021a). When a constant sub-zero temperature is applied to the surface of a fine-grained soil, a frost front (the 0°C isotherm) progresses through it. Frost heave initiates through not only the in situ freezing of pore water, but also through water entering from unfrozen soil or an external source (Konrad and Morgenstern 1980, Seto and Konrad 1994, Jin *et al*. 2021). In contrast, coarse-grained soils often avoid frost heave, and are usually considered to be non-frost-susceptible. However, the presence of fines in coarse-grained soil affects the soil's frost susceptibility (Konrad and Lemieux 2005).

Frost susceptibility classification criteria are an enduring issue in frozen ground engineering. Over 100 frost susceptibility classification methods have been proposed (Chamberlain 1981, Konrad 1999), and geotechnical engineers have not yet agreed a common standard for cold regions design. Jin *et al*.'s (2017) review of frost susceptibility criteria concluded that criteria derived from laboratory frost heave testing are the most appropriate, being more suitable than other criteria such as particle grading. Since Konrad and Morgenstern's (1980, 1981) innovative accounting of ice segregation in freezing soils and their proposed Segregation Potential (SP), SP has become one of the most widely used indicators for frozen soils obtained from laboratory frost heave testing. Specifically, the SP at the onset of formation of the last ice lens (near the thermal steady-state condition, t_p) in step-freezing tests is a representative value applicable in the field due to the low freezing rate (Konrad 1994, 1988, 1989a, 1999, 2005, Saarelainen 1996, Dore *et al*. 2006). Despite the excellent field reproducibility and applicability of the SP at the onset of formation of the last ice lens, the determination process requires extremely specialized and complicated skills. That is, foundation engineering design in cold regions requires a simple analysis method for engineering application since the specialized and complicated skills are needed for direct classification using the representative SP (Konrad 1999).

Jin *et al*. (2021) proposed a simple method to derive the representative SP, involving empirical semi-log fitting combined with simple laboratory frost heave testing using a temperature-controllable cell. The newly proposed SP determination method was cross-checked using frost ratio (F_z) concept which is newly defined by calculating the ratio of the area of the normalized triangle consisting of the initial and final linear temperature line and the area of the temperature profile at a certain. However, the reported application and verification only considered fine-grained soils. Tester and Gaskin (1996) conducted frost heave test

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considering fines contents ranging from 2% to 14% weight fraction using the CRREL II (Cold Regions Research and Engineering Laboratory) frost heave testing method and frost susceptibility classification criterion (Chamberlain, 1987). Based on the CRREL II criterion using heave rate, not the representative SP, frost susceptibility increased as fines content increased. Konrad and Lemieux (2005) also analyzed the correlation between the representative SP and fines content, but did not analyze frost susceptibility classification.

This paper reports experimental research to supplement limited data considering frost susceptibility classification using the representative SP as well as frost heave behavior with respect to fines content. Empirical semi-log fitting was also applied to soil mixtures containing various fines contents. In discussion part, the threshold of fines contents as well as the reliability of the empirical semi-log fitting were assessed in detail using the representative SP.

2. Representative SP determination method

The widely accepted definition of SP used in frozen ground engineering is as follows (Konrad and Morgenstern 1981)

$$v(t) = SP(t) \times gradT(t) \tag{1}$$

where t is the time (h), $v(t)$ is water intake rate at t (mm h^{-1}), $gradT(t)$ is the overall temperature gradient in the frozen fringe at t (°C mm^{-1}), $SP(t)$ is Segregation Potential at t (mm^2 °C^{-1} h^{-1}).

As SP varies with time, it is important to determine the representative SP for use in the field when considering engineering design and frost heave prediction. The representative SP is obtained at t_p in step-freezing laboratory tests (Konrad 1988, 1989a, 1989b, 1994, 1999, 2005, Dore *et al*. 2006, Jin *et al*. 2021). Although t_p should be derived first, its determination is very difficult by methods such as extruding a frozen soil specimen to measure the last ice lens thickness or measuring temporal temperature profiles across a soil specimen (Konrad and Morgenstern 1982a, b, Konrad and Nixon 1994, Konrad and Seto 1994). Therefore, Jin *et al*. (2021) proposed a simple method for determining the representative SP in upward-step-freezing laboratory tests using three frost-susceptible soils. In particular, they reviewed in detail the use of the newly defined concept of frost ratio (F_z) and empirical semi-log fitting for the determination of t_p. The F_z is defined using normalized temperature profile area as follows (Jin *et al*. 2021)

$$F_z = 1 - {}^{A_t}/_{A} \tag{2}$$

where A is the area at the assumed thermal steady-state condition, and A_t is the area from the progressive temperature profile at time t.

