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Laboratory investigations of frost susceptibility of aggregates applied to road base courses

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Abstract

In order to ensure the bearing capacity and durability of road pavements in cold climate areas, it is necessary to use materials which are resistant to harmful frost impact, known as frost heaving. Frost heave cause adverse volume changes, the upwards swelling of a 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 unbound pavement structural layers. Road bases made of unbound mixtures of continuously graded aggregates may be frost susceptible. Potential frost susceptibility of road materials and soils is determined by laboratory testing. Frost susceptibility is connected directly with the content and quality of fine particles in an aggregates. Frost heave can be predicted on the basis of different properties of soils or aggregates. The article presents the results of laboratory tests of 14 typical natural aggregate road mixtures, continuously graded 0/31.5 mm and practically applied to road base courses. Frost susceptibility of the aggregates was determined during laboratory testing of the following properties: content of fine-grain fractions <0.002 mm, <0.02 mm, <0.075 mm, plastic limit, liquid limit and sand equivalent. The aggregates were also compacted and frozen in a cylinder and then their frost heave value was determined. Correlations between fine-grain fractions, plastic limit, liquid limit, plasticity index, sand equivalent and frost heave of the aggregates were analysed. The tests showed no correlations between plastic limit or plasticity index and frost heave of the aggregates. Differences were also noted in criteria applied for predict frost susceptibility of aggregates based on fines content. The conclusions of the tests can be used in practice to determine or verify requirements for aggregates or their mixtures applied to road base courses.

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1. Introduction

Roadbase layers in Poland are made of hydraulically bound mixtures Kraszewski (2009); Gajewska et. al, (2012), but predominately of unbound aggregates. In subsoil and unbound aggregates containing silty and clayey components intended for roadbase layers the phenomenon of frost heave susceptibility may occur, to which many tests summarized in Poland, among others in Rafalski and Wilczek (2006); Rafalski (2007); Rafalski (2009), were devoted. The creation of a frost heave consists of the creation of ice lenses or ice layers in the soil as a result of the increase in the volume of frozen water in the soil or aggregate and attracting water to the frost zone. The similarity of the phenomenon of volumetric change under frost impact to soil consolidation may be used in frost heave tests, whereas the consolidation phenomenon causes a decrease in ground base volume, and the frost heave phenomenon - an increase in volume. It results from model tests of kaolinite columns frozen from the top Han and Goodings (2006) that, upon contact of frozen and not frozen layers, there appears an intermediate layer, characterized by visually lacinate ice crystals in the ground. Due to the creation of crystals, water velocity in this layer is lower than in the bottom, unfrozen soil column layer. In effect, the kaolinite column volume increases, so a frost heave is created. The pace of frost heave creation is influenced by water velocity in the intermediate layer. The phenomenon of creation of frost heaving is related to soil or aggregate capillarity wherein the height of capillary rise is influenced by soil or aggregate graining, but the chemical composition of water located in a capillary also matters Cwiąkała et. al (2013).

Determination of the structure and road pavement subgrade freezing depth is a significant issue as well Rafalski et. al. (2014). Freezing depth may be calculated theoretically e.g. as per Ickiewicz (2003).

In engineering practice approximate solutions are also applied, in which attempts to link the freezing depth and ratios characterizing frost intensity in winter-time are most frequently taken up e.g. Gontaszewska (2003).

Aggregates which do not contain fine particles (silty and clayey) should be applied for roadbase layers. However, such aggregates are not always available. Moreover, weaker aggregates e.g. those made of colliery shales, which may be subject to some fragmentation during compaction and water and frost impact, as a result of which they may change their graining and other properties, may be used for roadbase layers Rafalski and Wilczek (2006); Rafalski and Wilczek (2012). For this reason, the recognition of frost heaving properties of aggregates applied for roadbase layers poses a significant research problem.

Various criteria are applied for the assessment of soil and aggregate frost heave susceptibility. Frost heave susceptibility may be assessed on the basis of graining, namely the content of fine fractions. According to Catalogue (2014-1), Catalogue (2014-2) soil frost heave susceptibility requirements based on fine fraction content are applied (<0.02 mm and <0.075 mm), given in table 1.

