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STEELWORK WASTE – NON-STANDARD METALLURGICAL BY-PRODUCT

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ABSTRACT

More than 20 years ago a material named "studený odval" (steelwork waste) was decided to use as an alternative fill in embankments of the D47 motorway. This material was certified and its price was very interesting therefore it became the object of interest of all investors and construction companies in the Ostrava region. In all constructions, where the steelwork waste was used, its volume changes were found as soon as the structure was handed over to the Client resulting in pavement deformations in case of motorway or deformations of floors in case of business or shopping centres. Volume stability was not cast in doubt in time of its utilization and therefore it was not analysed. Existing results show, that although the volume changes have lasted for many years, their stabilization has not been proven so far. Therefore it is not possible to predict how long volume changes will persist.

Keywords: Deformations, Steelwork Waste, Volume Changes

I. INTRODUCTION

Metallurgical by-products belong to traditional alternative source of material used as fill not only during construction of transport infrastructure but also in construction of shopping and business centres, simply in constructions with high demands on the fill volume.

Metallurgical by-products tend to be termed "*slags*" not just by laymen but even by the professional public. An accurate description and the use of correct terminology in designating the material are indispensable for determining the marginal conditions of its application as well as in retrospect, for analysing any defects or failures of structures caused by volume changes of the metallurgical by-products. The properties of aggregates based on blast furnace or steel slag are determined to a decisive degree by the process employed by the specific ironmaker or steelmaker in question, or as the case may be, the specific producer of a nonferrous metal.

More than 20 years ago a material named "*studený odval*" (steelwork waste) was decided to use as an alternative fill in embankments of the D47 motorway.

This decision, when investor began to think about this material as fill of the D47 motorway, started the execution of lot of laboratory and field tests, however also the certification of this material as the product. This material was certified and its price was very interesting therefore it became the object of interest of all investors and construction companies in the Ostrava region. All these inputs were resulted in usage of this material not only in embankments of the D47 motorway, but also in the subgrade of shopping and business centres in the Ostrava region.

In all constructions, where the steelwork waste was used, its volume changes were found as soon as the structure was handed over to the Client resulting in pavement deformations in case of motorway or deformations of floors in case of business or shopping centres.

A contribution tries to describe known properties of the steelwork waste and it does not plan to comment the dispute between the investor and the contractor of the D47 motorway. Unfortunately, now more than 10 years from its first utilisation as fill we do not know all aspects of behaviour of this very non-standard material.

II. STUDENÝ ODVAL (STEELWORK WASTE) – WHAT IS IT?

Material named as steelwork waste or alternatively, mineral blends from the smelter, was not known in time of its utilisation in constructions even by professionals. The mark "*studený odval*" is a slang expression (it was a tipped material which was not hot and got cold) or a brand name. From the name itself it is not possible to estimate its origin, composition or properties.

Nevertheless, a definition of the steelwork waste occurred in 1995 in one report that was ordered by the Directorate of Highways and Motorways of the Czech republic. *"It is a heterogeneous mixture of metallurgical by-products (mixed metallurgical slags, foundry sands, and refractories - lining e.g. of blast furnaces; such materials are produced in ironmaking and steelmaking. Steelworks waste or similar mineral blends may contain minor admixtures of other materials as well - such as wood, PVC etc.)."* [1].

The owner of the steelwork waste decided to make use from the interest of it and steelwork waste was certified as the product: "*Aggregate class A, B, C for road construction type /variant: Aggregate for subbase. Artificial aggregate homogenised material, aggregate B-0-125*". From the definition itself it does not follow that it is a mixture of metallurgical by-products.

The use of other metallurgical by-products than blast furnace or steel slags (materials analogous to steelworks waste) in foreign countries is rather limited. U.S. federal regulations even require steel slags to be free from any residues of furnace lining (FHWA RD 97-148) [2].

The German regulation TL BuB E-StB 07 also describes, in addition to blast furnace and steel slags, mixtures of mineral substances deriving from ferrous metallurgical (*Hüttenmineralstoffgemischen)* composed entirely of slags produced in ironmaking and steelmaking, plus unsorted refractories.

