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Laboratory Examination of Frost-Heaving Properties of Road Unbound Mixtures Based on Fines Content and Plasticity Index

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Abstract
In order to ensure the bearing capacity and durability of road pavement in cold climate areas, it is necessary use materials which are resistant to harmful frost impact, known as frost-heaving. Frost heave cause adverse volume changes, the upwards swelling of the pavement after freezing and deterioration of the bearing capacity of the structure after thawing. In winter, road carriageway temperatures may reach t_{min} = -30°C under Polish conditions, which results in the freezing of the structural pavement and subgrade layers. Due to frost penetration into the pavement and the subgrade, heaves may form in soils and in structural layers (unbound mixtures), and during the thaw period a high level of moisture is maintained in the frozen layers, and therefore the structure has a low bearing capacity. The aim of this research was to evaluate frost susceptibility of aggregates mixtures based on content of fine-grain fractions and plasticity index I_P. Potential frost susceptibility of road materials and soils is determined by laboratory testing. Frost susceptibility is connected directly with the content and quality of fines, which is why the basic test is that material grading. The criterion based on fines content is the most frequently used indicator in determining frost susceptibility for soils. The article shows whether the limit values adopted for this criterion are also applicable to aggregates. The results of frost-heaving properties are presented of 14 typical natural aggregate road mixtures, continuously graded 0/31.5 mm. Frost susceptibility was determined based on laboratory testing of the following features: content of fine-grain fractions, smaller than 0.002mm, 0.02mm, 0.075mm, 0.125mm, plasticity index I_P and the value of the actual frost-heave of a compacted aggregate mixture frozen in a cylinder. The article shows the test results and their analyses according to the frost susceptibility evaluation criteria for unbound mixtures in road construction. The tests presented in the article were carried out at the Road and Bridge Research Institute in Warsaw.

Keywords: road base, frost susceptibility, frost heave, unbound mixture, aggregate, grain size, plastic limit, liquid limit, plasticity index

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1 Introduction

Road pavement is a multi-layer system consisting of: surface layer, road base and sub-base, frost blanket or drainage layer (if required) laid on load bearing subsoil. The average thickness of road structures, depending on traffic volume, ranges from 30 to 90 cm, which means that these layers and the subsoil are exposed to the negative impact of frost and temperature changes. Soil freezing depth in Poland reaches even up to 140 cm. The possibility of subsoil freezing results from limited anti-frost protection applied in road structures in many countries (Kraszewski *et al.* 2014). Road structure layers should thus be characterized by resistance to frost action (Kraszewski, 2008), i.e. resistance to freezing and thawing cycles (mechanical stability) and resistance to the occurrence of frost heaves (volumetric stability).

In the subsoil and unbound aggregates containing silty and clayey fractions intended for road bases, the phenomenon of frost susceptibility, to which much research has been devoted in Poland, (Rafalski and Wilczek, 2006, 2012; Rafalski, 2007; Rafalski, 2009; among others) may occur. The occurrence of a heave consists of the creation of ice lenses in the soil or aggregate or ice layers as a result of increasing the volume of frozen water and attracting water to the frost zone. In the winter, under the conditions in Poland, road carriageways may reach the temperature of t_{min} = -30˚C (Rafalski, 2007), as a result of which the pavement structure and subsoil layers freeze. Frost penetration inside the pavement and subsoil causes heaves to occur in soils and unbound mixtures and, in the period of thawing, high moisture level and related low bearing capacity of the structure maintain. Technical requirements concerning unbound mixtures (WT-4, 2010) introduced in Poland in connection with the implementation of the European standards, evoked many discussions on the method of aggregate frost susceptibility determination with the sand equivalent SE_4 as per standard EN 933-8:2001 and the adopted requirement level: SE_4^{min} = 35 to 45 relevant to other countries (Nikolaides *et. al,* 2007, COST 337, 2000). While expressing opinions on these requirements, the doubts of many road contractors and aggregate manufacturers arose due to too rigorous requirements regarding the value of sand equivalent, limiting the use of aggregates present in the country. Other geotechnical properties applied in some countries for determining the material frost susceptibility e.g. plasticity index I_P or methylene blue MB_F were used as an argument. The suitability of the plasticity index was particularly substantiated and it was argued that this parameter should be accepted for the assessment of road aggregate frost susceptibility.