Table 1. Soil frost heave susceptibility based on fine fraction content.

Fraction content	Non-frost-susceptible soil	Low-frost-susceptible soil	High-frost-susceptible soil
<0.075 mm (or 0.063), %	<15	15-30	>30
<0.02 mm, %	<3	3-10	>10

The plasticity index $I_p = w_L - w_P$ is applied for the analysis of cohesive soils' properties, and in some countries also for the assessment of aggregate frost heave susceptibility. Test of liquid limit w_L and plastic limit w_P performed on material going through a sieve with openings of 0.425 mm. Janoo et al, (1997); Chamberlain (1981) gave the frost heave susceptibility criterion on the basis of plasticity index I_p . In case of $I_p < 4$, frost heave susceptibility is low. If $I_p = 4-6$, then frost heave susceptibility is medium. Materials whose $I_p > 6$ are considered very susceptible to heaves. Sand equivalent SE is very often applied for determination of soil and aggregate frost heave susceptibility Kraszewski et. al. (2015), and it is particularly recommended for the assessment of non-cohesive and low-cohesive materials. A limit value, determining non-heave soil or aggregate is $SE_4 \geq 35$ as per Catalogue (2014-1); Catalogue (2014-2). The test is performed on material going through a sieve with 4 mm openings. The assessment of the content of fine fractions in the aggregate may be performed on the basis of methylene blue test MB_F , determining the

content of dye absorption per a fraction kilogram 0/0.125 mm. Category MB_F10 is adopted as the boundary value for aggregates in some countries Nicolaidis et. al. (2007), WT-1 (2014).

Technical requirements concerning unbound aggregate mixtures implemented in Poland WT-4 (2010) have evoked many discussions on the method of determination of aggregate frost heave susceptibility with sand equivalent and adopted requirement level: $SE_4^{\min}=35-45$. When expressing an opinion of these requirements, many road contractors and aggregate manufacturers expressed doubts as regards too rigorous requirements of the sand equivalent value, limiting the use of aggregates present in the country. Different geotechnical properties applied in some countries for the purpose of determining the material frost heave susceptibility e.g. plasticity index I_p or methylene blue MB_F constituted the argument. The suitability of the plasticity index was particularly substantiated and the said parameter was accepted for the assessment of frost heave susceptibility index.

In connection with the aforementioned doubts, laboratory tests of 14 typical natural aggregate road mixtures, continuously graded and practically applied to road base layers were carried out. Frost heave susceptibility of the aggregates was determined during laboratory testing of the following properties: content of fine-grain fractions <0.002 mm, <0.02 mm, <0.075 mm, plastic limit, liquid limit and sand equivalent. This article presents a significant part of these tests.

2. Materials and test methods

Typical natural crushed aggregates with continuous grading of 0/31.5 mm, applied for the execution of roadbase layers were selected for testing. In petrographic terms, tested aggregates represented various rock types: igneous, sedimentary and metamorphic. In total 14 aggregate samples marked as: basalt (B), granite (G), lime (L1-L3), dolomite (D1-D8) and sandstone (S) were tested. Most aggregates were of sedimentary origin and they contained lime and dolomite because in the case of these rocks higher frost susceptibility in comparison to aggregates containing granite, basalt or sandstone was expected.

The following tests of geotechnical properties of those aggregates were performed:

- grading (sieve analysis and aerometric analysis) as per standard PN-88/B-04481,
- plastic limit and liquid limit (with Casagrande method) as per standard PN-88/B-04481,
- sand equivalent SE_4 as per standard PN-EN 933-8:2012,
- optimum moisture and maximum dry bulk density as per PN-EN 13286-2:2010.

Plasticity index $I_p = w_L - w_p$ was calculated on the basis of liquid limit and plastic limit.

It should be noticed that the sand equivalent value depends on grain composition of tested material. The valid standard PN-EN 933-8:2012 contains two methods of sand equivalent determination: $SE(10)$ - sample sieved through 2 mm sieve and SE_4 - sample sieved through 4 mm sieve. The standard does not specify when $SE(10)$ should be determined and when SE_4 . In case of 14 aggregates tested SE_4 was determined as the one corresponding to the methodology previously applied in Poland and described in industry standard BN-64/8931-01 Kraszewski et. al. (2015).