Chemical composition of this material is similar to the composition of steelwork waste (Fig. 1). In practice, however, these materials which we may regard as similar to steelworks waste are not used in roadbuilding, owing to the substantial risk of volume instability [3, 4].

The steelwork waste contain higher share of Al_2O_3 and especially of CaO than steel slags. Very good conformity between the steelwork waste from pits [5] and the *Hüttenmineralstoffgemischen* composition is apparent from the phase diagram. Anomalous is the sample from km 155.350 (of the D47 motorway) with lower share of SiO_2 and higher share of CaO. The reason of this different composition has not been clarified, yet.

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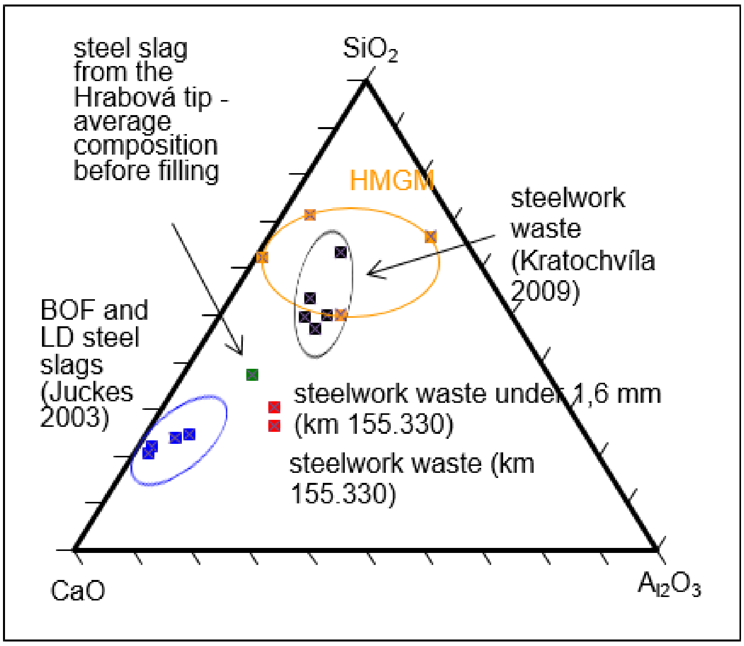

Figure 1: Composition of the steelwork waste, HMGM (*Hüttenmineralstoffgemischen*) and steel slags in the phase diagram CaO-SiO_2-Al_2O_3

Figure 2: The steelwork waste (heap on the right) with debris of metallurgical ceramics excavated form the pit under the floor of the Demos hall in Ostrava (11/2014)

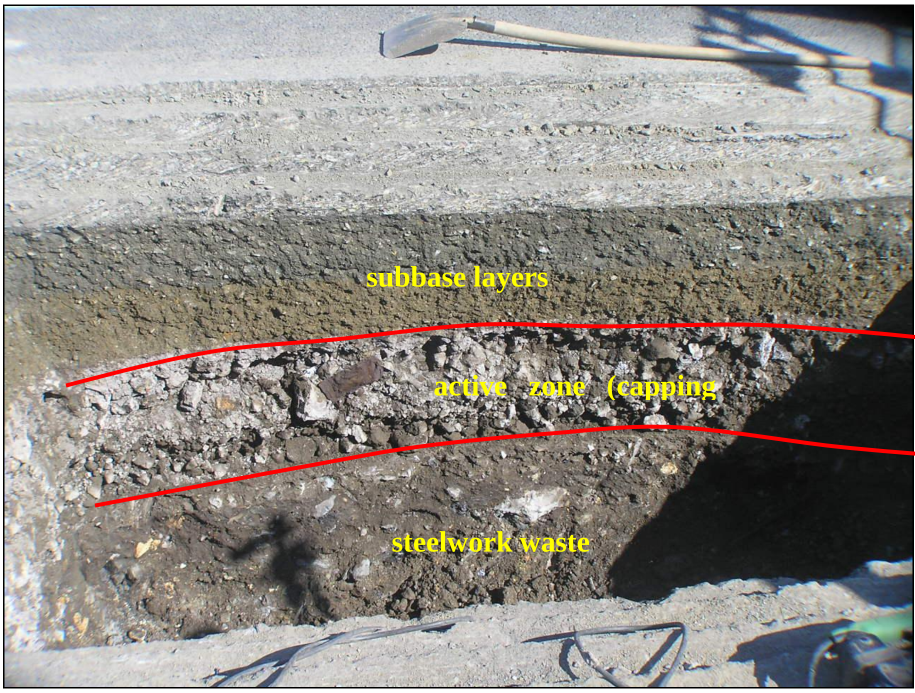

Figure 3: Pit KSJ22 (km 155.876 of the D47 motorway, right lane) with visible deformed layers of the active zone (capping layer) resulting by the volume changes in underlying steelwork waste in embankment

