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Thickness design charts

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Järnsand är en biprodukt från Bolidens Rönnskärs kopparframställning. Den har god isolering och dränerande egenskaper. Här har tjäldjups- och tjällyftsberäkningar utförts för att förbereda diagram och tabeller för bestämning av lagertjocklekar av järnsand i vägar och gator, typiskt avsedda för bostadsområden, parkeringsplatser och andra låg- till medeltrafikerade vägar, samt för markisolering.

För att generera konstruktionsdiagrammen och konstruktionstabellerna användes en beräkningsmetod baserad på segregationspotential. Metoden gör det möjligt att förutsäga både tjällyft och frostpenetrationsdjup i en vägkropp för förbestämda vintertemperaturer eller frysindex. Det utarbetades därför diagram för lagertjocklek och tabeller för järnsand, för vägar för olika nivåer av maximalt tillåten tjällyft motsvarande 50, 80, 100 och 120 millimeter. För markisolering utformades däremot diagrammet eller tabellen för att eliminera all påverkan av tjäle i marken. Utöver tjälberäkningarna, utfördes två triaxialförsök för att utvärdera järnsandens bärförmåga. De begränsade testresultaten indikerade att järnsandens bärförmåga liknar konventionell sand både när det gäller styvhetsegenskaper och permanent deformationsbeteende.

Nyckelord

Järnsand, Tjällyft, Tjälldemensigering, Markisolering, Triaxialförsök.

Abstract

Frost depths and frost heaving calculations were performed to prepare design charts and tables for the iron sand (järnsand) layer thickness design for roads typically used for residential area, parking lots and other low to medium traffic roads, and for ground insulation.

A segregation potential based frost design method was employed to generate the design charts and tables. The segregation potential method allows the prediction of both frost heaving and frost penetration depth of a pavement structure for a prescribed winter temperature profile or freezing index. Thus, the iron sand layer thickness design tables/charts for roads were prepared for different levels of maximum permitted heaving criteria of 50, 80, 100, and 120 mm. Whereas for ground insulation, a design chart/table was prepared to eliminate any frost action in the ground. In addition to the frost design calculations, two triaxial tests were conducted to evaluate the bearing capacity of the iron sand material. The limited test results indicated that, the bearing capacity of iron sand is similar to conventional sand both in terms of stiffness as well as permanent deformation behavior.

Keywords

Iron sand, Frost heave, Frost design, Ground insulation, Triaxial test.

Preface

VTI was commissioned by the Boliden Mines to prepare a järnsand thickness design chart or table as a frost protection layer for roads typically used for residential area and parking lots. The design charts and tables were generated using frost design method based on a segregation potential. A limited number of triaxial tests were also conducted to check the bearing capacity of the järnsand layer. The report presents the design charts for the thickness of the järnsand layer as well as the results of the triaxial tests. The project began in 2021 shortly after the summer.

Per Boström from Boliden Mines was the contact person for the project.

Linköping, October 2022

Abubeker Ahmed
Project leader

Granskare/Examiner

Björn Kalman, VTI

De slutsatser och rekommendationer som uttrycks är författarens/författarnas egna och speglar inte nödvändigtvis myndigheten VTI:s uppfattning./The conclusions and recommendations in the report are those of the author(s) and do not necessarily reflect the views of VTI as a government agency.

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1. Background

One of the main causes of pavement damage in cold regions is frost action. Frost action refers to the damage caused to roads due to freezing and thawing of water which is trapped within the subgrade or the subsoil immediately below the subgrade. Three conditions must exist for frost action to occur, i.e., water, freezing temperature and frost susceptible soil layer (Doré and Zubeck, 2009; Zeinali, Dagli and Edeskär, 2016). The freezing of the moisture stored in the pores and ice lenses formed due to capillary action of water to the frost front (ice segregation) leads to an upward displacement (also called frost heave) of the frost susceptible soil layer which eventually leads to cracking or unevenness of the pavement surface (Doré and Zubeck, 2009; Zeinali, Dagli and Edeskär, 2016). The frost heave due to freezing of the moisture stored in the pores (in situ freezing) is relatively small compared to the ice lenses formed due to ice segregation (Fredlund et al., 1991). This is because the volume of water stored in pores expands by about 9% while the formation of the ice-lenses due to ice segregation continues as long as water is available in the surrounding and there is little overburden pressure to balance the heaving pressure (Fredlund et al., 1991).

Frost action involves a complex interaction of heat flow, movement or migration of water, and the suction buildup due to heaving (Shoop, 2020). Factors affecting the rate of frost penetration into the pavement are temperature gradient, solar radiation, wind speed, air temperature, the material and water content of the pavement and subgrade. Understanding the mechanisms of the frost action is thus vital to select the appropriate mitigation strategy that limit the damage due to frost action.

To limit the effects of frost action in roads, mitigation measures involving structural design considerations as well as other techniques are applied to the base, subbase, and subgrade layers. The measures generally involve eliminating one of the three conditions that must exist for the frost action to occur which are access to water, freezing temperature, and frost susceptible subgrade. The two common measures are to provide good drainage system that removes access to water from the system and/or to utilize a thermal insulation layer that keeps the freezing temperature from penetrating the frost susceptible subgrade layer. Thicker pavement, base, or subbase layer are also employed to keep the frost from reaching the frost susceptible subgrade layer.

In Skellefteå municipality, north of Sweden, iron sand (locally known as Järnsand) has been used as a road subbase layer to limit road damage due to frost action. Iron sand is a by-product from Boliden copper production. It has good insulating and drainage properties (Boliden). 90% of the iron sand material is within the sand fraction (Sweco Viak, 2004). Its bulk density is 2120 kg/m^3. Its dry density is 2060 kg/m^3 while its thermal conductivity 0.45 w/mK (Swerim, 2021). Figure 1 shows an image of the iron sand from Boliden.

Figure 1. Iron Sand (Järnsand) material. Foto Boliden.

This report presents design charts/tables that can be used to determine the thickness of the iron sand subbase layer required to limit the frost heaving of roads typically used in residential area, parking lots and other low to medium traffic areas. The report describes the methods and assumptions, as well as presents the data used for the analysis conducted to generate the design charts and tables.

2. Methods and Data

2.1. Frost heave

The Seppo-Saarelainen-Routanousu (SSR) frost heave model was used for this work (Saarelainen, 1992). The SSR model applies thermal equilibrium at the freezing front and the theory of segregation potential (SP) to estimate the frost penetration depth as well as the frost heave. According to the theory of segregation potential, the rate of water flow to the freezing front is directly proportional to the temperature gradient at the level of ice segregation. The coefficient of proportionality is called segregation potential (SP). The mathematical expression of the SSR mode is given in Equation 1.