The test of direct frost heave F_H was performed as per a proprietary procedure. Samples for the tests were prepared in a CBR cylinder type B as per standard PN-EN-13286-2:2010, with instrumentation for the measurement of linear swelling installed. The objective of the test was to obtain a frost heave by means of inducing a negative temperature with a granulate of solidified carbon dioxide CO_2 with a temperature of $-32^\circ C$ at the sample top surface, leaving the bottom part of the surface in the water with temperature of $+4-6^\circ C$ (Fig. 1). Results of the tests of direct frost heave size with respect to TRRL criterion as per the British standard BS 812-124:2009 were not analyzed as the compaction method and sample dimensions were varied and this criterion was not possible to be adopted for the assessment of frost susceptibility. However, the adoption of the same method of testing of each sample enabled the comparison of measured direct frost heave with respect to tested geotechnical properties.



Fig. 1. Measurement of frost heave in CBR cylinder.

3. Test results and analysis thereof

Grain compositions of 14 tested aggregates are presented in table 2.

Table 2. Grain or particle size distribution of the aggregates, (%).

Grain or particle size (mm)	Aggregate													
	G	S	B	D1	D2	D3	D4	D5	D6	D7	D8	L1	L2	L3
63	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
31.5	94.8	98.8	94.2	98.7	100.0	98.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
16	65.4	67.4	66.4	86.2	78.7	70.7	89.5	90.9	80.6	73.4	78.0	68.3	87.7	86.5
8	49.4	47.7	44.3	66.5	54.0	49.8	60.4	72.1	58.3	51.3	52.4	49.8	64.0	65.5
4	38.2	31.7	29.0	37.8	35.6	36.3	30.3	51.0	40.8	36.9	34.0	38.4	42.5	44.7
2	30.1	22.7	20.1	19.1	26.6	27.4	16.9	38.9	29.3	22.7	24.7	27.3	29.8	29.6
1	22.0	18.1	13.8	9.5	21.2	20.2	9.8	26.6	21.1	15.0	18.6	20.7	21.8	18.8
0.5	14.5	15.5	9.6	6.0	17.7	16.4	6.7	17.9	16.3	11.5	15.1	15.1	17.6	12.5
0.25	8.8	12.7	7.0	4.4	15.1	13.8	5.2	11.8	13.3	9.5	12.5	10.7	14.8	8.5
0.125	5.2	9.2	5.5	3.4	13.0	11.5	4.3	8.3	11.2	8.1	10.6	7.4	12.7	5.9
0.075	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
0.02	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
0.002	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

Table 3 presents the test results of plastic limit, liquid limit, sand equivalent, fraction content: <0.075 mm, <0.02 mm, <0.002 mm, optimum moisture, maximum dry density and frost heave. Also, plasticity index was calculated on the basis of liquid limit and plastic limit. In case of aggregates: G, B, D1, D4, D5, L1 and L3 plasticity index was not determined due to their low aggregate cohesion.

Table 3. Test results of the aggregates.

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	-
Sand equivalent, SE_4	80	46	52	83	27	41	66	79	34	28	26	53	32	91
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/cm^3	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

In the tested aggregates, fraction <0.075 mm content ranged from 2.9% to 11.8%. This means that those aggregates have never been heave-causing ones as per the criterion of the content of fraction smaller than 0.075 mm, amounting to <15% (tab. 1). In contrast, the fraction of content 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 can be ranked as problem materials with respect to frost susceptibility. Analysing grain composition test results, it was noticed that assessment of frost susceptibility of the tested aggregates, based on the content of fraction smaller than 0.02 mm and fraction smaller than 0.075 mm, is discrepant.

The relationship between the content of fine fractions and frost heave is presented in Fig 2.