III. THE STEELWORK WASTE PROPERTIES

During preparatory phase of the D47 motorway construction there were carried out pilot plant compaction trials of the blast furnace slag, steel slag and steelwork waste from the Hrabová tip. Works were ordered by the Directorate of Highways and Motorways of the Czech Republic. Measured and recommended parameters from 1996 are summarized in the Table 1.

Table 1: Recommended mechanical properties of metallurgical by-products (adapted after [6])

parameter	blast furnace slag (the Hrabová tip)	steel slag (the Hrabová tip)	steelwork waste (the Hrabová tip)
fraction	0-300 mm	0-200 mm	0-300 mm
CSN 736133 classification	G2 GP	G1 GW	G3 GF
moisture w_n (%)	4	2	6,9-12,9
maximum dry density (ρ_{dmax}) (kg.m^{-3}) according to the Proctor Standard test	2330	2681	1930
internal friction angle ϕ (°)	37	35	30
cohesion c (kPa)	3	5	5
coefficient of permeability k_f (m.s^{-1})	1,00.10^{-2}	4,20. 10^{-2}	1,00.10^{-8}
deformation modulus E_{def} (MPa)	100-131	90-130	80-100

The steelwork waste represents by its grain size distribution very suitable and well compacted fill. Grain size distribution curves of the steelwork waste samples from pits on the D47 motorway from 2012 and samples from the Hrabová tip from 1996 [6] are shown in the Fig. 4. Samples from 2012 contain smaller share of sandy and gravel fractions (over 0.25 mm) and higher share of coarse fraction (over 63 mm) comparing with samples from 1996 either from tip, or from the trial test.

At a general level, the shearing properties of coarse-grained materials - which is what the metallurgical by-products represent - are relatively favourable. In case that the steelwork waste is formed of a mixture of coarse-grained and fine-grained fractions, with the share of undersize up to 4 mm constituting at least 10%, the shear strength of the material is determined by the shear strength of the 0-4 mm fraction. In 1996, this fraction was subjected to tests in the shear box apparatus using samples compacted by Standard Proctor energy.