The F_z reaches 90% at the same time as the starting point of the tangent in the heave curve with a logarithmic timescale coincides empirically with the t_p. Thus, it is no longer necessary to measure temperature across the soil specimen in order to derive the representative SP (Jin *et al*. 2021). However, Jin *et al*. (2021) only considered frost-susceptible soils and did not analyse fines content effect on frost susceptibility more broadly. This paper evaluates applicability of the empirical semi-log fitting using soil mixtures containing various fines contents and fines content effect on frost susceptibility.

Table 1 Frost susceptibility criteria using representative SP

	Frost susceptibility	SP (mm^2 °C^{-1} h^{-1})
Version I (Slunga and Saarelainen 1989, 2005)	Negligible	SP<0.5
	Low	0.5≤SP<1.5
	Medium	1.5≤SP<3.0
	Strong	3.0≤SP
Version II (Nurmikolu 2006, Sinnathamby *et al*. 2015)	Non-frost-susceptible	SP<0.5
	Slightly frost-susceptible	0.5≤SP<1.6
	Moderately frost-susceptible	1.6≤SP<3.3
	Highly frost-susceptible	3.3≤SP
Version III (St-Laurent 2010, St-Laurent *et al*. 2019)	Negligible	SP<0.5
	Low	0.5≤SP<1.5
	Moderate	1.5≤SP<3.0
	High	3.0≤SP<8.0
	Very high	8.0≤SP

3. Overview of frost susceptibility classification criteria using representative SP

Table 1 summarizes similar versions of frost susceptibility criteria using the representative SP that have been developed at different times. Version I was proposed based on the literature: a series of laboratory tests and field observations conducted in Finland 1986-1987 (Slunga and Saarelainen 1989, 2005). The materials were, however, limited, and updated criteria (version II) were proposed by the Finnish Rail Administration (Nurmikolu 2006, Sinnathamby *et al*. 2015). The version III frost susceptibility criteria proposed by Transport Québec have become widely accepted for engineering design in frozen ground (St-Laurent 2010, St-Laurent *et al*. 2019).

4. Testing condition

4.1 Equipment and methodology

Jin *et al*. (2019a, b) proposed a simple frost heave testing method. The main apparatus was a transparent temperature-controllable freezing cell able to independently control the temperatures of the top, bottom, and periphery of a tested specimen using three freezing pumps. The freezing cell comprised an acrylic double-ring, and anti-freeze liquid circulated between the rings to realize one-dimensional freezing without a freezing chamber. Jin *et al*. (2021b) modified the freezing cell as shown in Fig. 1. A temperature sensor module installed on the inner ring of the freezing cell measured the temperature profile across the

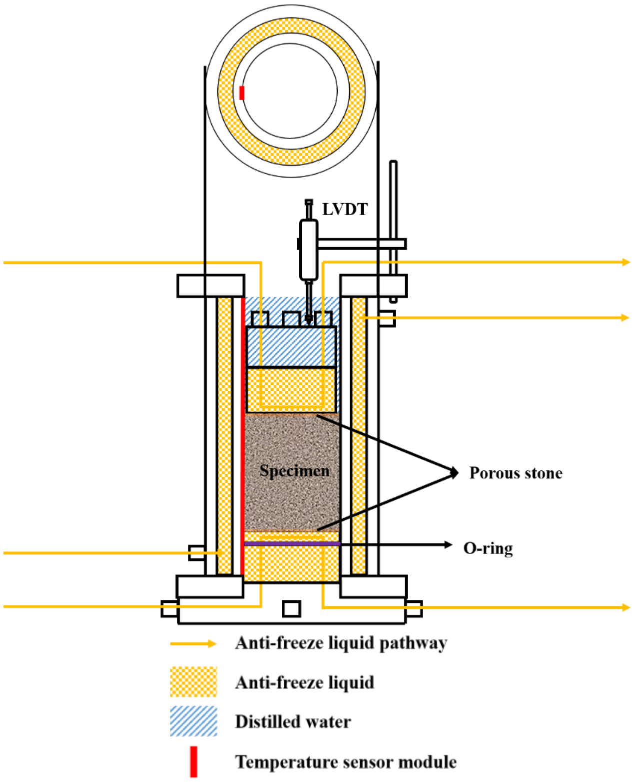


Fig. 1 Frost heave testing apparatus (Jin *et al*. 2021b)

soil specimen during freezing. Therefore, it is also possible to derive SP directly using the modified freezing cell.