Equation 1

$$k_f \nabla T_- \quad = \quad L\frac{\Delta z_0}{\Delta t} \quad + \quad k_t \nabla T_+ \quad + \quad L_w SP\, \nabla T_-$$

Where:

$k_f \nabla T_-$ = heat flow through the frozen layer, Stefan (1891)

$L\frac{\Delta z_0}{\Delta t}$ = heat flow generated by the freezing pore water, Stefan (1891)

$k_t \nabla T_+$ = heat flow from the unfrozen ground, Skaven Haug (1971)

$L_w SP\, \nabla T_-$ = heat flow generated by the ice segregation, Konrad & Morgenstern (1981)

Where Δz_0 is frost front penetration during a time increment Δt. SP is segregation potential. L_w is latent heat of water fusion. k_t and k_f are thermal conductivities of the unfrozen ground and frozen ground at the frost front, respectively. L is latent heat of frozen ground fusion at the frost front. $\nabla T+$ is temperature gradient of the unfrozen ground. $\nabla T-$ is temperature gradient of the frozen ground at the segregation front.

The input data required for the SSR model are winter temperature, frozen and unfrozen conductivities of the pavement layers, the latent heat of soil as well as dry densities of the pavement layers. The input data used for the analysis are described in the following sections.

2.1.1. Temperature data

The temperature data for the analysis was obtained from historical measurements of freezing temperatures (Erlingsson and Saliko, 2020). The data considered covers climate zones 3, 4 and 5. Figure 1 shows the minimum, maximum and mean of the calculated freezing indexes for each measurement station, which are based on 10 years of measurements, from 2007–2017.

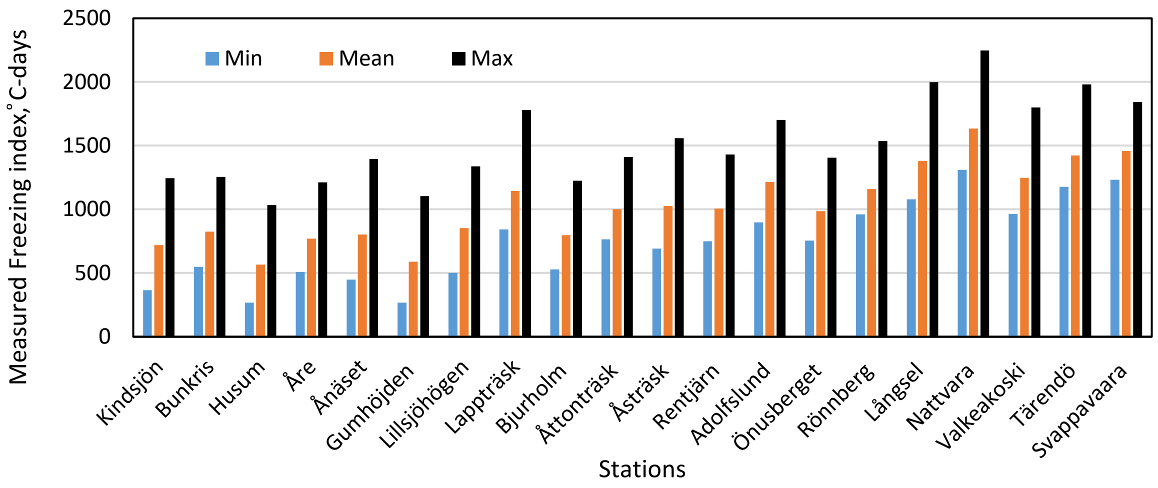

Figure 2. Mean, minimum, and maximum values of freezing index values based on 10 years of measuremnt.

2.1.2. Materials

The material properties required for the analysis of frost heave and frost penetration are frozen and unfrozen thermal conductivities, latent heat of fusion, dry density, porosity, water content, and the segregation potential or SP value. For the iron sand, measured values of thermal conductivities, densities, porosity, and dry density were used whereas nominal values from published reports were used for asphalt concrete, granular base, and subgrade materials (VVMB 301:2001). Table 1 shows the properties of the materials used for the analysis. The ranges of the SP values for different classes of frost susceptible subgrade materials are shown in Table 2. For this work, subgrade materials with frost susceptibility class of 2, 3 and 4 according to the classification by the Swedish Transport Administration (TDOK, 2011) were considered. The SP values for medium, high, and very high frost susceptible materials corresponding to class 2, 3 and 4, respectively from available literature was used for the analysis (St-Laurent, 2006). For the sake of comparison, thermal conductivities of other insulating materials, XPS and foam glass are also shown in Table 1. Table 2 shows the range of SP values for frost susceptible subgrade materials.

Table 1. Thermal properties of the materials used for the analysis.

Layer	Unfrozen conductivity (w/mK)	Frozen conductivity (w/mK)	Dry density (g/cm³)	Water content (%)	SP (mm²/°Ch)
Asphalt concrete	2.0	2.0	2.24	1	0
Granular base	1.56	2.04	2.04	3.5	0
Iron sand	0.45	0.45	2.06	5	0
Extruded polystyrene XPS	≤ 0.035	≤ 0.035	-	-	-
Foam glass	≤ 0.045	≤ 0.045	-	-	-
Subgrade	1.52	2.51	1.63	24	3, 8, 15

Table 2. Recommended SP values of frost susceptible subgrade materials (St-Laurent, 2006).

Frost susceptibility	SP (mm²/°Ch)
Negligible	<0.5
Low	0.5 - 1.5
Medium	1.5 - 3
High	3 - 8
Very high	> 8

2.1.3. Pavement structures and ground insulation layer

Pavement structures that are mainly used for roads in residential or parking areas and for typical medium traffic volume roads were considered in the analysis. Additionally, a two-layer system consisted of an iron sand and subgrade/ground was also analyzed. The roads in residential areas are modelled as a 40 mm thick asphalt surface layer, a 150 mm thick granular base, and an iron sand subbase over subgrade layer. Whereas the medium traffic volume road consisted of a 40 mm thick asphalt surface layer, a 65 mm thick asphalt base, a 150 mm thick granular base, and an iron sand subbase layer over subgrade layer. The cross sections of the pavement structures were shown in Figure 3. The thickness of the iron sand layer for the pavement structures are determined based on the maximum permitted heave criteria for the frost design. A minimum thickness of 300 mm was considered in the analysis.