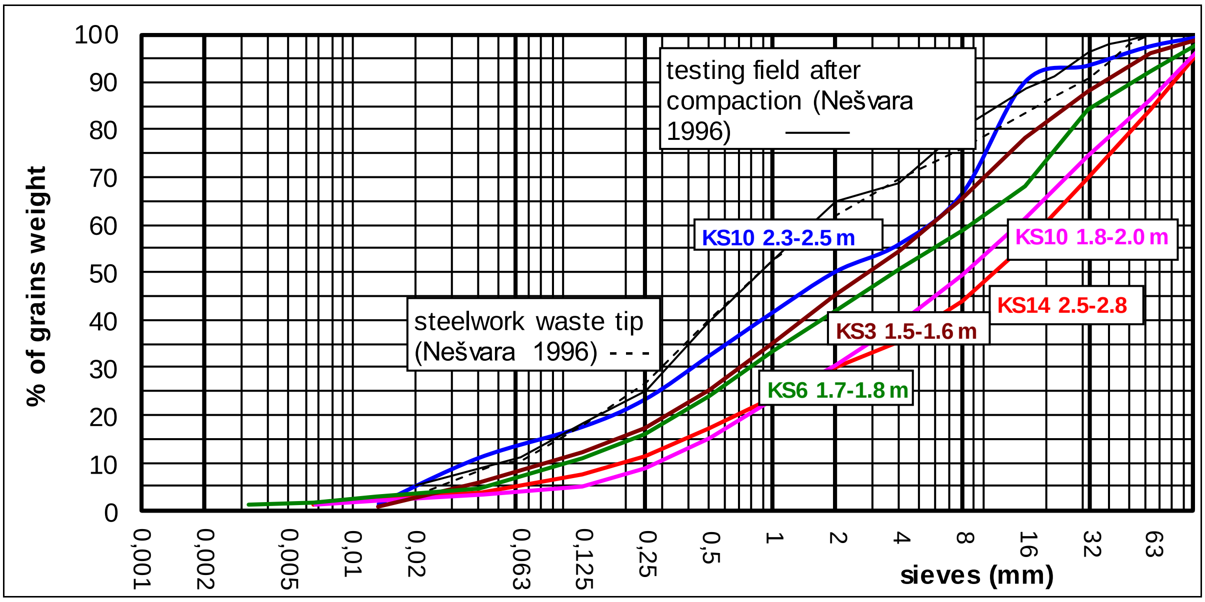

Figure 4: Grain size distribution of the steelwork waste sampled from pits from 2012 and from preparatory phase of the D47 motorway (1996)

It is necessary to stress considerably lower maximum dry density of steelwork waste in comparison with blast furnace and steel slags. It is caused by higher share of silica and magnesium materials and by higher porosity, too. Steelwork waste is less permeable after compaction than blast furnace and steel slags.

The internal friction angle values are nearly the same for both blast furnace and steel slags. The value was lower for steelworks waste (ϕ = 27.11°), due to a higher content of the fine-grained fraction. High values of effective cohesion are due to the coarser grains being securely braced against one another *i.e.*, wedged. In the long term, however, the high cohesion values cannot be counted on to persist [7].

The deformation properties of metallurgical by-products were determined *i.a.*, by on-site plate loading tests. Generally, the deformation modulus values attained are high (above 80 MPa). Pilot scale tests conducted in 1996 confirmed that the value of the deformation modulus grows higher with the number of passes of the compactor and with decreasing E_{def2}/E_{def1} ratio.

Out of the 146 static loading tests run for the purpose of inspection on the steelworks waste layers along the section of km 150.330-152.660 on the D47 motorway, only three tests gave deformation modulus values below

80 MPa. The median value of the entire set of these data was E_{def2}=118.3 MPa. For no more than six tests the E_{def2}/E_{def1} ratio was higher than 3.00. Results of statistic evaluation of plate loading tests for each embankment layer in km 150.330-152.660 are presented in Table 2 and Fig. 5.

Table 2: Statistical evaluation of static loading tests conducted on steelworks waste layers used as fill of the D47 motorway embankment at km 150.330-152.660

Steelworks waste layer	E_{def2} (MPa) - median)	E_{def2}/E_{def1} (median)	Number of tests
1	117,8	2,01	11
2	111,0	2,12	6
3	119,3	2,30	9
4	119,7	2,16	10
5	128,7	1,93	14
6	104,0	2,25	13
7	110,3	2,44	11
8	107,3	2,06	7
9	101,2	2,17	7
10-14	114,1	1,90	12
15-19	111,6	1,79	10
20-25	142,6	1,63	6
final layer under active zone	188,5	1,63	30
whole set	118,3	1,99	146

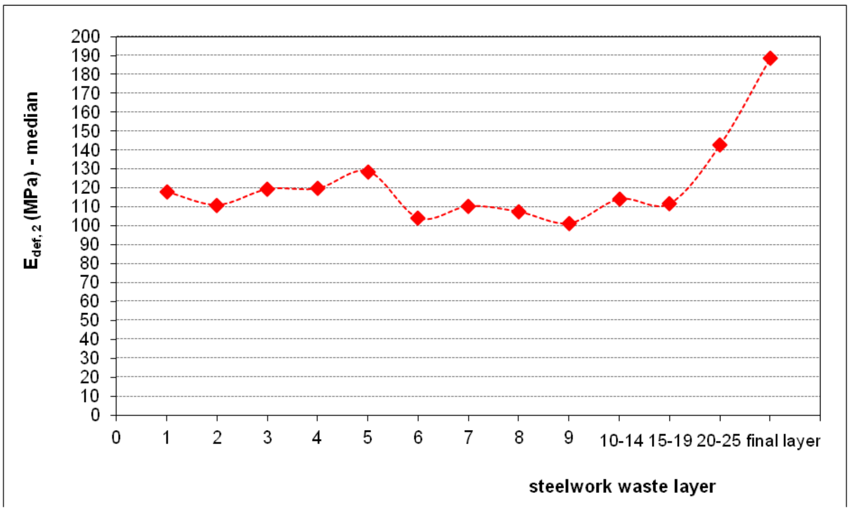

Figure 5: Trend followed by the deformation modulus values deriving from static loading tests conducted in course-by-course fashion on steelworks waste fill of D47 motorway embankment at km 150.330-152.660