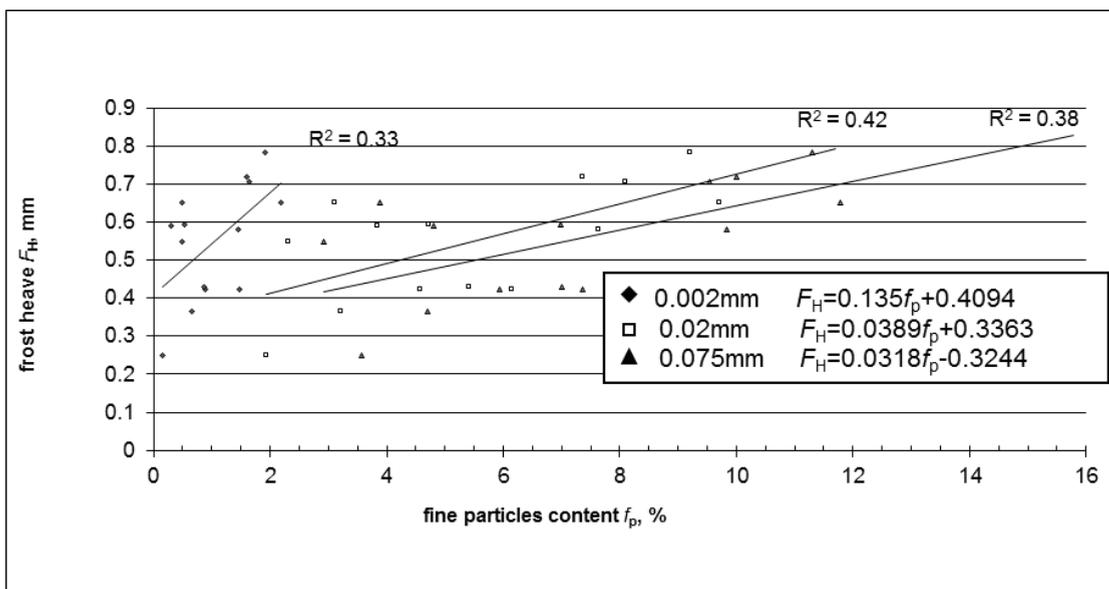


Fig. 2. Relationship between fine particles content and frost heave.

Adopting linear relationships between fine fraction contents and frost heaves, it may be noticed that the size of the frost heave is directly proportional to dust content. Between fine fraction contents <0.02 mm, 0.075 mm and 0.002 mm and the frost heave, the correlation with the coefficient of determination $R^2=0.33-0.42$ was obtained. Trend lines of frost heave relation to the fraction content <0.02 mm and <0.075 mm are close to each other. This means that the frost heave size may be anticipated on the basis of percentage content of material going through the sieve 0.02 mm or 0.075 mm. The relationship of the frost heave size on the fraction content 0.002 mm differs slightly from the remaining ones, which is connected with greater influence of the particles on frost heave susceptibility as compared to dust particles.

Plasticity index tests were possible to be performed with only in 7 out of 14 aggregates. This was due to low clayey fraction which amounted to 0.2-2.2%. In the cases of 7 aggregates it was not possible to determine liquid limit, and in the cases of 6 aggregates – plastic limit. The value of plasticity index of 7 aggregates, Atterberg's limits of which were possible to be determined, amounted to 0.0-4.0. Adopting the criterion of frost heave susceptibility based on plasticity index, all 7 tested aggregates should be classified as non-heave ones.

The lack of correlation between plasticity index of 7 tested aggregates and frost heaves (Fig. 3) was declared. This means that in the scope of $I_p=0-4$, plasticity index is not a feature appropriate for forecasting aggregate frost heave susceptibility. A similar lack of correlation may be noticed in the relationship of frost heave susceptibility to plastic limit (Fig. 4). By contrast, in the case of liquid limit and frost heaves, there is a correlation with coefficient of determination $R^2=0.38$ (Fig. 5).

