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Seasonal and locational variation in the flexural strength of lake ice in Saimaa area

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Inland waterways offer a sustainable and efficient way to transport goods and people. The vessel design for winter conditions require knowledge about the mechanical properties of ice from the planned operational area. To gather knowledge about the mechanical properties of ice, and seasonal and locational variation in the properties in Saimaa area in Finland, three measurement campaigns were planned that covered different parts of Northern and Southern Saimaa in January, February, and March in 2021.

This paper studies the measured seasonal and locational variation in the mechanical properties of ice in the Saimaa area. The measurements include the flexural strength and strain modulus determined from the 3-point bending tests. The measured flexural strength and strain modulus did not have any clear trend along the season and the variation between the location is negligible. However, the study indicates the bottom of the ice to be slightly stronger than the surface, except in one occasion. The average measured flexural strengths were 0.8 MPa, 1.0 MPa, and 1.3 MPa for the top, middle and bottom layers, respectively. The corresponding average strain modulus were 3.7 GPa, 4.7 GPa, and 4.5 GPa. The measured ratio between the strain modulus and flexural strength varied between 2000 and 9500, the average being around 5000.

1. Introduction

Increasingly demanding sustainable development goals are putting pressure to develop and utilize more efficient and sustainable solutions for the transportation of goods and people. Maritime transportation offers good possibilities for this that has raised the interest to utilize the inland waterways more efficiently. However, frozen waterways hinder the navigation during the wintertime, but the transportation of goods and people is still required. Thus, the vessels need to be designed to be able to operate in winter conditions or have an assisting icebreaker to secure the safety and efficiency of the transportation. The design of such vessels requires knowledge on the operational conditions.

The flexural strength of ice is the most common parameter to describe the strength of ice as the ice breaking vessels are commonly designed to break ice through bending. For these reasons, the flexural strength of sea and freshwater ice has been extensively measured in the past (Timco and O'Brien, 1994; Aly et al., 2018). Despite the attempts, a simple formulation to determine the flexural strength of freshwater ice, similar to the strength of saline ice (Timco and O'Brien, 1994), has not been able to develop. As the freshwater ice is a brittle material, several parameters affect the strength and the measurements have shown a great variation (Timco and O'Brien, 1994; Aly et al., 2018) the average ranging from 500 kPa to 2.2 MPa (Aly et al., 2018). Thus, defining the design conditions and strength is challenging. One possibility is to organize a measurement campaign to define the conditions in the planned operational area.

Saimaa has been an important inland waterway and area for Finland. To enhance the usage of inland waterways, a project called INFUTURE was launched to develop new ship designs and concepts for inland waterways. As the available strength measurements from Saimaa area are rare (see e.g. John et al., 2018), a field measurement campaign was launched in 2021 to determine the flexural strength of ice in Saimaa area for the design purpose, and to define the conditions for model scale testing (Suominen et al., 2021). Discussions with the local operators revealed that the conditions vary significantly in different parts of Saimaa. Furthermore, the seasonal variation in the strength properties of freshwater ice has shown a large scatter (Frankenstein, 1961; Fransson, 2002). Although a decreasing trend in the strength values has been observed towards the spring, relatively large strength values has been measured in late season for the freshwater ice (Frankenstein, 1961; Fransson, 2002). For these reasons, three measurement campaigns were planned for different time of the season (January, February, and March) that would cover different parts of Saimaa at different times of the season.

This paper focuses on the measured flexural strength and strain modulus during these campaigns. Earlier studies have shown that the cantilever beam testing leads to smaller flexural strength values that is related to the stress concentration at the root corner of the cantilever beam (Frankenstein, 1961; Gow, 1977; Schwartz et al., 1981; Timco and O'Brien, 1994). Our earlier study related to the presented testing campaigns focused on the effect of testing methods and showed similar results (Suominen et al., 2021). To minimize the effect of sample preparation, 3-point bending was chosen as the repeated testing method to determine the flexural strength. The strain modulus was determined from the beam deflection measured during the bending tests. The ratio between the strain modulus and flexural strength is considered an important factor to describe the breaking of ice in model-scale as it indicates the deflection of ice before breakage (Schwarz, 1977). For saline ice, this ratio typically is between 2000 and 5000. As this is available from the measurements, it is briefly studied here for freshwater ice. The following chapters present the measurement methods and locations that are followed by the results, and discussion and conclusions.