In connection with the aforementioned doubts, laboratory tests of 14 local natural aggregate road mixtures, continuously graded applied to road base courses were carried out. Frost susceptibility of the aggregates was determined during laboratory testing of the following properties: content of fine-grain fractions, smaller than 0.002mm, 0.02mm, 0.075mm, 0.125mm, plasticity index I_P, and direct frost heave F_H. This article includes test results as regards plasticity index, granulation, direct frost heave and it presents the analysis of relationships between these parameters.

2 Analysed Frost Susceptibility Criteria

Frost susceptibility may be assessed on the basis of granulation, namely fines content. The oldest test method is the method proposed by Casagrade in 1930 (Chamberlain, 1981), which is also being applied today. The method consists of determining of the content of grains smaller than 0.02 mm in the tested material. As per Catalogues (Catalogue 2014-1, Catalogue 2014-2) soil frost susceptibility requirements based on fines content (<0.02mm and <0.075mm), given in table 1, are applied. Around the world (Witczak, 2000; Janoo, 1997) sieve 0.075 mm (sieve No. 200 as per AASHTO) is most often applied and frost susceptibility criteria are presented in table 2.

Particle content	Non-heave soil	Doubtful soil	Heave soil
<0.075mm, %	<15	15 to 30	>30
<0.02mm, %	<3	3 to 10	>10

Table 1: Soil frost susceptibility based on fines content

Agencies	Frost-susceptibility criteria (% passing no.200 sieve)
Asphalt Institute	7
Newfoundland, Canada	6
Japan	6
Alaska	6
Colorado	5÷10
Kansas	15
Maryland	12
Massachusetts	10
Minnesota	10
New Hampshire	8
Ohio	15
Vermont	10
Washington	10
Wisconsin	5

Table 2: Soil frost susceptibility criterion based on sieve 0.075 mm passing

Plasticity index $I_P=w_L-w_P$ is applied for the analysis of cohesive soils and, in some countries, also for the assessment of aggregates. Test of liquid limit w_L and plastic limit w_P is carried out at material passing through sieve with openings of #0.425 mm. Research papers (Janoo *et al*, 1997; Chamberlain, 1981) gave the frost susceptibility criterion on the basis of plasticity index I_P (table 3). In case of $I_P<4$ frost susceptibility is low. If I_P=4 to 6, then frost susceptibility is average. Materials whose $I_P>6$ are considered very heave-susceptible ones. $I_P<6$ is the limit value usually adopted for road materials (Siswosoebrotho *et. al*, 2005, Series 800, 2005).

Material and layer type	I_P	Relative frost- susceptibility
Subbase course	6	medium
Aggregate base course	6	medium
Crushed aggregate base course	4	low
Lime rock base course	6	medium
Sand-clay base course		
Gradation A	4	low
Gradation B	6	medium

Table 3: Frost-susceptibility as a function of the Plasticity Index

3 Materials and Test Methods

Tests were performed on natural crushed aggregate mixtures with granulation of 0/31.5mm. These were typical crushed aggregate mixtures with continuous granulation, applied for the execution of road bases. In petrographic terms, the tested aggregates represented various kinds of rocks: igneous rocks, sedimentary rocks and metamorphic rocks which came from domestic manufacturers. In total 14 rock aggregate mixtures were tested, namely: basalt aggregate (B), granite aggregate (G), lime aggregate (L), dolomite aggregate (D), sandstone (S). The majority of tested materials were of sedimentary origin (lime, dolomite) where higher frost heave properties were expected. Mixtures with potential of low frost susceptibility constituted comparative background (granite, basalt, sandstone). Mixture granulation is presented in Fig. 1.