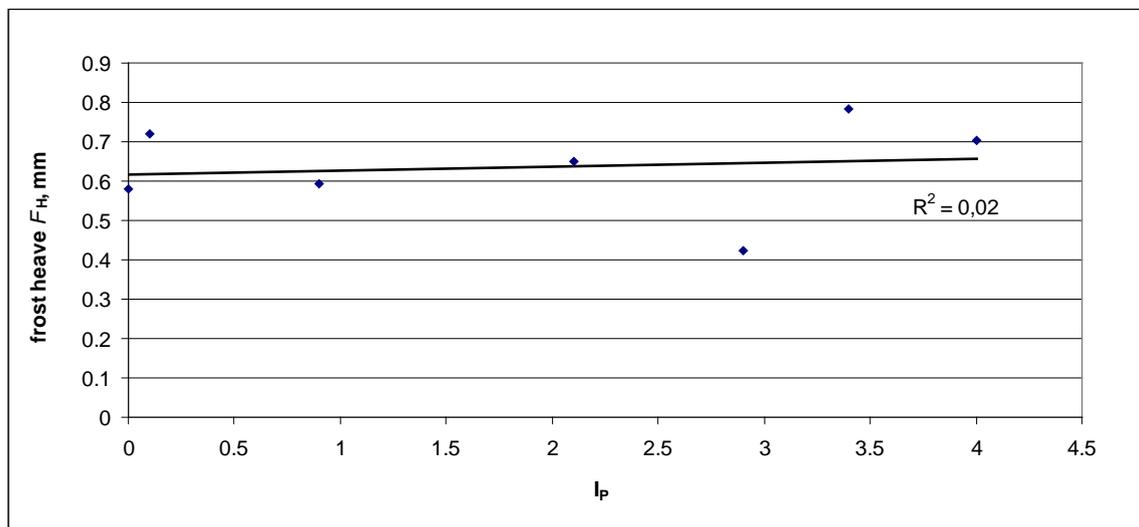


Fig. 3. Relationship between plasticity index and frost heave.

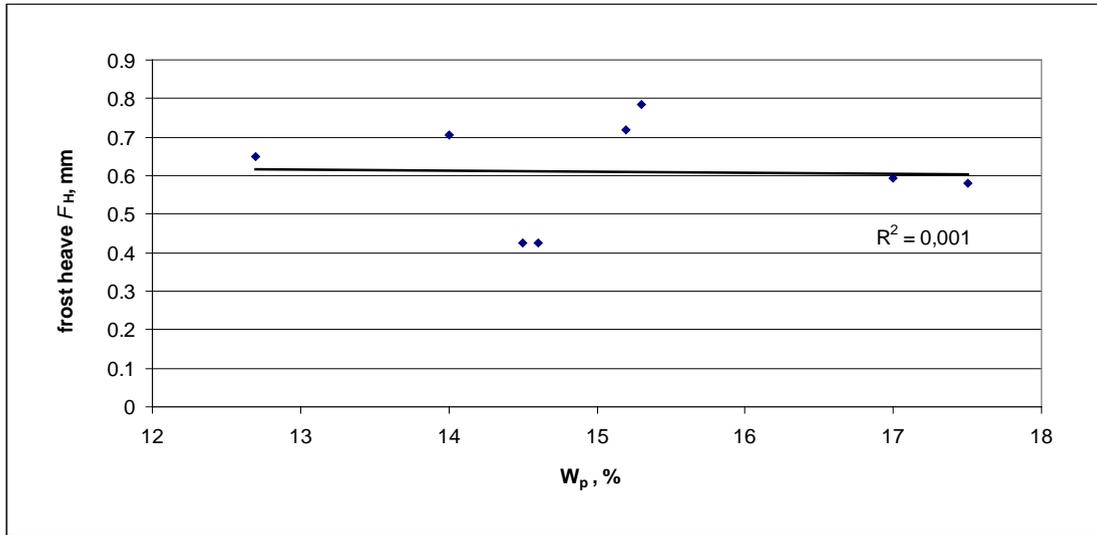


Fig. 4. Relationship between plasticity limit and frost heave.