Distilled water was injected through the drainage line connected to the bottom pedestal to saturate the soil specimen. When the water level reached ~30 mm above the specimen surface, the water level was kept for one day in a hydrostatic condition. The soil specimen was always submerged in distilled water to maintain a continuous water supply during freezing. Vertical displacement induced by frost heave was measured using a linear voltage displacement transducer (LVDT) positioned on the top pedestal. Pressure applied to the specimen was negligible, comprising only the top pedestal's weight (with anti-freeze liquid) of 1.62 kPa. Upward step freezing was applied to eliminate lateral confinement (Konrad and Morgenstern 1982a, Jin *et al*. 2019a, 2019c). The time at the onset of the formation of the last ice lens (near the thermal steady-state condition) during step-freezing tests could be assessed from both temperature measurement data and visual observation of the transparent freezing cell.

4.2 Materials and program

Joomunjin sand with an average grain size of 0.47 mm and crushed basalt comprising soil particles passing through a #200 sieve (0.075 mm) were used. The reason why crushed basalt was used in this paper instead of a well-known fines material such as kaolinite is that the crushed basalt is the optimized silty soils for analyzing the frost heave mechanism. In general, clay soils generate thin and curved ice lenses, whereas siltier soils generate thicker and fairly planar ice lenses in one-dimensional conditions

Table 2 Particle grading characteristics and soil classification (Jin *et al*. 2019c)

Soil	$*D_{10}$	$*D_{30}$	$*D_{60}$	Uniformity coefficient, C_u	Coefficient of curvature, C_c	Specific gravity, G_s	USCS
Joomunjin sand	0.36	0.44	0.51	1.42	1.05	2.65	SP
Crushed basalt	0.0076	0.03	0.1	13.16	1.18	2.94	ML

$*D_n$: The portion of particles with diameters smaller than this value is n%

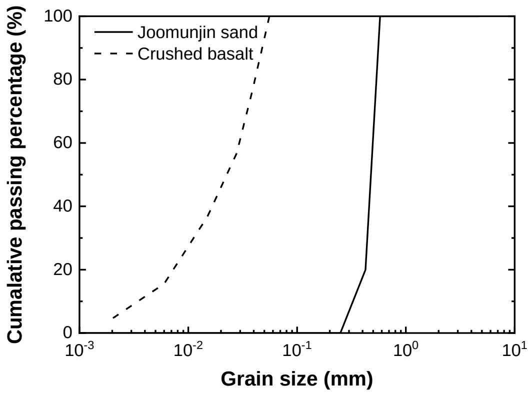


Fig. 2 Grain size distributions of Joomunjin sand and crushed basalt (Jin *et al*. 2019c)

(Konrad 1994). Grain-size distributions are shown in Fig. 2. Table 2 lists the particle grading characteristics and soil classification. The sand and crushed basalt are respectively classified as SP and ML by the unified soil classification system (USCS).

Table 3 gives details of the six tested soil specimens (~100 mm diameter, ~50 mm height) made from the following mixtures of Joomunjin sand with 5%, 10%, 20%, 30%, 50%, and 70% by weight of crushed basalt. The soil mixtures were reconstituted by air pluviation, dry tamping, and vibration. Each mixture's porosity, dry density, and temperature at the start of test and at freezing are also listed.

5. Testing results

5.1 Frost heave behavior

A Measured frost heave with respect to elapsed time is shown in Fig. 3. The frost heaves (i.e., vertical volume expansion) measured for each soil mixture (Nos 1-6) were 3.66, 7.89, 21.15, 26.23, 39.69, and 42.81 mm, respectively, at the end of the tests (~72 h for Nos 2-6 and ~54 h for No. 1). Frost heave increased with increasing fines content: the increase was particularly great between specimens 2 and 3 when the weight fraction of the fines content reached 20%. Frost heave was below 10 mm for weight fractions of fines up to 10% (Nos 1 and 2). Also, the frost heave behaviors were similar when the weight fraction of the fines content was high (specimens 5 and 6). That is, the increasing rate of frost heave tends to become lesser compared to a certain fraction.