Based on the above results it can be stated that according to these criteria, the part of the embankment filled with steelworks waste material and the active zone where steel slag of the 0-90 mm fraction was used were sufficiently compacted and that the degree of compaction and deformation modulus parameters attained, as verified by the inspection tests, were fully compliant with the stipulations of relevant standards, regulations, and project documentation. Similar results as in case of the D47 motorway there were recorded also in constructions of business and shopping centres. This fact caused that steelwork waste became an interesting fill without any possible "*problems*" during its utilization.

IV. VOLUME CHANGES OF STEELWORK WASTE AND THEIR DEVELOPMENT

As it was above-mentioned steelwork waste fulfilled common criteria used by investors and contractors during earthworks. All constructions were passed by investors without defects and backlogs. During construction and finishing of all critical constructions in the Ostrava region (including the D47 motorway) nobody from responsible representatives both on the investor and contractors´ sides suppose that a few time after constructions finishing the worst property of steelwork waste – volume instability – will start to manifest.

The chief cause underlying the volume changes (swelling) of steelwork waste is the presence of free lime and the mineralogical composition of the materials concerned and surface of grains under 1 mm. Free lime converts to portlandite $Ca(OH)_2$ in the presence of water. The density of portlandite is less than that of calcium oxide; hence the reaction is manifested by an increase of volume. Free lime originates from undissolved (residual) rock particles in the furnace charge and from lime precipitated during the cooling process and during the transformation of C_3S to C_2S.

Based on the experimental studies it is possible to say that principal influence on the volume changes is done by the fraction less than 1 mm. It forms minimally 20% of total volume of steelwork waste: in some samples its share was even 50% (e.g. sample from dump from 1996). Lower grains have in total greater surface that increases a volume changes potential. Higher the share of coarse fraction, the lower the volume changes potential [8]. In case of coarser grains only the surface crust has been originated.

The best information regarding values that volume changes steelwork waste can achieve are resulted from measured deformations. Laboratory tests have not lasted sufficiently long time and they are biased by the scale error, because small samples in laboratories cannot simulate behaviour of material in the embankment. In case of tests accelerating behaviour of volume instable materials by the combination of higher pressure and temperature (autoclave tests, steam chamber tests) there is a lack of correlations to estimate based on these results behaviour of material on the normal temperature and pressure.

Time development of vertical deformations in the D47 motorway was monitored in the period of 2007-2012 and it is similar for measured points. It is evident quick increase in the first year from construction finish (2007-2008) to the first grind off pavement. Then it is evident deceleration of vertical deformations in winter 2008/2009 and slower increase of deformations in the next period. Remedial works did not stop the process of volume deformations and vertical changes continued also in 2012. In the Fig. 6 there is shown a dependence of pavement uplift in km 150.334 in the right lane of the D47 motorway on time without influence of remedial works.

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The volume changes within the embankment act in all directions, and this is why the various cases of deformation were not limited to vertical lifts alone of the motorway but were also manifested in displacements of bridge abutments due to increased pressures within the soil in situations where the changes of volume were restricted by the rigid structure of the bridge abutments.