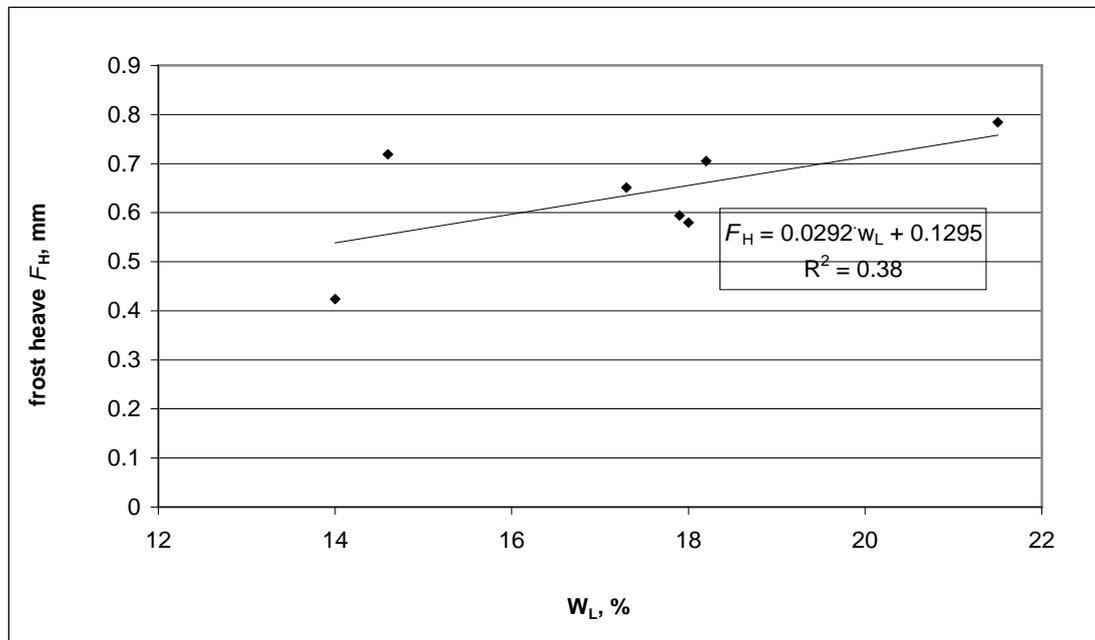


Fig. 5. Relationship between liquid limit and frost heave.

Sand equivalent test results, presented in table 3, demonstrated that adopting frost heave susceptibility criterion $SE_4=35 - 45$, aggregates may be assessed as heave ones and 9 aggregates as non-heave ones. Comparison of criteria I_p and SE_4 shows that they give very different results of frost heave susceptibility of tested aggregates. In 5 out of 7 aggregates, the plasticity index (I_p) which was calculated on the basis of liquid limit and plastic limit, contradictory results classifying aggregates to various frost heave susceptibility groups were obtained.

Tested aggregates were characterized by sand equivalent SE_4 values from 26 to 91. Tests proved that there is the following relationship: the higher the value of sand equivalent SE_4 , the lower the frost heave (Fig. 6). This relationship is characterized by the coefficient of determination $R^2=0.41$. Applying the criterion of sand equivalent $SE_4=35$ frost heave susceptibility, it may be adopted that frost heaves with the size of 0.62 mm corresponds to that value of the sand equivalent.

Fig. 7 presents the relationship between fine fraction content and sand equivalent SE_4 . These relationships are characterized by the coefficient of determination $R^2=0.69-0.74$ and they demonstrate good correlation between fine fraction content and sand equivalent. This means that sand equivalent may be used for the assessment of frost heave susceptibility of aggregates intended for roadbase layers.