Table 3 Testing program and initial conditions of soil mixtures

Specimen No.	Weight fraction (%)		Initial height (mm)	Porosity (%)	Dry density (g/cm^3) Initial	Temperature (°C)		
	Joomunjin sand	Crushed basalt				Initial	Initial	
							Top	Bottom
1	95	5	52.92	39.24	1.59	1.42	0.97	−3.77
2	90	10	49.92	37.30	1.68	1.34	0.81	−3.82
3	80	20	46.81	32.41	1.79	1.25	0.98	−3.65
4	70	30	43.74	28.42	1.92	1.30	0.85	−3.65
5	50	50	45.47	31.16	1.85	1.37	1.13	−3.64
6	30	70	45.77	31.61	1.84	1.26	0.99	−4.13

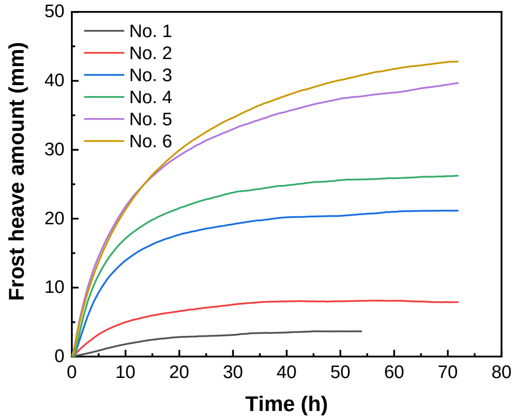
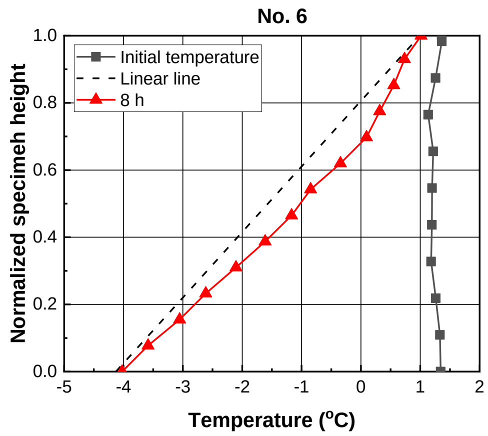
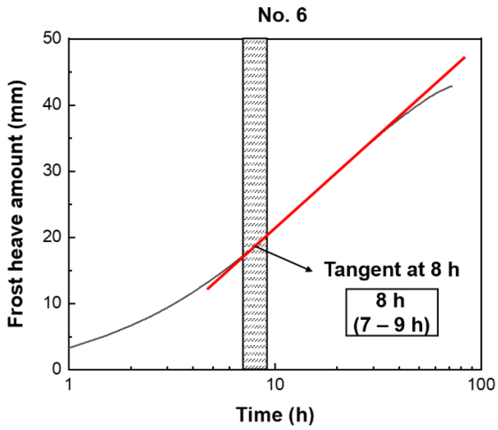


Fig. 3 Frost heave amount with respect to time for specimen Nos 1-6



(a) Frost ratio (F_z)



(b) Semi-log fitting

Fig. 4 Comparison of t_p determination methods

5.2 Frost susceptibility classification using SP

The empirical semi-log fitting method proposed by Jin *et al.* (2021b) was applied to the test results reported here. For specimen No. 6, as in the previous study, F_z reaching 90% and the starting point of the tangent to the heave curve with a logarithmic timescale empirically coincided with t_p (see Fig. 4). The Appendix gives the remaining semi-log fitting results. Table 4 compares tp values determined by the two methods. As described by Jin *et al.* (2019a, 2021b), *gradT* was calculated using the top and bottom temperatures, and frost susceptibility was classified using the version III criteria (Table 1) and the representative SP. Both methods determined similar t_p values for each specimen. Differences between the two t_p values emerged within 1-2 h, but they had insignificant effect on the *gradT* and heave rate. The six specimens were classified as having low (No. 1), moderate (No. 2), and high (Nos 3-6) frost susceptibility.