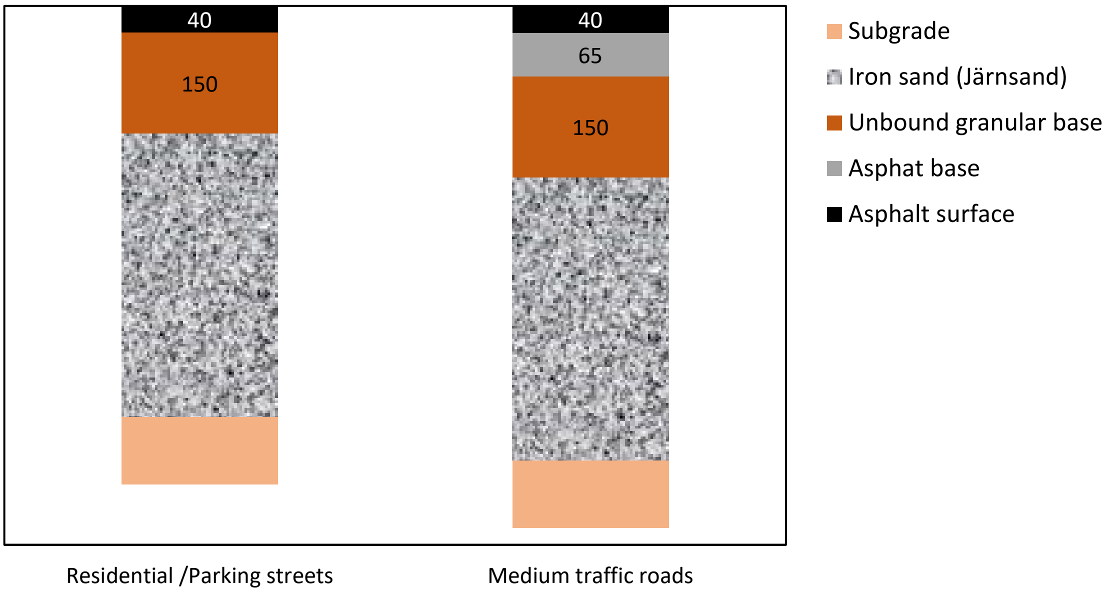

Figure 3. Pavement structures considered for the analysis including the thicknesses of the surface, asphalt base and granular base layers in mm.

Figure 4 shows the analyzed two-layer system, representing an iron sand layer which is used to insulate or protect the subgrade/ground from any frost action. One such application is when the iron sand is used to insulate the ground from frost action before a planned construction during the winter, thus, avoiding the destruction needed to remove the ice-formation. Another application of the two-layer system is when the iron sand is used as an insulation layer under industrial buildings to eliminate the effect of frost action. The thicknesses of the iron sand layer required to limit the frost action on the subgrade/ground were calculated for different values of permitted heave criteria.

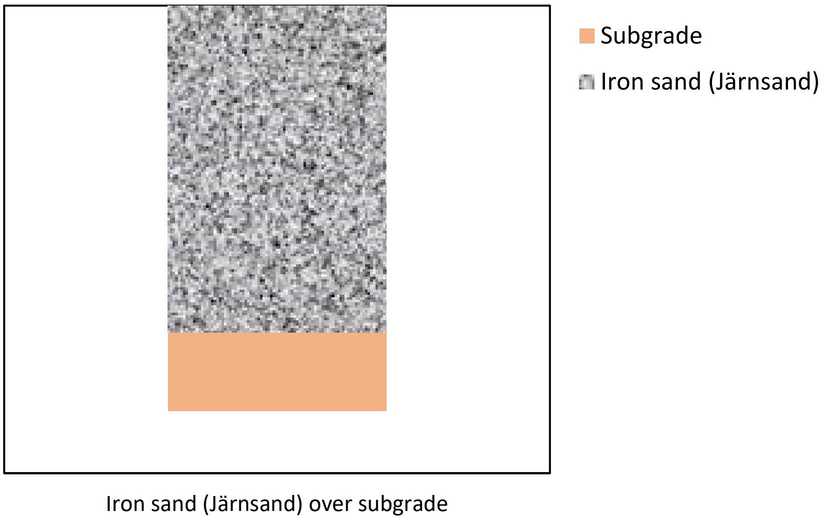

Figure 4. Frost protection/insulation layer.

2.1.4. Frost design criteria

The frost design/analysis was carried out based on the maximum permitted frost heaving criteria. The design charts for the pavement structures are prepared for the maximum frost heave criteria of 50, 80, 100, and 120 mm. Whereas the design chart for the two-layer system is prepared for maximum frost heave criteria of 0 mm, i.e., iron sand thickness required to eliminate any frost action on the ground as in cases of insulation layer. The values of maximum heaving criteria were chosen based on the Swedish Transport Administration's recommendations for the maximum permitted heaving criteria for newly built roads. The maximum permitted frost heave varies with the maximum reference speed of the road. Table 3 shows the frost heave criteria for newly built paved roads (TRV2021/141044).

Table 3. Maximum permitted frost heave for newly built paved roads (TRV2021/141044).

Reference speed (km/h)	**Climate zone**	**Permitted maximum heave (mm)**
120	1 - 5	10
110	1 - 2	20
110	3 - 5	50
100	1 - 5	50
80	1 - 5	80
≤ 60	1 - 5	120

2.2. Bearing capacity

The bearing capacity of the iron sand was evaluated by means of repeated load triaxial tests. The optimum water content of this material was 9.4% and the corresponding maximum dry density was 2.19 ton/m^3, as determined by the modified Proctor method (EN 13286-2). Two triaxial tests were conducted. One with 40% and another with 60% of the optimum water content of the material. The target dry densities of the specimens were about 92% of the maximum dry density of the material. The tests were performed according to the European standard EN 13286-7:2004. The multistage loading procedure with low stress level was adopted for the tests. Figure 5 shows the triaxial test setup.

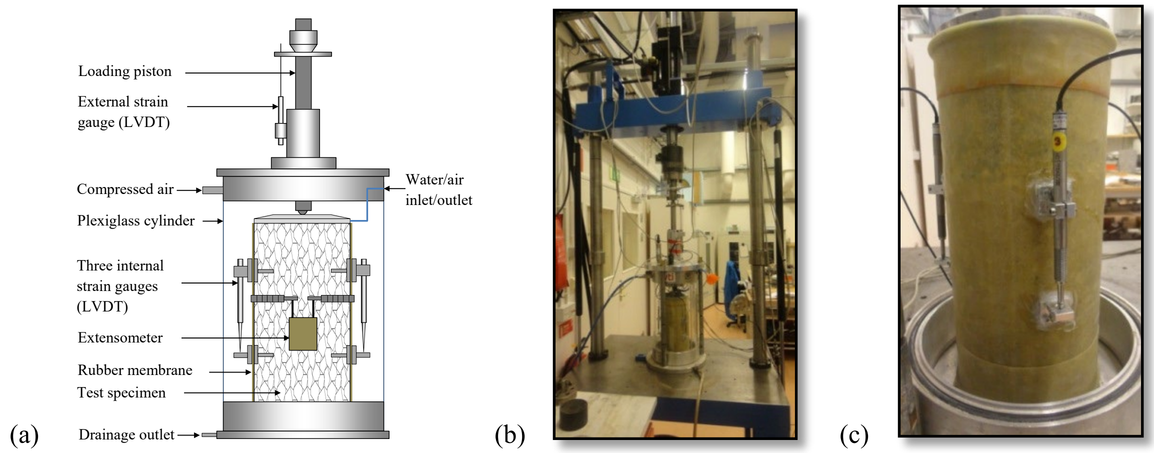

Figure 5. **(***a) Schematic overview of the triaxial test cell, (b) axial deformation gauges mounted on the specimen, (c) triaxial cell placed in the loading frame.*

3. Results

3.1. Frost design charts

The subsequent sections present the frost design charts for frost susceptibility class 2, 3 and 4 according to the classification by the Swedish Transport Administration (TDOK, 2011). In the analyses, it was assumed that water is available in the system or in the frost sensitive material so frost heaving problems are likely to occur.