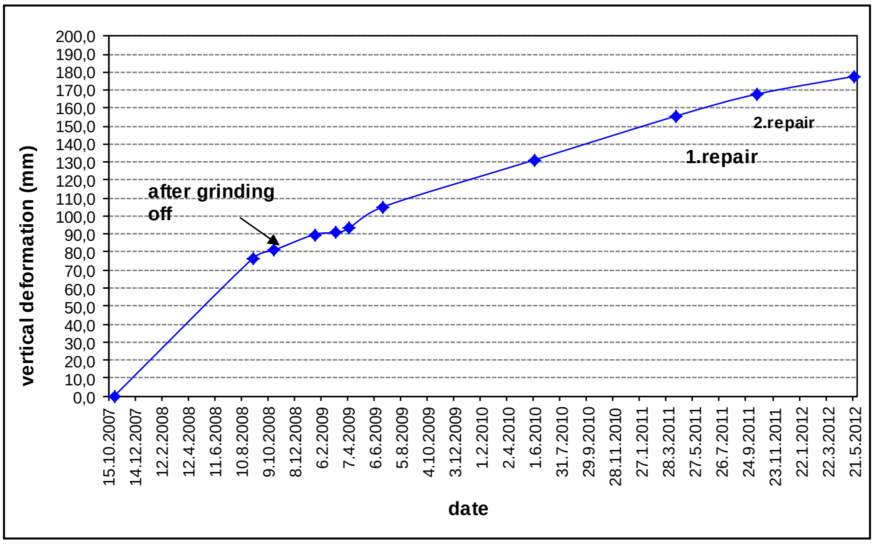

Figure 6: Development during 2007-2012 of vertical deformation bumps in the right lane of the D47 motorway at km 150.344, disregarding the effect of remediation works (obtained by processing the results of geodetic surveying)

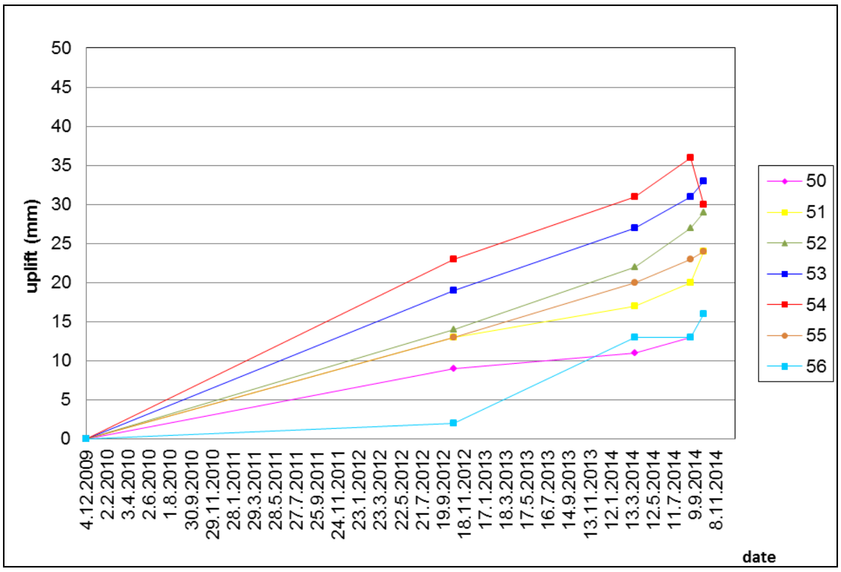

Figure 7: Uplifts of floor, profile 16, the Demos hall in Ostrava in period of 12/2009-10/2014 (50-56 are numbers of measured points on the floor surface)

Slow and not finishing development of vertical deformations was not observed not only in case of the D47 motorway embankment but also in case of other constructions. The Demos company hall in Ostrava should be an example. Under the floor there is 1.5 m of steelwork waste. Since 2009 deformations have been measured and in profile 16 they achieved in October 2014 approx. 40 mm (Fig. 7).

Based on the measured data an approximately linear character of progressive lifts of individual points is evident. Any indication towards to stabilization of deformations or their slowing down has not been observed.

The measurement of volume changes in laboratory conditions is limited. Short time tests under higher temperature and pressure (e.g. autoclave test) provide results very quickly; however, it is complicated to correlate them with behaviour of material under normal conditions. Methodological limits represent difficulties, too. Autoclave test is carried out on the fraction 8/16 and according to the present specifications it is valid for blast furnace slag aggregate only (see appendix A of TP138) [9]. Steam test according to the EN 1744-1 is used only in case of steel slag aggregate and test is carried out for fraction 0/22.5. General short term test for any material has not been installed, yet.