6. Discussion

Soil mixtures composed of sand and silt can be broadly classified as being either coarse- or fine-grained. The boundary between the two, the threshold fines content ($F_{c,th}$), is based on the weight fraction (Park *et al.* 2018). Starting from a soil skeleton of pure sand, as the fines content increases the pores decrease and are filled with fines. In this case, the soil's engineering characteristics such as shear strength are governed by those of sand. When the pores of the sand are fully filled with silt, the $F_{c,th}$ is achieved. As fines content exceeds the $F_{c,th}$ contact between sand particles reduces and so too does friction between them. The soil can then be considered as sand interspersed in the pores of silt, and the engineering characteristics become governed by those of silt. Thus, many previous studies have considered the $F_{c,th}$. Kim and Zhuang (2015) analyzed shear behavior of soil mixtures composed of sand and silt below the $F_{c,th}$ (~20% fines) with respect to confining pressure. Kim *et al.* (2017) investigated the $F_{c,th}$ of sand-fines (Iwakuni clay and Tottori silt from Japan) mixtures considering the void ratio. The mixtures transformed from having a sand skeleton structure to one of fines when the fines content exceeded approximately 16.7%. Liquefaction resistance is also affected by the fines

Table 4 Frost susceptibility classification (Version III) and representative SP

Specimen No.	t_p (h)		$gradT$ (°C mm^{-1})		Heave rate (mm h^{-1})		SP (mm^2 °C^{-1} h^{-1})	
	Frost ratio	Semi-log fitting	Frost ratio	Semi-log fitting	Frost ratio	Semi-log fitting	Frost ratio	Semi-log fitting
1	3	5 (4-6 h)	0.09	0.08	0.04	0.05	0.50 (Low)	0.60 (Low)
2	3	4 (3-5 h)	0.09	0.09	0.15	0.15	1.70 (Moderate)	1.74 (Moderate)
3	5	4 (3-5 h)	0.08	0.09	0.34	0.42	4.18 (High)	4.87 (High)
4	5	4 (3-5 h)	0.08	0.09	0.38	0.47	4.61 (High)	4.91 (High)
5	8	7 (6-8 h)	0.07	0.07	0.35	0.37	4.80 (High)	5.04 (High)
6	8	8 (7-9 h)	0.08	0.08	0.35	0.35	4.53 (High)	4.53 (High)

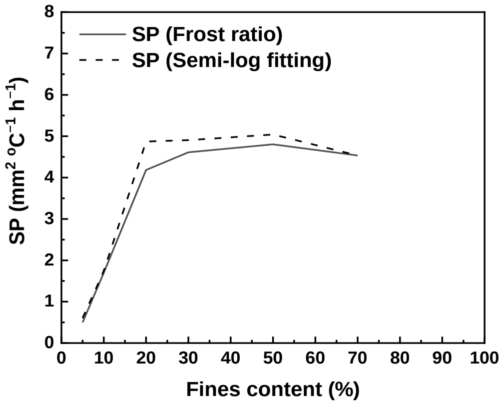


Fig. 5 Representative SP with fines content

content. Sands containing more than 10% fines passing through a #200 sieve (0.075 mm) have much greater liquefaction resistance than pure sands with the same N-values from standard penetration testing (Tokimatsu and Yoshimi 1983). Chien *et al*. (2002) reported that when the fines content exceeds 10%, the liquefaction curve reduces significantly.

The $F_{c,th}$ does not only appear in unfrozen sandy soil mixtures. Jin *et al*. (2020) reported that frozen soil mixtures show a brittle-to-ductile transition of failure pattern at a 10%-20% weight fraction of fines (the same fines as used here). The threshold remains within this range of fines contents regardless of whether the soil is frozen. Frost heave caused by fines is also a representative engineering phenomenon that occurs in frozen soils. Konrad (1999) found (using limited data and referring to soil classification method) that frost heave is negligible at fines contents below 12%. The frost heave tests reported here were conducted using reconstituted soil mixtures with various fines content, and frost susceptibility was assessed. The results in Fig. 5 support that $F_{c,th}$ is within the 10%-20% fines weight fraction range for frozen soil mixtures.

7. Conclusions

This paper reports laboratory frost heave tests conducted using soil mixtures composed of sand and silt, which showed various frost heave behaviors. The following conclusions were derived.

• Frost heave amounts strongly depend on the weight fraction of fines. As fines content increases from 5% to 70%, the frost heave amount and t_p increase but the representative SP increases up to a point. In other words, the representative SP after -20% fines changes very little.

• Semi-log fitting combined with simple laboratory frost heave testing determined t_p for engineering applications using various soil mixtures. In estimating representative SP from the total heave amount and cold-warm end temperatures, the method is verified to be applicable not only to frost-susceptible soils but also to non-frost-susceptible soils.