3.1.1. Residential streets and parking lots

Figure 7, Figure 8, and Figure 9 show the iron sand layer thickness charts for residential and parking area streets shown in Figure 6. The thickness is plotted as a function of the freezing index (FI). Regions for climate zones 3, 4 and 5 which are based on freezing index values, are also shown in the figures.

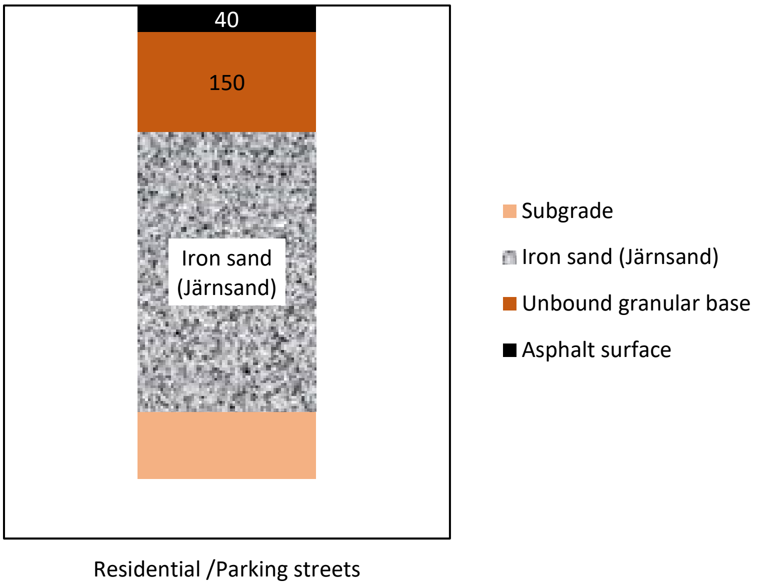

Figure 6. Cross section of a residential and parking area street. The thicknesses of surface and granular base layers are given in mm.

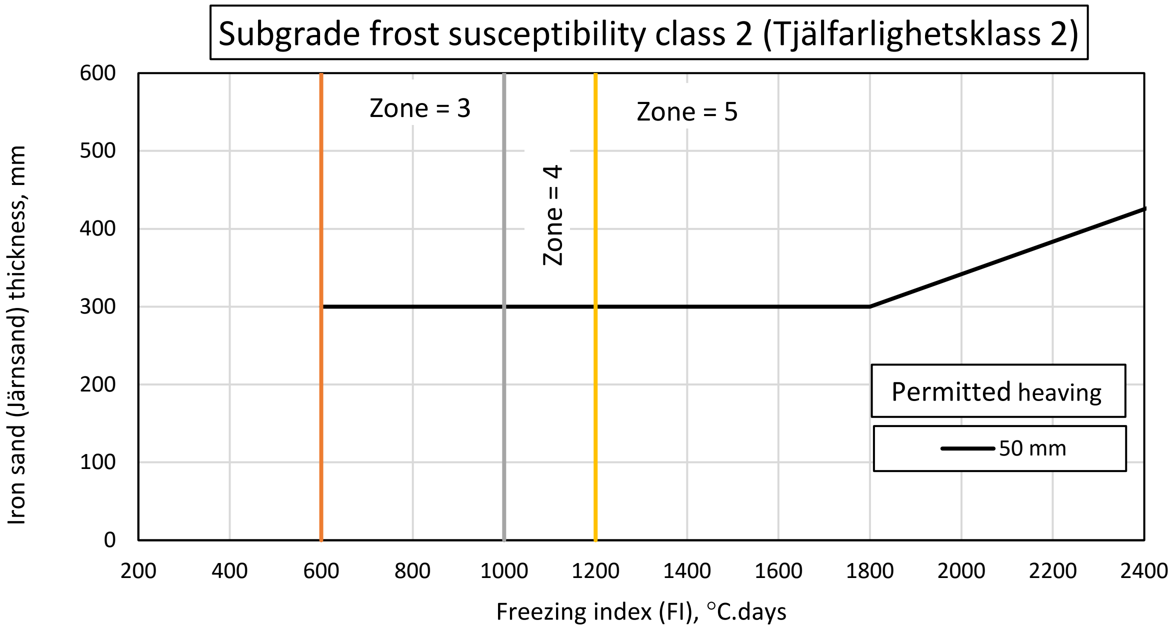

Figure 7. Iron sand layer thickness chart for residential and parking streets on frost susceptible subgrade class 2 and for maximum permitted heaving of 50 mm. Vertical lines indicate climate zones (Zone) based on freezing index values.

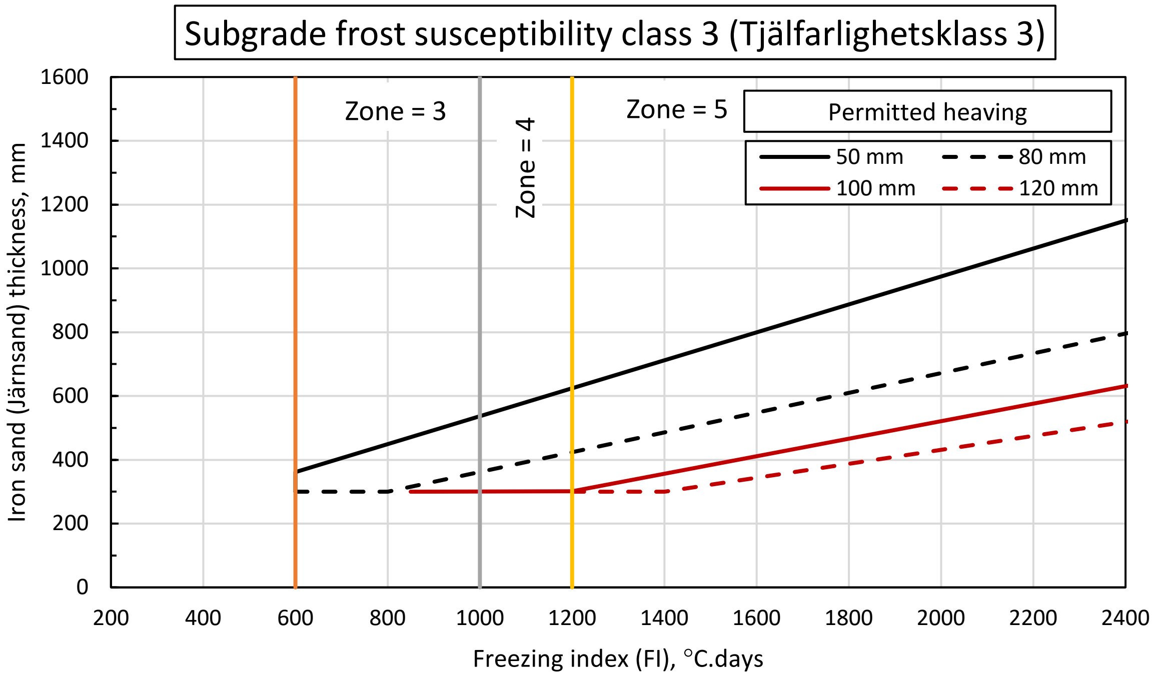

Figure 8. Iron sand layer thickness chart for residential and parking streets on frost susceptible subgrade class 3 and for maximum permitted heaving of 50 mm, 80 mm, 100 mm, and 120 mm. Vertical lines indicate climate zones (Zone).