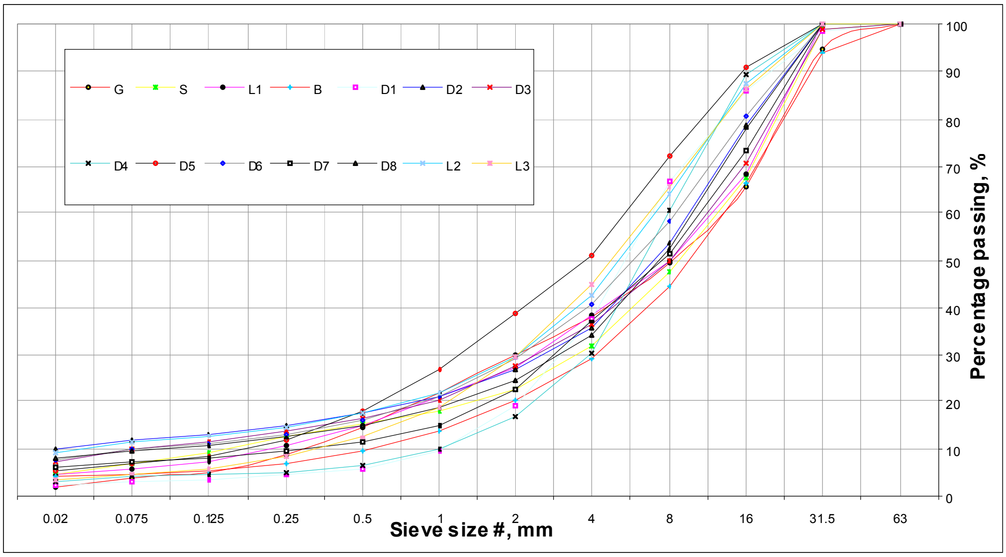

Figure 1: The gradation curves of the tested mixtures

This article presents results of tests of the following geotechnical properties of aggregates:

- granulation (sieve analysis and areometric analysis) as per polish standard PN-88/B-04481 *Building soils. Laboratory tests*.,
- plasticity limit w_P and liquidity limit w_L (with Casagrande method) as per standard PN-88/B-04481,
- optimum moisture and maximum dry density of the mixture as per PN-EN 13286-2:2010,
- direct heave measurement as per a proprietary procedure.

The test of direct frost heave was performed as per a proprietary procedure. Test sample was prepared in the standard form CBR type B as per the standard PN-EN – 13286-2:2010 *Unbound and hydraulically bound mixtures Part 2: Test methods for laboratory reference density and water content — Proctor compaction* to which the instrumentation for linear swelling measurement was installed. The sample was compacted with the use of standard Proctor energy 0.59 J/cm^3 at optimum moisture. The dimensions of the compacted sample were as follows: height – h=120 mm, diameter – d=150 mm. The objective of the test was to obtain a frost heave by invoking a negative temperature with the granulate of solidified carbon dioxide CO_2 at a temperature of -32ºC at the sample surface, leaving the bottom part of the sample in water at a temperature of +4 to 6ºC. The length of the test lasted 4 days. Direct frost heave size test results were not analysed with respect to TRRL criterion (BS 812-124; Roe and Webster, 1984) as the method of compaction and sample dimensions were different and this criterion could not have been adopted for frost susceptibility assessment. In contrast, the acceptance of the same test method for each sample enabled the comparison of the measured direct frost heave with respect to the tested geotechnical properties; granulation, plasticity index.

4 Test Results and Analysis

Summary of the test results of the study were presented in the table 4.