Long term tests than remains to analyse volume changes. They are applicable for any material (both natural, or artificial origin). It is the swell test in the CBR mould according to the EN 13286-47 [10]. A disadvantage of this test is fact that volume changes are slow and results are obtained during several months, even years. Comparison of test results of steelwork waste swelling under standard and non-standard conditions is shown in Fig. 8 and 9.

The volume changes of water saturated samples tested at the temperature of 75°C amounted to 27.4% after 122 days for the samples compacted by 100% Proctor Standard energy, and 43.1% after 188 days for the sample compacted by Proctor Modified energy (Fig. 8).

The volume changes of steelwork waste sample under normal temperature and pressure after 3.5 years achieve 4.9% and still the trend to stabilization has not been observed (Fig. 9).

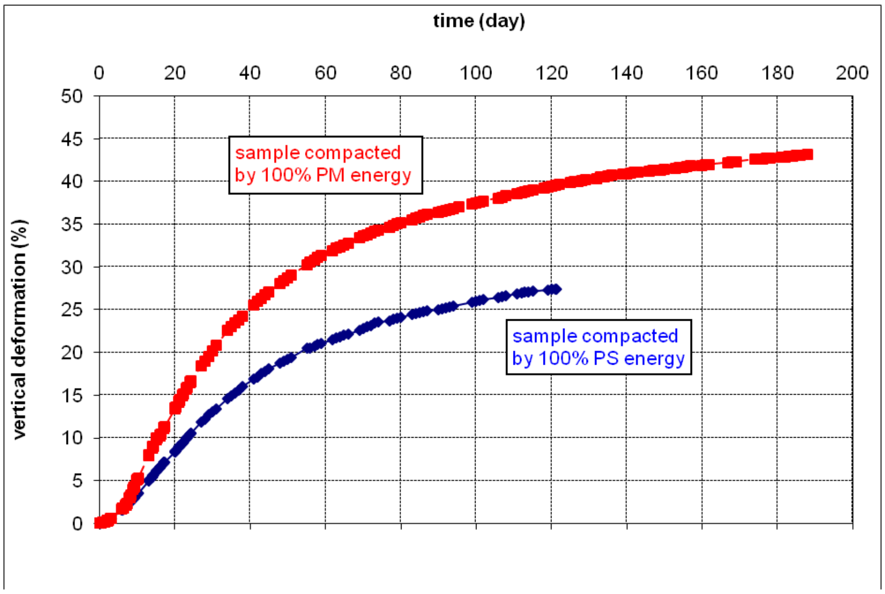

Figure 8: Progression with time of the increment of vertical deformation of steelworks waste samples soaked with water at the temperature of 75°C

Swelling pressure values of steelwork waste were measured in case of experimental samples only. The swelling pressure value of 1.548 MPa obtained for the sample KS1 from 1.7-2.0 m after 48 days at 70°C was higher than the values obtained from the autoclave test conducted at the pressure of 357 kPa and the temperature of 137°C for 1 hour (max. 1.28 MPa) presented by Wang [11] for samples of BOF steel slag [12].

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For two samples of steelworks waste, the time dependence of swelling pressure tested at the temperature of 70°C was approximately the same. A more substantial series of tests will have to be run for the data learned to be valid. Increase of deformation is originated in mineralogical composition and changes of mineral phases of individual components of steelwork waste.

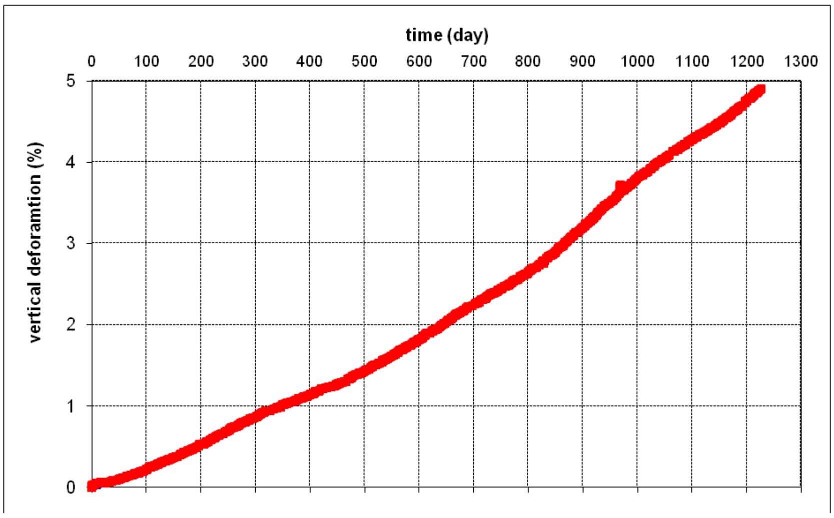

Figure 9: Progression with time of the increment of vertical deformation of steelworks waste samples soaked with water under normal pressure and temperature (period of 30.1.2012-10.6.2015)