2. Measurement Methods

Flexural Strength

The flexural strength was measured applying ex-situ 3-point bending tests. During the first campaign, the tested samples were cut from the tested cantilever beam sample (Suominen et al., 2021). During the second and third campaign, the samples were cut and prepared separately for the 3-point bending tests. As the samples were extracted from the lake ice, the samples were not perfectly flat. To reduce the torsion and to improve the contact at supports, one of the supports of the rig was rigid while small rotation around the length of the beam was allowed to the other support. An actuator was applied to load the sample at the mid span of the beam with a rounded head to reduce the possible torsion in the beam, see Figure 1. The applied load was measured with a load sensor attached to the actuator.

Figure 1. An ex-situ 3-point bending test (Suominen, et al., 2021).

Assuming the beam behaves as an Euler-Bernoulli beam, and the first failure occurs on the surface in tension, the equation for the flexural strength can be defined from:

$$\sigma_x = \frac{M(x)y}{I} \qquad \textbf{[1]}$$

where σ_x [Pa] is the normal stress, $M(x)$ [Nm] is the bending moment affecting the cross-section, y [m] is the vertical distance from the neutral axis, and I [m^4] is the second moment of cross-sectional area. For this test setup, the bending moment is considered to consist of the applied external force and the weight of the sample. After defining the moment equation and substituting it to Equation [1], following form for the flexural strength can be determined:

$$\sigma_{3Point} = \frac{3x_f}{bh^2}\left[F_b + \left(L_{sup} - x_f\right)g\rho_i bh\right] \qquad \textbf{[2]}$$

Where F_b [N] is the force required to break the sample, L_{sup} [m] is the distance between the supports, b [m] and h [m] are the width and height of the sample, respectively, g [m/s^2] is the acceleration due to gravity, ρ_i [kg/m^3] is the density of ice, and x_f [m] ($0 \le x_f \le ½L_{sup}$) is the distance from the closest support to the location where the ice failed occurred. As notified e.g. by Schwartz et al. (1981), flexural strength is not an actual material property and the assumptions behind this formulation are not valid for ice, as ice is inhomogeneous and anisotropic. Thus, the values should be considered as index value.

Strain Modulus

With the same assumptions, the displacement equation, $w(x)$, for the beam can be derived along the beam from the following relation:

$$EI\frac{d^2w}{dx^2} = -M(x) \qquad \textbf{[3]}$$

Where E is the strain modulus. Measuring the change in deflection, $\Delta\delta$, and force, ΔF, at a distance of x_d [m] from the support, the strain modulus can be determined with the following equations:

$$E = \frac{\Delta F}{\Delta\delta}\frac{3x_d}{bh^3}\left(\frac{L^2}{4} - \frac{x_d^2}{3}\right) \qquad \textbf{[4]}$$

Density of Ice

The determination of ice density followed the ITTC Guidelines (ITTC, 2014) where the density is determined by submerging the ice and measuring the weight in three phases. First, the weight of the water and the bucket where the ice is to be submerged is recorded, w_1. Then, the ice sample is placed in the bucked and the second weight is recorded, w_2. Finally, the ice sample is submerged, and the third weight is recorded, w_3. The ice density can now be calculated with the following formula:

$$\frac{\rho_i}{\rho_w} = \frac{w_2 - w_1}{w_3 - w_1} \qquad \textbf{[5]}$$

where ρ_w [kg/m^3] is the density of water, assumed to be 1000 [kg/m^3].

3. Measurement Campaigns

The aim of the measurements was to determine the prevailing ice conditions in common operational areas in Saimaa. The locations were determined based on the discussions with the local operators. As the discussions indicated that the conditions vary in different areas of Saimaa, three different parts of Saimaa were chosen for measurements - south, northeast, and northwest, see Figure 2. More detailed description is given in Suominen et al. (2021). To study the seasonal variation in the ice conditions, three campaigns were conducted - late January, late February, and late March.

The campaigns visited the same measurement sites. The locations and dates are summarized in Table 1. Figure 3 presents the measured daily temperatures on weather stations in different parts of Saimaa at midnight (UTC+0). The data was obtained from FMI data services (FMI, 2021). The location at Lappeenranta (Hiekkapakka) is between Päihäniemi and Tiuruniemi, Kuopio (Ritoniemi) location is close to Puutossalmi, and Liperi (Tuiskavanluoto) location is close to Vitasniemi. As can be noted, the air temperatures were close to zero at the beginning of the first campaign and decreased towards the end. The second campaign was started during the cold period, but temperature raised during the campaign. During the third campaign the temperatures raised slightly during the campaign being above freezing at the end. As this study focuses on the seasonal variation in ice conditions, the locations that were visited within different campaigns are in focus.