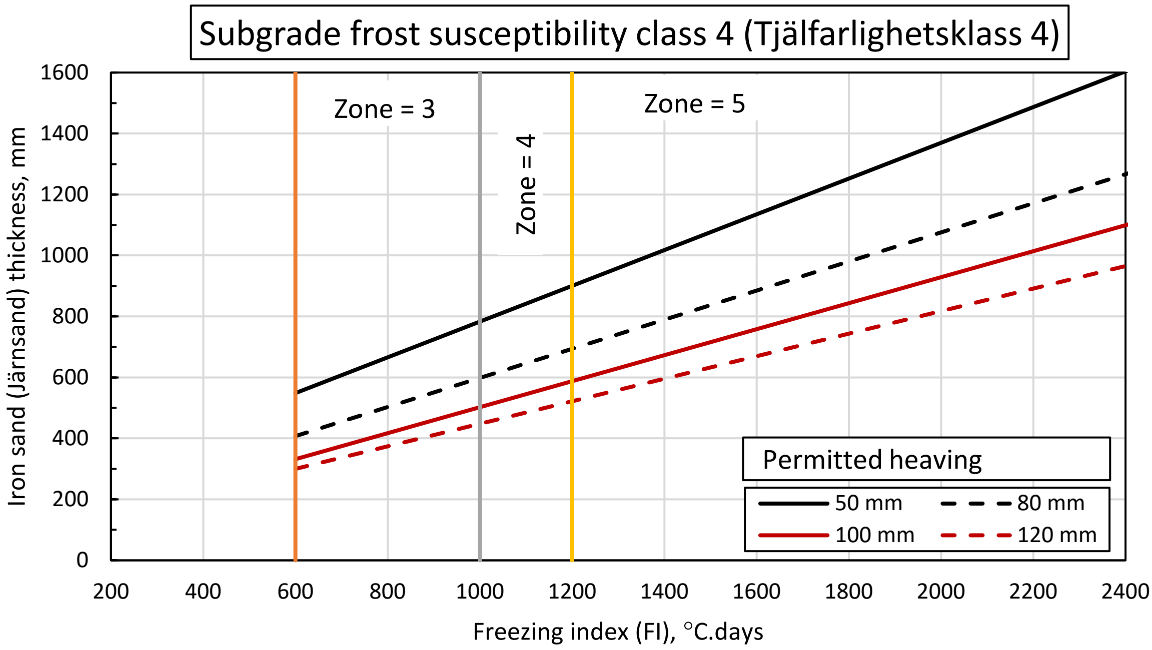

Figure 9. Iron sand layer thickness chart for residential and parking streets on frost susceptible subgrade class 4 and for maximum permitted heaving of 50 mm, 80 mm, 100 mm, and 120 mm. Vertical lines indicate climate zones (Zone).

3.1.2. Medium traffic roads

Figure 11, Figure 12, and Figure 13 show the iron sand thickness charts for medium traffic roads as shown in Figure 10. The thickness is plotted as a function of the freezing index (FI). Regions for climate zones 3, 4 and 5 which are based on freezing index values are also shown in the figures.

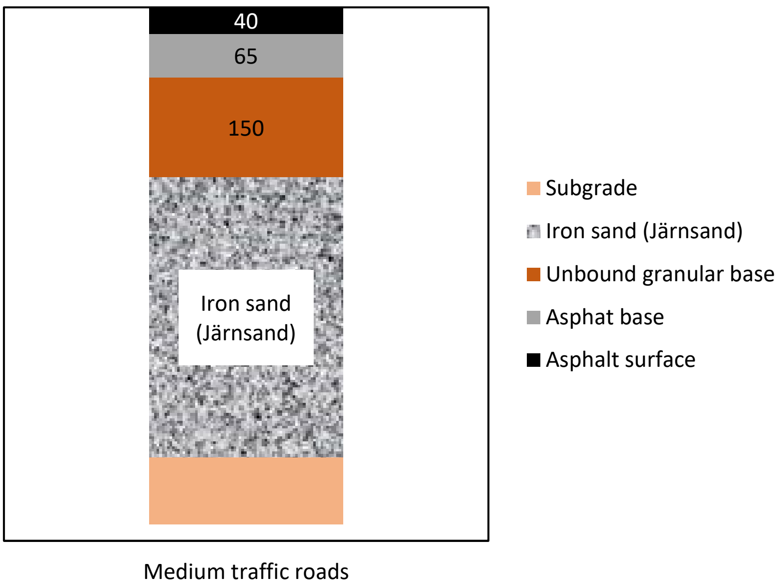

Figure 10. Cross section of a typical low to medium traffic road. The thicknesses of surface, asphalt base and granular base layers are given in mm.

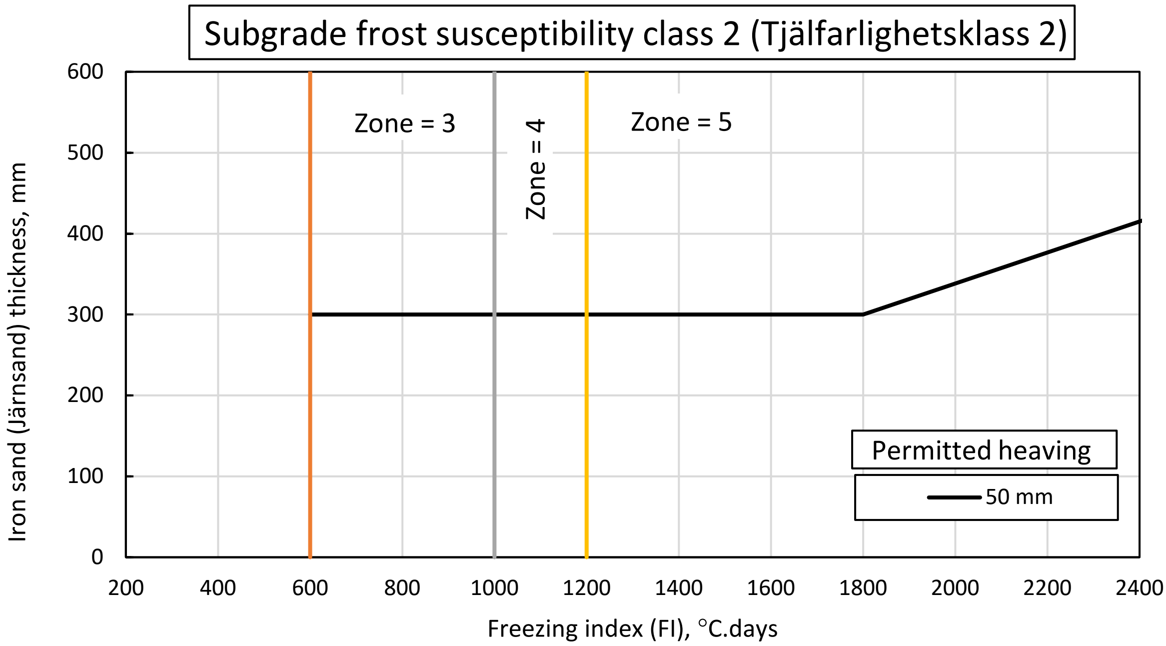

Figure 11. Iron sand layer thickness chart for medium traffic roads on frost susceptible subgrade class 2 and for maximum permitted heaving of 50 mm. Vertical lines indicate climate zones (Zone).