Property	Aggregate													
	G	S	B	D1	D2	D3	D4	D5	D6	D7	D8	L1	L2	L3
Plastic limit, w_P, %	-	17.0	-	-	15.2	14.5	-	-	14.0	15.3	17.5	12.7	14.6	-
Liquid limit, w_L, %	-	17.9	-	-	17.3	14.6	-	-	14.0	18.2	21.5	-	18.0	-
Plasticity index, I_P, %	-	0.9	-	-	2.1	0.1	-	-	0.0	2.9	4.0	-	3.4	-
Finer than 0.125 mm content, %	5.2	9.2	5.5	3.4	13.0	11.5	4.3	8.3	11.2	8.1	10.6	87.4	12.7	5.9
Finer than 0.075 mm content, %	3.6	7.0	4.8	2.9	11.8	10.0	3.9	7.0	9.8	7.4	9.6	5.9	11.3	4.7
Finer than 0.02 mm content, %	1.9	4.7	3.9	2.3	9.7	7.4	3.1	5.4	7.6	6.1	8.1	4.6	9.2	3.2
Finer than 0.002 mm content, %	0.2	0.5	0.3	0.5	2.2	1.6	0.5	0.9	1.5	1.5	1.7	0.9	1.9	0.7
Frost heave, mm	0.25	0.59	0.59	0.548	0.65	0.72	0.65	0.43	0.58	0.42	0.71	0.42	0.78	0.36
Optimum moisture content, %	6.5	7.7	7.6	7.6	7.7	7.2	6.7	6.6	6.5	8.8	7.0	6.7	7.2	5.5
Maximum dry density, g/cm3	2.005	2.022	2.070	2.009	2.170	1.999	2.018	2.148	2.143	2.073	2.010	2.200	2.100	1.991

(-) impossible to perform the test due to low cohesion

Table 4: Test results of the aggregates

It results from the recognition of the state-of-the-art analysis that frost heave properties depend mainly on fines content. Fines contents with the following dimensions: 0.002mm, 0.020mm, 0.075mm and 0.125 mm in the tested mixtures and their impact on the frost heave size were analysed. In the tested aggregates the content of fraction smaller than 0.075 mm ranged from 2.9% to 11.8%. This means that these aggregates were not heave ones as per the criterion of the content of fraction smaller than 0.075 mm, amounting to <15% (tab.1). In contrast, the content of fraction below 0.02 mm ranged from 1.9% to 9.7%. As per this criterion, 12 aggregates contained >3% of fraction smaller than 0.02 mm and they may be ranked as frost heave materials. Analysing the particle distribution test results, it was noticed that the assessment of frost heave of tested aggregates based on the content of fraction smaller than 0.02 mm and fraction smaller than 0.075 mm is divergent. The relationship between fines content and frost heave is presented in Fig. 2.

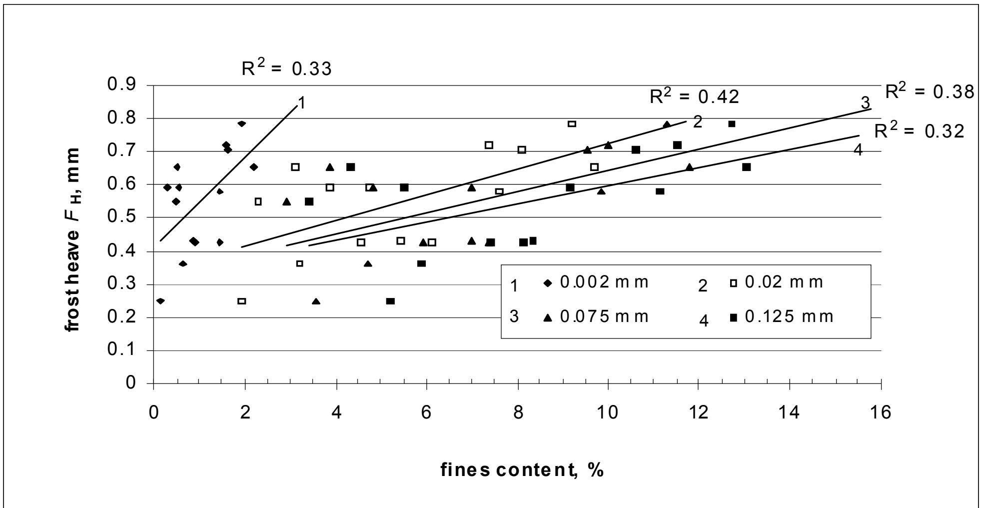

Figure 2: Relationship between frost heave and the fines content

Adopting linear relationships between fines contents and the frost heave, it may be noticed that the size of the frost heave is directly proportional to the fines content (Fig. 2). Between fines contents smaller than 0.002 mm, 0.02 mm, 0.075 mm and 0.125 mm, and the frost heave, the correlation with a coefficient of determination R2=0.32 to 0.42 was obtained. It is shown that the tendency lines of the relationship between the frost heave size and fines content are approximate. It may be stated that the frost heave size may be anticipated on the basis of the percent of the content of material passing through a sieve: 0.02 mm, 0.075 mm or 0.125 mm with similar accuracy. However, for each fraction individual criterion should be determined. This also results from strong relationship presented in Fig. 3. The relationship between the frost heave size and 0.002 mm fines content demonstrates to be of a different nature, which may be connected with a bigger influence of these particles on frost heave compared to fines particles. Due to very low content of this fraction in tested aggregates (0.16 to 2.18%), this criterion was not analysed.