Table 1. The measurement sites and dates.

	Päihäniemi	Tiuruniemi	Kyläniemi	Vitasniemi	Vehkaniemi	Siilinjärvi	Puutossalmi
1st Camp	Jan 25	Jan 26	Jan 27	Jan 29	Jan 30	Jan 31	Feb 1
2nd Camp		Feb 22, 24-26	Feb 23				
3rd Camp		Mar 22	Mar 23	Mar 25, 26			Mar 24

Figure 2. Measurement locations (Suominen, et al., 2021). The map produced from Maanmittauslaitos Karttapaikka (Maanmittauslaitos, 2021).

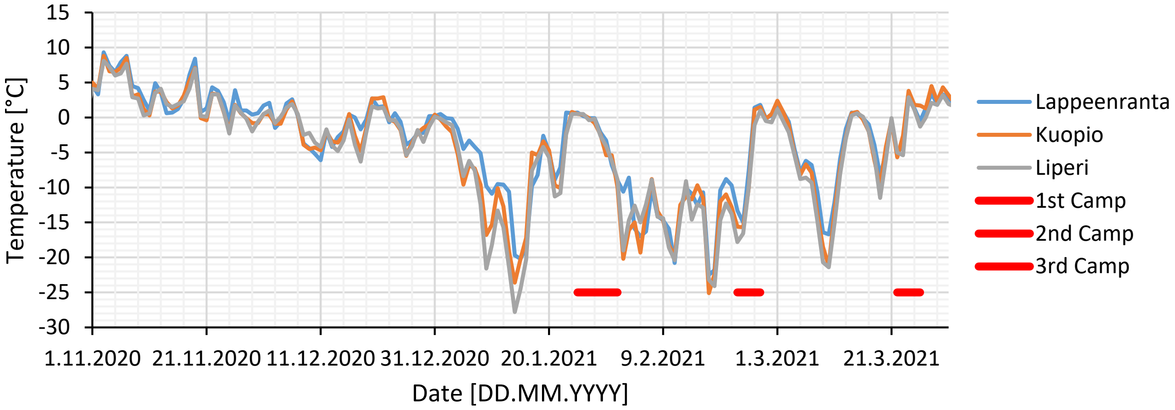

Figure 3. Daily temperatures at 0:00 (UTC+0) measured at weather stations in different parts of Saimaa during the winter 2020-21 and the time of the campaigns. The data has been obtained from FMI data services (FMI, 2021).

Tiuruniemi – 3-point bending measurements on Jan 26, Feb 22 & 26, Mar 22: The measurements on Jan 26 were conducted between the ship route and shore. The ice was transparent and 20 cm thick with no snow. The same location was not accessible in February. The location was moved along the shore approximately 500 m away. Due to the cold period, the ice was fragile that made it difficult to handle and only few measurements were successful on Feb 22. The raise in the temperature made the ice less fragile and more measurements were successful on Feb 26. However, the location was again changed approximately 200 meters along the shore still in the vicinity of a shipping route. The thickness in the location was 30 to 35 cm of which 20-25 cm was transparent ice and 10 cm frozen snow. The ice was covered by a 20 cm of snow. In March, the measurement location of the first campaign had melted due to a strong current, and the location of the second campaign was not accessible due to ice breakage. The measurements were conducted approximately 200 meters away from the first campaign location to the opposite direction along the coast with respect to the second campaign location. The ice thickness was 48 cm of which 35 cm was transparent ice at the bottom, and the top layer had a 13 cm layer of snow ice.

Kyläniemi - 3-point bending measurements on Jan 27, Feb 23, Mar 23: The measurements on Jan 27 we conducted approximate 400 m SW from Haikanniemi nearly 750 m away from the shipping route. Ice thickness was 14 cm with only a small cover of slush. The same site was revisited on Feb 23 and Mar 23. The low temperature with strong wind made the ice too fragile to be handled ex-situ in February. All the prepared samples cracked prior testing, as cracks formed rapidly after lifting the sample out from the water. Thus, no successful measurements are available from February. In March, ice was less fragile, and the measurements were possible. The ice was 45 cm thick of which 15 cm top layer was snow ice.