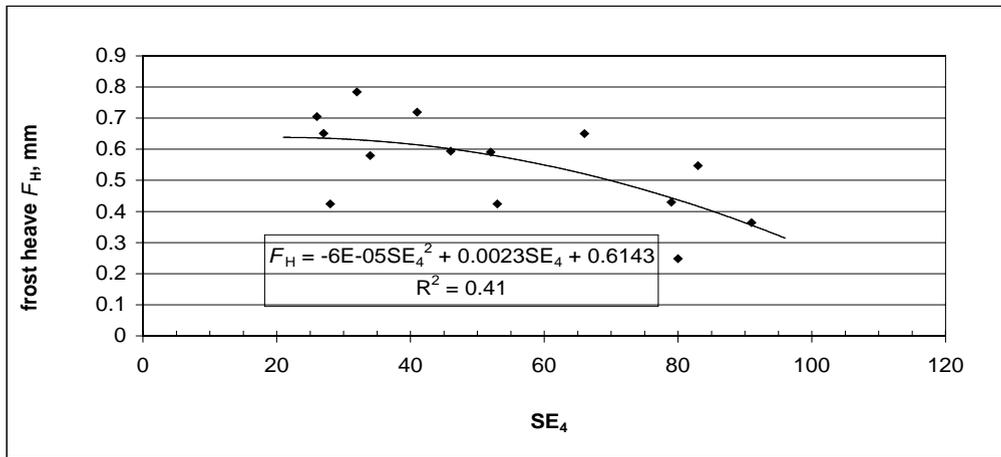


Fig. 6. Relationship between sand equivalent and frost heave.

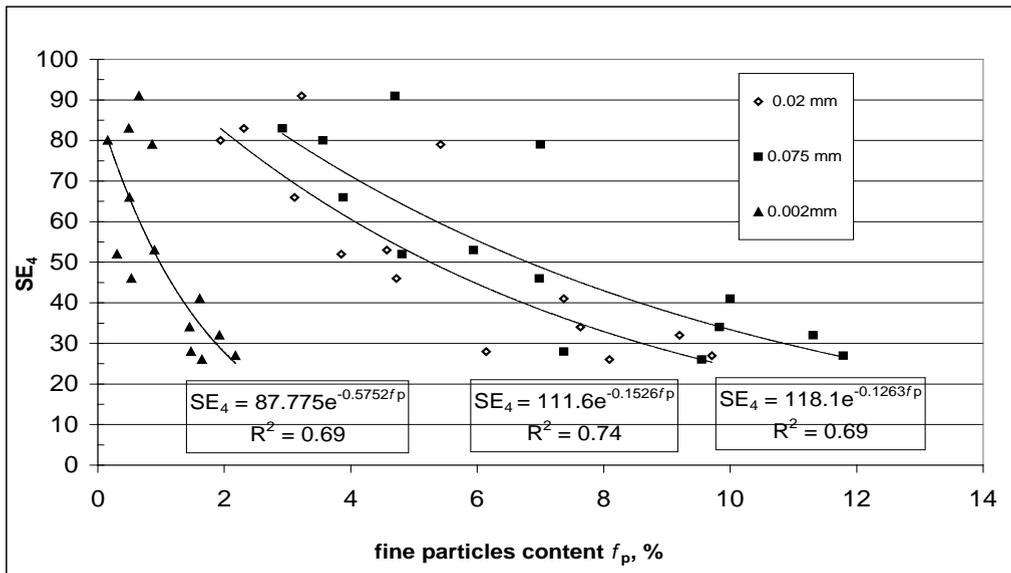


Fig. 7. Relationship between the fine particles content and sand equivalent.

4. Conclusions

Presented test results of properties of aggregates intended for roadbase layers indicate divergent assessments of frost heave susceptibility in the cases the of analyzed properties i.e. fine particle content (<0.02 mm, <0.075 mm and <0.002 mm), plastic limit, liquid limit, plasticity index and sand equivalent.

It was shown that frost heaves depend on fine fraction content in the aggregate and its value may be anticipated e.g. on the basis of the content of particles <0.02 mm or <0.075 mm. However, adopting previous frost heave criteria based on percentage content of fine particles <0.02 mm (<3%) and <0.075 mm (<15%), significant discrepancies in the assessment of frost heave susceptibility of tested aggregates were obtained. This means the need for verification of currently applied frost heave susceptibility criteria.

Plasticity index is a property used for the assessment of frost heave susceptibility of cohesive soils. As a result of performed tests, no relationship between plasticity index and frost heave of tested aggregates, which were characterized by low values of plasticity index in the range of 0-4, was shown. It was shown that plasticity index is not a property adequate for the assessment of frost heave susceptibility of aggregates intended for roadbase layers. The lack of possibility of testing plastic limit or liquid limit of some aggregates poses a significant problem as well.

It was shown that there is a relationship of the frost heave size to the sand equivalent value, and moreover there are correlations between fine fraction contents e.g. <0.02 mm and <0.075 mm. This means that sand equivalent is a property adequate for the assessment of frost heave susceptibility of aggregates intended for roadbase layers.

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