The analysed relationships between the content of fractions smaller than 0.075 mm and 0.125 mm and the contents of fractions smaller than 0.02 mm, demonstrate that there is strong relationship between the content of these fractions. This relationship is very well matched, with a coefficient of determination R^2=0.92 to 0.98 (Fig.3).

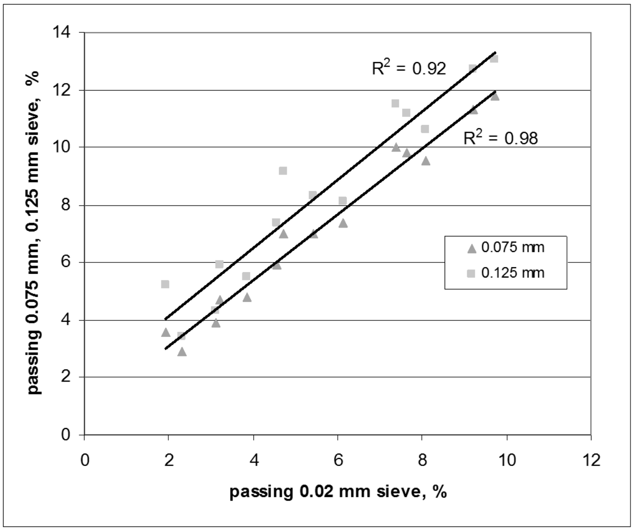

Figure 3: Relationship between percentage passing 0.075mm and 0.125mm of the percentage passing 0.02mm.

The next tested parameter was the plasticity index $I_P = w_L - w_P$ determined at material passing through the sieve #0.425mm. Plasticity index tests were possible to be performed only for 7 (S, D2, D3, D6, D7, D8, L2) out of 14 tested aggregate mixtures. This was caused by low contents of clay fraction which ranged from 0.16 to 2.18%. The values of plasticity index of 7 aggregates, whose Atterberg limits were possible to be determined, amounted to I_P= 0.0 to 4.0. Adopting the frost susceptibility criterion based on plasticity index (Table 3), all tested 7 aggregates should be classified as non-heave ones $I_P<4$. The lack of correlation between plasticity index of tested 7 aggregates and the frost heave was determined (Fig. 4). This means that in the scope of I_P=0 to 4, the plasticity index is not a feature adequate for forecasting aggregate frost susceptibility. A similar lack of correlation may be noticed in case of the relationship between the frost heave and the plastic limit (Fig. 5). Between the liquid limit and the frost heave there is a correlation with the coefficient of determination R^2=0.39 (Fig. 6).