Vitasniemi – 3-point bending measurements on Jan 29, Mar 25: The measurements were conducted approximately at the same location 500 m away from the shore towards the shipping route. On Jan 29 the ice field was covered by 15-20 cm snow layer. The ice seemed to consist of two layers, a 6 cm top layer of ice formed from frozen snow and 14 cm clear bottom ice. In March, the total thickness had increased to 45 cm of which 22 cm was transparent bottom ice and 22 cm frozen snow ice. The air temperature increased during the day and the top layer seemed to get weaker along the day.

Puutossalmi – 3-point bending measurements on Feb 1, Mar 24: The measurements were conducted approximately 200 m towards south from the western point of the ferry channel. The ice had approximately 30 cm snow layer, and the ice was clear and had a thickness of 23 cm in February. Due to the cold air, the equipment malfunctioned and only few measurements could be executed. When the site was returned in March, the thickness of the clear ice had remained the same, but the total ice thickness was 52 cm of which 29 cm was snow ice.

4. Results

The measurements were conducted in seven locations during the first campaign. Two and four of these locations were revisited during the second and third campaigns, respectively. The flexural strength and strain modulus were measured in these occasions applying the 3-point bending test. As the first campaign focused on comparing the influence of the testing method on the results, the flexural strength of the top surface was only determined during the first campaign.

By the time of the second and third campaign, the thickness of the ice sheet had grown from the first campaign. The ice had to be cut in horizontal layers to fit the samples in the testing rig. Testing in the second and third campaign included the flexural strength of the top, middle and bottom layers. In these cases, the horizontal separation was done at the border of the snow and clear ice. In a case of top and middle layers, the top surface of the sample was put in tension, while for bottom samples the bottom was in tension. In Tiuruniemi and Kyläniemi, the top layer of the second and third campaigns was snow ice. In Puutossalmi, the top and mid layers were snow ice in the third campaign. In Vitasniemi, the top layer in the third campaign was snow ice and in the first campaign a mixture or snow ice and clear ice. In these cases, the snow ice layer was put in tension, as it was the topmost layer in the field. In other cases, the samples had only clear ice layer.

Figure 4 presents the results from the individual measurements from the revisited locations. The samples and tests are numbered in a manner that the first number gives the campaign. The second number presents the number of the sample in the location. Due to the sample preparation method, variation occurred in the tested samples. The common L_{sup} was 1.4 m. The average width and height were 0.15 m and 0.16 m with standard deviations of 0.019 m and 0.029 m, respectively. Table 2 presents the average of the measured densities from the days the 3-point bending tests were conducted. The average values calculated from the measurements shown in Figure 4 are presented in Table 3 and Table 4.