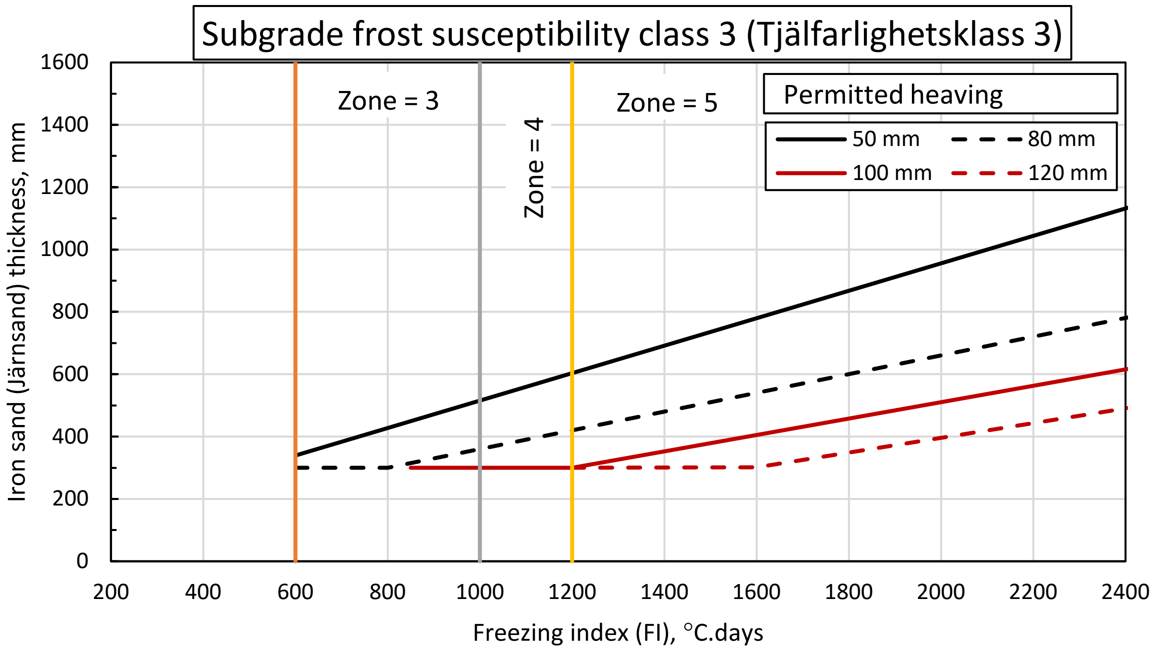

Figure 12.Iron sand layer thickness chart for medium traffic roads on frost susceptible subgrade class 3 and for maximum permitted heaving of 50 mm, 80 mm, 100 mm, and 120 mm. Vertical lines indicate climate zones (Zone) based on freezing index values.

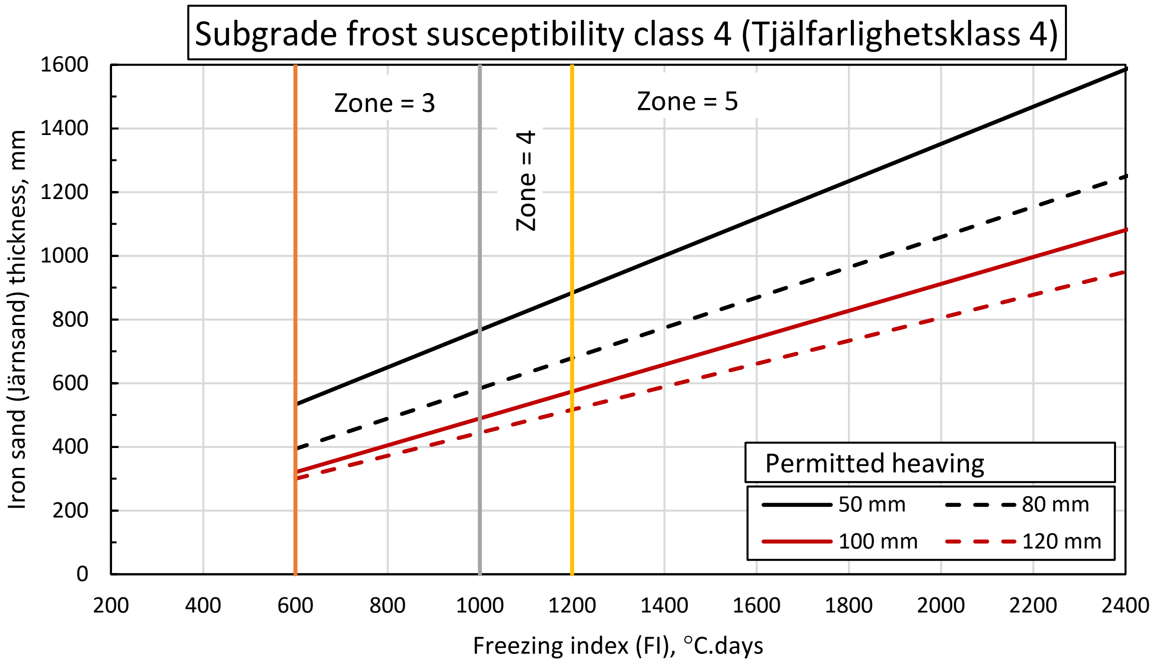

Figure 13. Iron sand layer thickness chart for medium traffic roads on frost susceptible subgrade class 4 and for maximum permitted heaving of 50 mm, 80 mm, 100 mm, and 120 mm. Vertical lines indicate climate zones (Zone) based on freezing index values.

3.1.3. Two-layer system - ground insulation layer

Figure 15 shows the thickness of the iron sand required to protect ground from frost action or when the iron sand is used as frost protection /insulation layer for ground, i.e., iron sand is placed over the subgrade as shown in Figure 14. In this case, the frost is not allowed to penetrate the ground or the subgrade, therefore, the chart is not dependent on the type of the subgrade and a single design chart is presented. The thickness is plotted as a function of the freezing index (FI). Regions for climate zones (Zone) 3, 4 and 5 which are based on freezing index values are also shown in the figure.