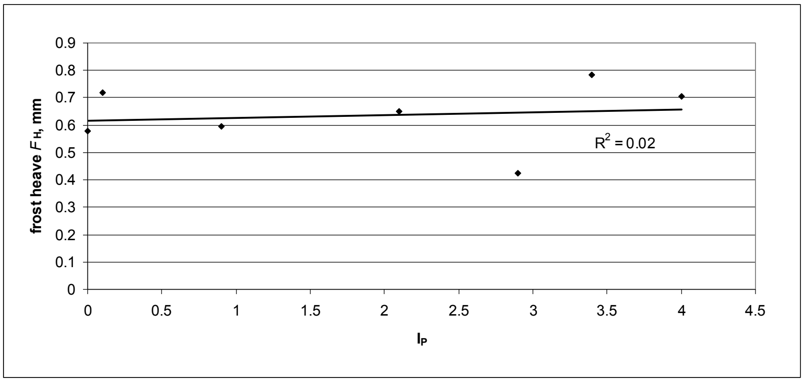

Figure 4: Relationship between plasticity index and frost heave

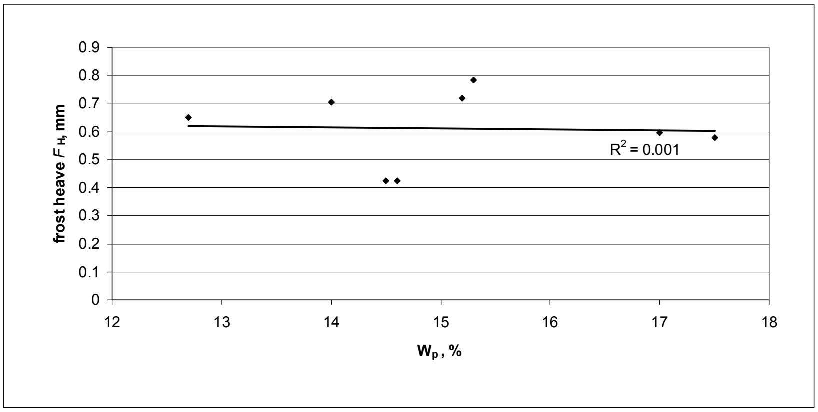

Figure 5: Relationship between plastic limit and frost heave

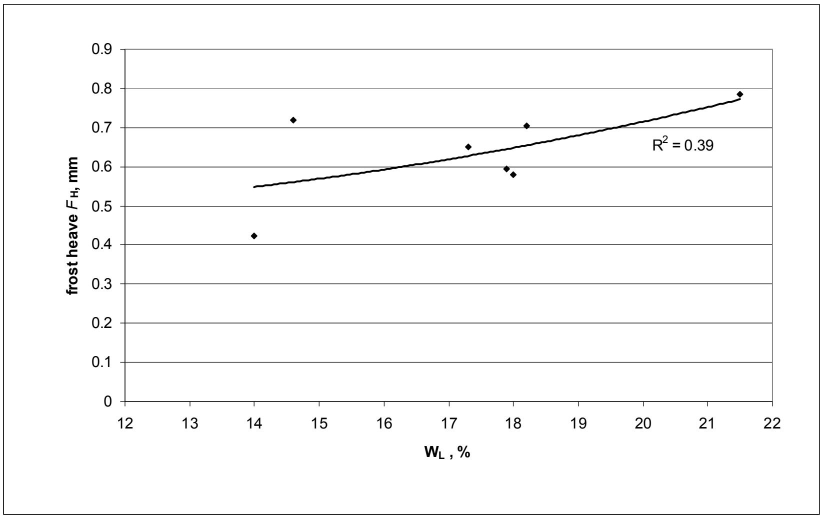

Figure 6: Relationship between liquid limit and frost heave

5 Conclusions

The test results presented indicate a divergent assessment of the frost susceptibility of aggregates intended for road bases in the case of the analysed properties, i.e. fines contents (<0.02mm, <0.075mm and <0.002mm), plastic limit, liquid limit, plasticity index. It was shown that the frost heave depends on fines content in the unbound mixture and the value thereof may be anticipated e.g. on the basis of the content of particles smaller than 0.02mm or 0.075mm. However, adopting the previous soil frost susceptibility criteria based on percentage of fines contents <0.02mm (<3%) and <0.075mm (<15%), substantial discrepancies in the assessment of frost susceptibility of tested aggregates were obtained. This means the need for verification of the currently applied frost susceptibility criteria for aggregate mixtures. Plasticity index is a property used for the assessment of frost susceptibility of cohesive soils. As a result of the tests that were carried out, no relationship between plasticity index and frost heave of tested aggregates, characterized by low plasticity index values ranging from 0 to 4, was found. It was demonstrated that the plasticity index is not a property adequate for the assessment of frost susceptibility of aggregates intended for road bases. The lack of possibility to test the plastic limit or liquid limit of some aggregates is a significant problem as well. Therefore, the classification of frost susceptibility based on I_P should not be applied for road mixtures in countries with a cold climate, where non-heave aggregates, with low fines content, should be applied.

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