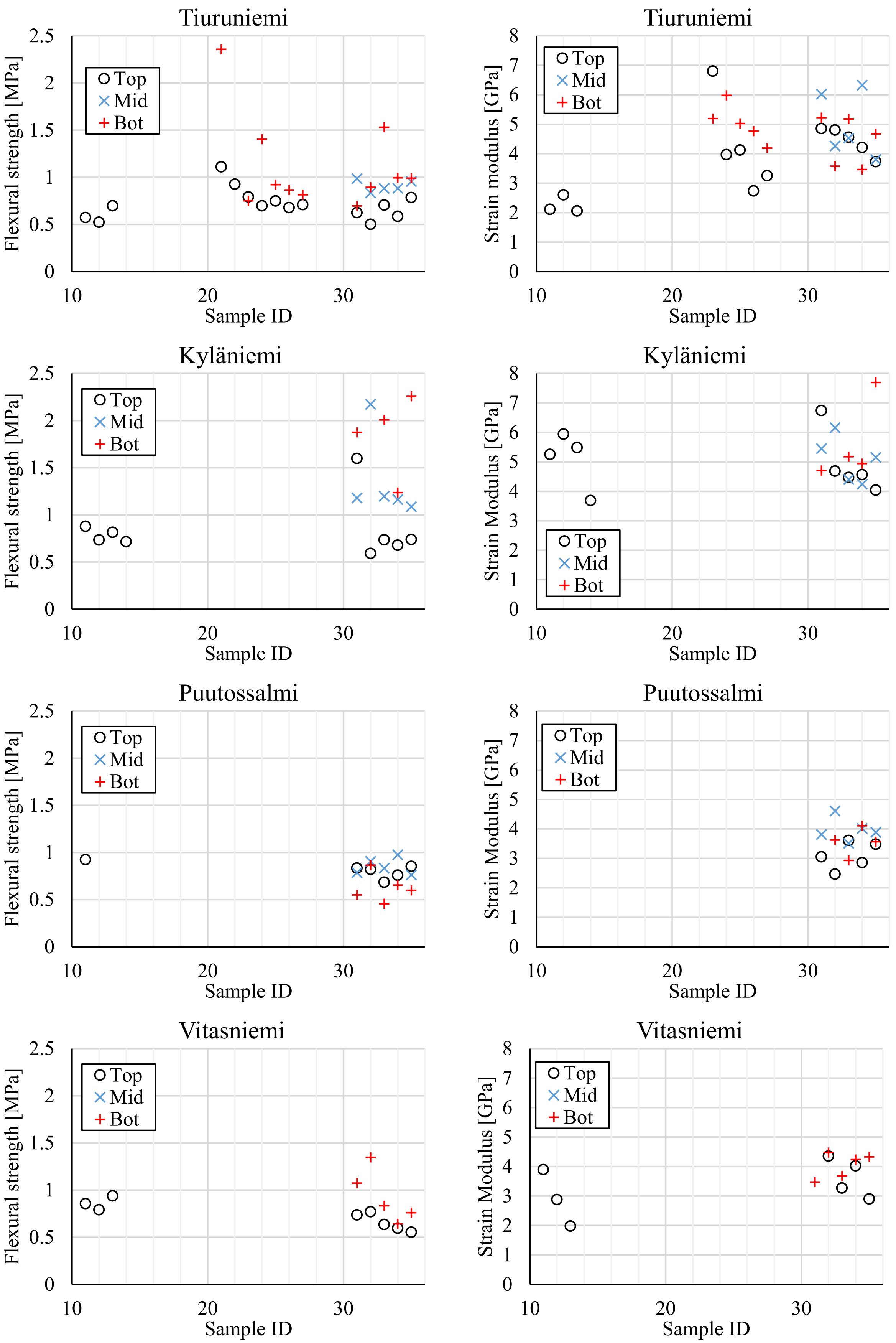

Figure 4. Measured flexural strengths during the three campaigns. The first and second number in Sample ID give the campaign and the order of the sample in the location, respectively.

Table 2. Measured densities during the campaigns.

	25.1.2021	26.1.2021	27.1.2021	29.1.2021	30.1.2021	31.1.2021	1.2.2021
Density [kg/m^3]	885.4	908.3	913.9	883.7	912.1	860.1	876.8
	22.2.2021	26.2.2021		22.3.2021	23.3.2021	24.3.2021	25.3.2021
	906.8	890.1		902.6	886.8	903.2	882.5

Table 3. The average measured flexural strengths of different layers in different locations. Brownish cell indicates snow ice samples and light brownish mixture of snow and clear ice.

Location	Date	Number of good tests [-]			Average flexural strength [MPa]		
		Top	Mid	Bot	Top	Mid	Bot
Päihäniemi	25.1.2021	1			0.8		
Tiuruniemi	26.1.2021	3			0.6		
	22.2.2021	2		1	1.0		2.4
	26.2.2021	5		5	0.7		1.0
	22.3.2021	5	5	5	0.6	0.9	1.0
Kyläniemi	27.1.2021	4			0.8		
	23.3.2021	5	5	4	0.9	1.4	1.8
Vitasniemi	29.1.2021	3			0.9		
	25.3.2021	5		5	0.7		0.9
Vehkaniemi	30.1.2021	3			0.8		
Siilinjärvi	31.1.2021	3			0.7		
Puutossalmi	1.2.2021	1			0.9		
	24.3.2021	5	5	5	0.8	0.9	0.6
	Total	**45**	**15**	**25**	**0.8**	**1.0**	**1.3**

Table 4. The average measured strain modulus of different layers in different locations. Brownish cell indicates snow ice samples and light brownish mixture of snow and clear ice.

Location	Date	Number of good tests [-]			Strain modulus [GPa]		
		Top	Mid	Bot	Top	Mid	Bot
Päihäniemi	25.1.2021	1			4.7		
Tiuruniemi	26.1.2021	3			2.3		
	22.2.2021	0		0	na		
	26.2.2021	5		5	4.2		5.0
	22.3.2021	5	5	5	4.4	5.0	4.4
Kyläniemi	27.1.2021	4			5.1		
	23.3.2021	5	5	4	4.9	5.1	5.6
Vitasniemi	29.1.2021	3			2.9		
	25.3.2021	4		5	3.6		4.0
Vehkaniemi	30.1.2021	3			2.6		
Siilinjärvi	31.1.2021	1			2.7		
Puutossalmi	1.2.2021	0			na		
	24.3.2021	5	5	4	3.1	4.0	3.6
	Total	**39**	**15**	**23**	**3.7**	**4.7**	**4.5**