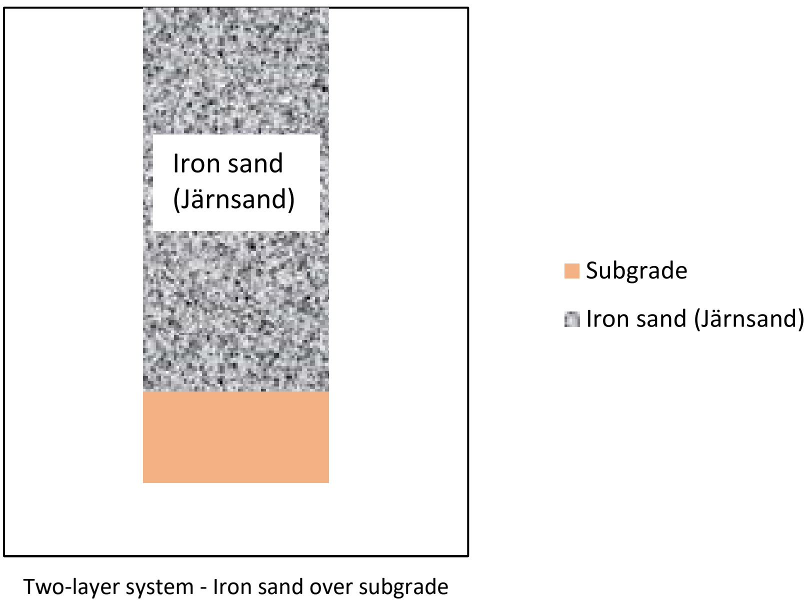

Figure 14. Cross section of two-layer construction with iron sand as ground insulation layer placed directly over the frost susceptible subgrade.

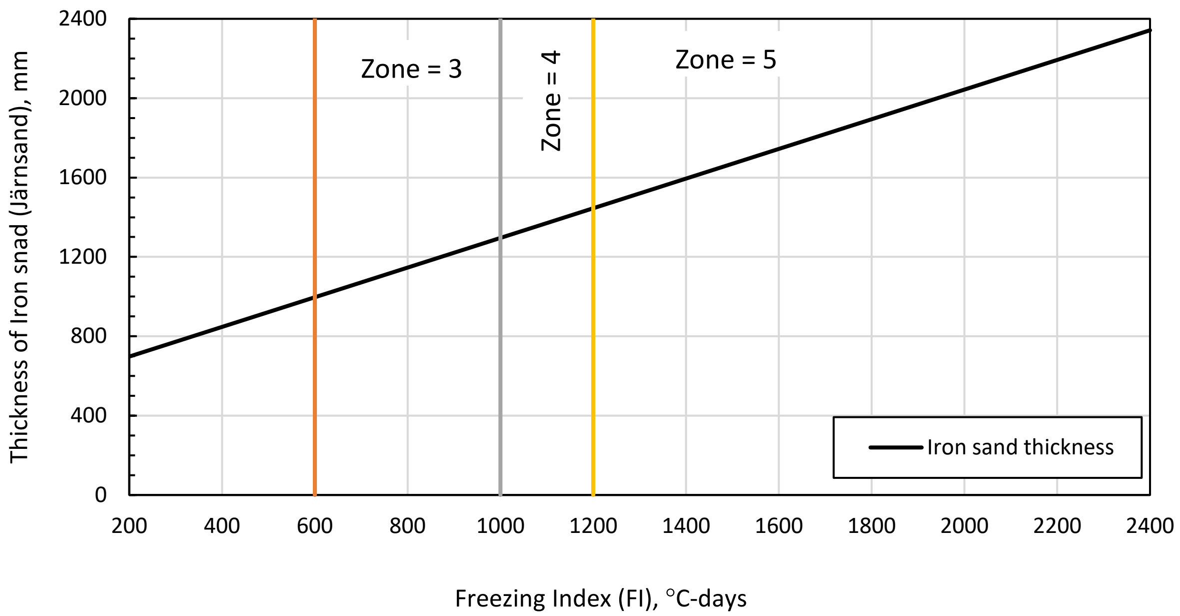

Figure 15. Iron sand layer thickness required as ground insulation layer (zero heaving). Vertical lines indicate climate zones (Zone).

3.1.4. Frost design procedure using the charts and tables

The following provides a step-by-step approach to perform the iron sand layer thickness design using the Charts in sections 3.1.1 and 3.1.2 or Tables in Appendix 1 and 2.

1. Select the road type
2. Determine the frost susceptibility class of the subgrade
3. Determine the freezing index for the project
4. Determine the maximum permitted heaving
5. Select the appropriate chart or table based on the road type and the frost susceptibility class of the subgrade
6. Use the chart or the table to read the thickness of the iron sand (Järnsand) required corresponding to the freezing index and the maximum permitted heaving. Note that the minimum thickness of the iron sand is 300 mm.

3.1.5. Design procedure for ground insulation layer

The following provides a step-by-step approach to perform the iron sand layer thickness design for ground insulation using the Chart in sections 3.1.3 or Table in Appendix 3.

1. Determine the freezing index for the project
2. Use the chart in *Figure* 15 or the table in Appendix 3 to read the thickness of the iron sand (Järnsand) required corresponding to the freezing index (FI)

3.2. Bearing capacity

The accumulated permanent deformation (strain) of the iron sand specimen during the triaxial test is shown in Figure 16. For comparison, triaxial test results of a commonly used sand is also included in the figure. The test results are shown for specimens containing around 60% of their respective optimum moisture contents. From the figure, it appears that the iron sand has very similar permenent deformation resistance as regular sand based on limited avilable data. Thus iron sand can be a very good alternative to ordinary sand with the added benefit of better insulaton properties. It should be noted that as subbase material, iron sand as well as ordinary sand do not have the same mechanical strength as regular crushed rock aggregates. Thus, proper consideration should be given when using iron sand as a pavement subbase layer. Stresses may need to be maintained at relatively low level by using thicker and/or stiffer upper layers (e.g., unbound base and asphalt concrete layers). Consideration should be also given when using this material for roads with medium to high traffic volumes and/or high share of heavy vehicles, i.e., with average daily truck traffic per lane ($ADTk_{Tung}$) of more than 1000 (TRVR Väg, 2011). Based on the limited data, the expected resilient modulus (stiffness) of the iron sand lies in the range of 100 to 150 MPa.