• Based on the frost susceptibility classification criteria using representative SP, a non-frost-susceptible to frost-susceptible transition occurred at 10%-20% weight fraction of fines. The observed threshold matches well with previously reported transitions in the engineering characteristics of unfrozen and frozen soil mixtures.

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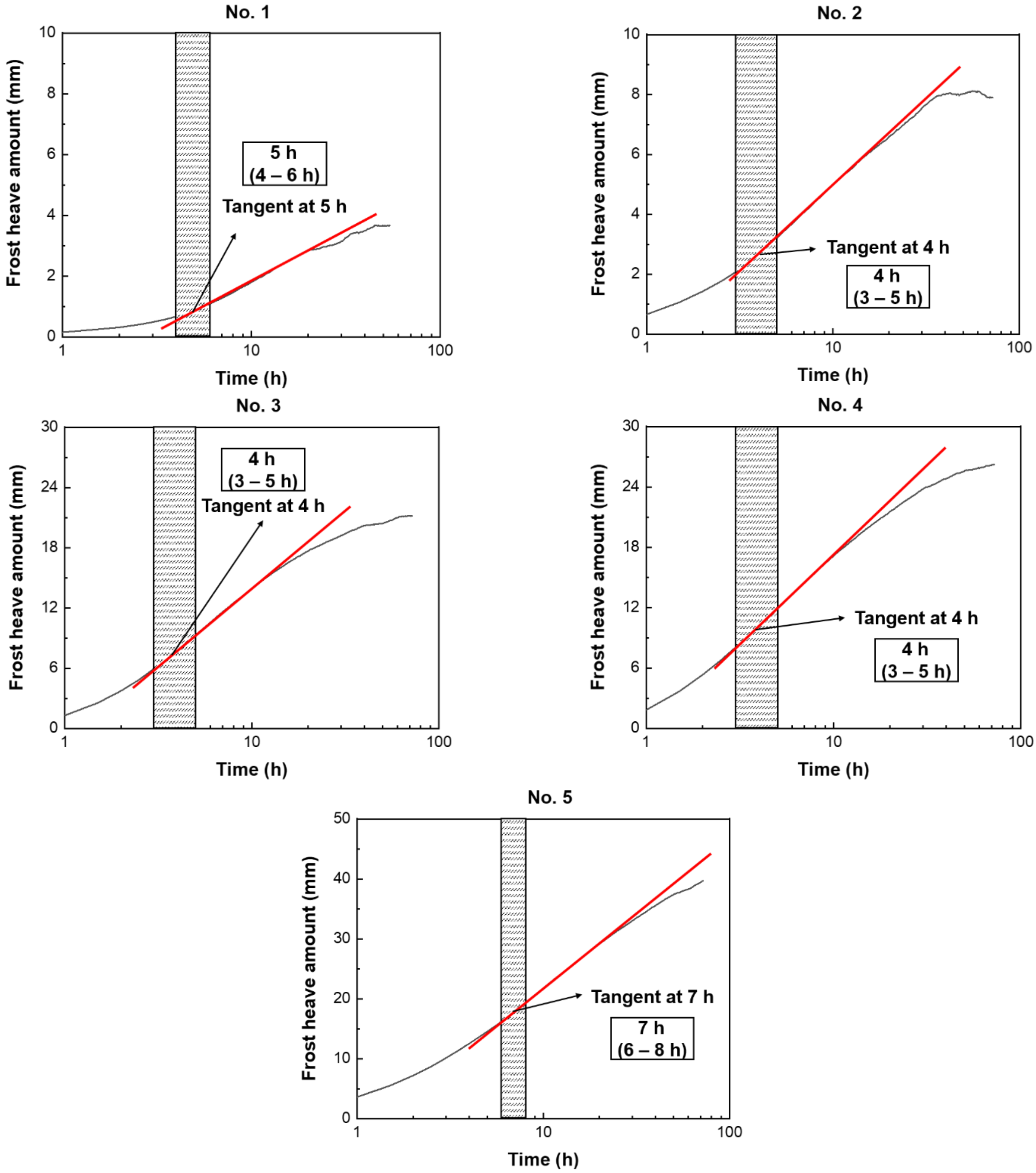
Appendix



Application of semi-log fitting method to all tested samples