Figure 4 and Table 3 do not show a clear seasonal variation in the measured flexural strength. The measurements in Tiuruniemi and Kyläniemi indicate a small increase in the strength while Puutosniemi indicates no change and Vitasniemi indicates decreasing strength. It is noted that the strength had a decreasing trend in in Vitasniemi along the day that decreased the values at noon during the measurements in March. On the opposite, the strength shows increasing trend from top surface to the bottom. Figure 4 and Table 4 do not show any clear trend for the strain modulus along the season. Figure 5 presents the measured ratios between the strain modulus and flexural strength from all the samples where both measurements are available. As Figure 5 shows, the measured ratios were mainly between 2500 and 9000. The average for the top, middle section, and the bottom are 5400, 4700, and 4700, respectively.

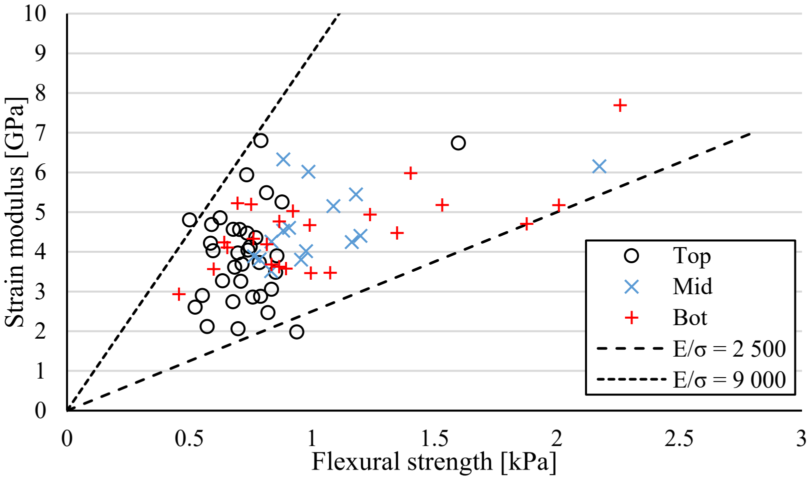

Figure 5. Measured strain modulus as a function of the measured flexural strengths from the 3-point bending measurement tests conducted in all the campaigns.

5. Discussions

The results indicate that the flexural strength and the strain modulus remain approximately the same or have a mild increase from January to the end of March. The measurements in January were conducted during a relatively warm period while the March measurements took place after a colder period. Earlier study considering the seasonal variation in flexural strength of freshwater river ice by Fransson (2002) indicated that the flexural strength decreases from December along the spring. However, the measurements scattered, and high strength values were also measured in April. The measurements by Frankenstein (1961) indicate a large scatter and no clear decrease in the values, until the strength collapses in April. Thus, it is considered that the results presented here are in line with earlier measurements. The strength values remain relatively constant through the season, until they come rapidly down. Our measurements did not indicate clear decrease, but it is anticipated that such would have been encountered, if the measurements would have been continued through April.

Frankenstein (1961) and Gow (1977) suggest that the flexural strength is larger when the surface is in tension in comparison to the bottom. The results in this paper indicate the opposite, i.e. the strength is more commonly higher when the bottom is in tension. In Tiuruniemi and Kyläniemi on March 22 and 23, respectively, top layer consisted of snow ice that explains the weaker surface, but the clear middle section is also weaker than the bottom. On the opposite, in Puutossalmi on March 24 the top and middle layers consisted of snow ice, but those were stronger than the bottom. The reason for this difference to earlier measurements in the results is not known and requires further studies.

6. Conclusions

This study presented the flexural strengths and strain modulus measured during the three measurement campaigns in different parts of Saimaa in January, February, and March 2021. The measurements did not show clear trends in flexural strength or stain modulus values between the campaigns or locations. However, the measurements indicate that the flexural strength increases towards the bottom of the ice, except on one occasion. The average measured flexural strengths were 0.8 MPa, 1.0 MPa, and 1.3 MPa for the top, middle and bottom layers, respectively. The corresponding average strain modulus were 3.7 GPa, 4.7 GPa, and 4.5 GPa. The measured ratio between the strain modulus and flexural strength varied between 2000 and 9500. The average ratios for the top, middle and bottom layers were 5400, 4700, and 4700, respectively. Samples were collected for structural analysis of ice. The analysis of the structure is still ongoing and will be left for the future studies.

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