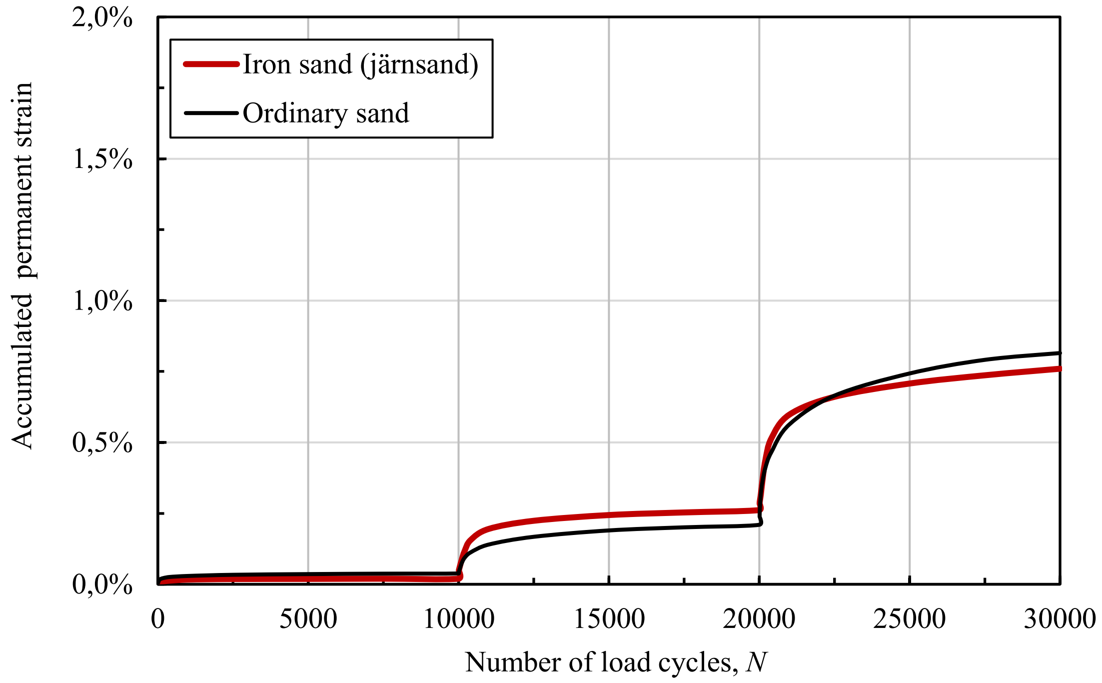

Figure 16. Accumulated permanent deformation (strain) for iron sand and ordinary sand in repeated load triaxial tests.

4. Conclusions

This report employed the Seppo-Saarelainen-Routanousu (SSR) model to calculate the thickness of the iron sand (Järnsand) layer required to control frost heave damage of typical residential streets, parking lots and other low to medium trafficked roads. In addition, the SSR model was applied in a two-layer system to determine the thickness of iron sand layer required for ground insulation that eliminates any frost action in the ground. The SSR model allows the prediction of both frost heaving and frost penetration depth of a pavement structure for a prescribed winter temperature profile or freezing index. Iron sand layer thickness design charts and tables were prepared for the road types considered. The charts and tables were prepared based on historical temperature data corresponding to climate zones 3, 4 and 5 according to the Swedish Transport Administration classifications. Similarly, frost susceptible subgrades of classes of 2, 3 and 4 were considered. Maximum frost heaving criteria of 50, 80, 100, and 120 mm were considered for the analysis. In addition to the frost design calculations, two triaxial tests were conducted to evaluate the bearing capacity of the Järnsand material. The limited triaxial test results indicated that, the bearing capacity of iron sand (Järnsand) is comparable to regular sand both in terms of stiffness as well as permanent deformation behavior. Thus, iron sand can be a substitute for ordinary sand with the benefit of better insulation properties.

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Appendix 1. Iron sand layer thickness tables for residential streets

Table 4. Iron sand layer thickness Table in mm for residential and parking streets on frost susceptible subgrade class 2. Colum headers are freezing index in ℃-days and row headers are criteria or maximum permitted frost heave.

Criteria	400	600	800	1000	1200	1400	1600	1800	2000	2200	2400
50 mm	300	300	300	300	300	300	300	300	335	380	425
80 mm	300	300	300	300	300	300	300	300	300	300	300
100 mm	300	300	300	300	300	300	300	300	300	300	300
120 mm	300	300	300	300	300	300	300	300	300	300	300

Table 5. Iron sand layer thickness Table for residential and parking streets on frost susceptible subgrade class 3. Colum headers are freezing index in ℃-days and row headers are criteria or maximum permitted frost heave.

Criteria	400	600	800	1000	1200	1400	1600	1800	2000	2200	2400
50 mm	300	315	425	530	630	725	820	910	995	1075	1155
80 mm	300	300	300	320	395	465	535	600	670	730	795
100 mm	300	300	300	300	300	350	410	470	525	580	635
120 mm	300	300	300	300	300	300	315	365	415	465	510

Table 6. Iron sand layer thickness Table for residential and parking streets on frost susceptible subgrade class 4. Colum headers are freezing index in ℃-days and row headers are criteria or maximum permitted frost heave.

Criteria	400	600	800	1000	1200	1400	1600	1800	2000	2200	2400
50 mm	325	510	665	810	940	1065	1185	1300	1405	1510	1610
80 mm	300	365	485	600	710	815	910	1005	1100	1190	1270
100 mm	300	300	400	500	595	690	775	865	950	1025	1105
120 mm	300	300	335	420	505	590	670	750	820	895	965

Appendix 2. Iron sand layer thickness tables for medium traffic roads

Table 7. Iron sand layer thickness Table for medium traffic roads on frost susceptible subgrade class 2. Colum headers are freezing index in ℃-days and row headers are criteria or maximum permitted frost heave.

Criteria	400	600	800	1000	1200	1400	1600	1800	2000	2200	2400
50 mm	300	300	300	300	300	300	300	300	320	365	405
80 mm	300	300	300	300	300	300	300	300	300	300	300
100 mm	300	300	300	300	300	300	300	300	300	300	300
120 mm	300	300	300	300	300	300	300	300	300	300	300

Table 8. Iron sand layer thickness Table for medium traffic roads on frost susceptible subgrade class 3. Colum headers are freezing index in ℃-days and row headers are criteria or maximum permitted frost heave.

Criteria	400	600	800	1000	1200	1400	1600	1800	2000	2200	2400
50 mm	300	300	410	515	615	710	800	890	975	1060	1135
80 mm	300	300	300	305	375	450	515	585	650	715	775
100 mm	300	300	300	300	300	335	395	450	505	560	615
120 mm	300	300	300	300	300	300	300	350	395	445	490

Table 9. Iron sand layer thickness Table for medium traffic roads on frost susceptible subgrade class 4. Colum headers are freezing index in ℃-days and row headers are criteria or maximum permitted frost heave.

Criteria	400	600	800	1000	1200	1400	1600	1800	2000	2200	2400
50 mm	310	495	650	790	925	1050	1170	1280	1385	1490	1590
80 mm	300	345	470	585	690	795	895	990	1080	1170	1255
100 mm	300	300	385	485	580	670	760	845	930	1010	1085
120 mm	300	300	315	405	490	575	655	730	805	880	950

Appendix 3. Iron sand for ground insulation layer

Table 10. Iron sand layer thickness Table for two-layer construction where Iron sand is placed directly over subgrade of frost susceptible class 2. Colum headers are freezing index in ℃-days and row headers are criteria or maximum permitted frost heave.

FI (°C-days)	200	400	600	800	1000	1200	1400	1600	1800	2000	2200	2400
Thickness (mm)	490	810	1035	1225	1390	1535	1670	1780	1910	2030	2135	2230

ABOUT VTI

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Our operations cover all modes of transport, and the subjects of pavement technology, infrastructure maintenance, vehicle technology, traffic safety, traffic analysis, users of the transport system, the environment, the planning and decision making processes, transport economics and transport systems. Knowledge that the institute develops provides a basis for decisions made by stakeholders in the transport sector. In many cases our findings lead to direct applications in both national and international transport policies.

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