Figure 10: View of a sample compacted by 100% Standard Proctor energy at the temperature of 75°C after 65 days

It has to be pointed out, however that we still lack the values of correlation between swelling pressure values obtained in environments that accelerate the changes of volume (at higher temperatures) and those that would be obtained in tests performed at standard temperature and pressure.

Another problem is to estimate in which stage of volume changes a steelwork waste material is. The velocity of mineralogical and phase changes is well described in case of pure minerals. In case of such heterogeneous mixture which is represented by the steelwork waste, it is not possible definitely to set any prognosis.

Mineralogical analyses before and after autoclave tests were carried out in case of the Ikea shopping centre samples to find out changes in mineralogical association. It was observed that after autoclave tests a share of calcite increase comparing with share of portlandite. However, it was not possible to quantify mineralogical changes after autoclave tests to predict behaviour of this material in the future [8].

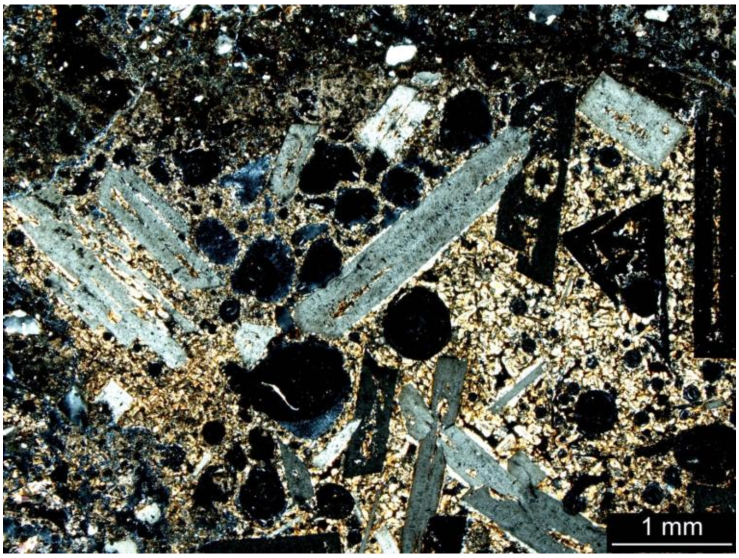

Figure 11: Cemented mass from slag grains. Typical product of steelworks waste transformation. Sample after autoclave test. Photo: J. Ščučka

V. CONCLUSIONS

Steelwork waste is non-standard material. A majority of its properties (almost all with exception of one – volume stability) shows sufficient results. Based on the existing analyses it is resulted that the reason of the pavement deformations on the D47 motorway and deformations of floors of many business, shopping and industrial centres in the Ostrava region was the usage of steelwork waste.

From the analyses performed so far it follows that the cardinal error committed in the case of the D47 motorway was the use of a material (steelworks waste) in respect of which no experience was available from other applications within the construction limits of a scope comparable to those of highways.

Results of tests show that although deformations lasted for many years their stabilization has not been definitely proven. Therefore we are not able to predict how many years deformations will be lasted. Values of swelling pressure are so high which show results of tests under non-standard conditions (temperature of 75°C), when there were measured values so far unpublished, but also consequences of volume changes in constructions where steelwork waste was used.

This very expensive experience, because the remedial works of steelwork waste usage will be very expensive, maybe increase the cautiousness in case of utilization of unknown and untested materials. On the other side probably the opposite extreme will not occur when good secondary material will be excluded from constructions only therefore that they have its origin in metallurgical production.

There are many questions, however, we do not know if they will anytime answered because research financing to understand properties of this material is not in comparison of disputes actual.

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