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ASSESSMENT OF A PLASTIC AND LIAPOR MIXTURE IN TERMS OF COMPRESSIVE STRENGTH

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Abstract

In the construction industry, efforts are continually being made to replace natural resources with recycled or artificial materials to promote sustainable development worldwide. This article explores the use of recycled plastic waste (expanded polystyrene and polyester fibers) combined with lightweight expanded clay aggregate (Liapor) to produce a mixture that could potentially be used as a structural layer in sub-ballast layers. Prior to testing this recycled material, it was hypothesized that the layer would serve a thermal insulation function and potentially provide partial reinforcement within the structural composition of the sub-ballast layers. The article outlines the procedure for manufacturing samples of the mixture made from plastic and Liapor, which was subjected to a compressive strength test. The results of the compressive strength test revealed that the sample's strength was insufficient for its intended use in the structural composition of the sub-ballast layers as the achieved maximum compressive strength was only approx. 0.40 MPa. However, its favorable thermal insulation properties remain promising and should be verified in future laboratory investigations after adjusting the ratio of material components and possibly the manufacturing process.

Keywords:

Recycling of Waste;
Sub-ballast layers;
Plastic and Liapor Mixture;
Compressive Strength;
Expanded Polystyrene.

1 Introduction

One of the primary research areas pursued by the staff of the Department of Railway Engineering and Track Management (DRETM), Faculty of Civil Engineering (FCE), University of Žilina (UNIZA) is monitoring the effects of non-traffic loads (water, frost, snow, etc.) on the railway track structure, specifically its substructure – the sub-ballast layers [1-2]. Currently, the protection of the frost-susceptible subgrade against non-traffic (climatic) loading is achieved by designing a sufficiently thick structural layer, typically composed of crushed aggregates with fractions of 0/31.5, 0/45, or 0/63 mm.

As natural material deposits (currently predominantly crushed aggregate, previously gravelly sand) are gradually being depleted, and new deposits are becoming increasingly scarce, it is essential, from the perspective of ensuring sustainable development, to explore new suitable materials. These materials should not only serve as replacements for natural resources but also provide protective functions for the subgrade surface against climatic factors within the sub-ballast layers.To achieve this goal, the DRETM research activities have recently focused on assessing several thermal insulation materials, including composite foam concrete, Liapor, extruded polystyrene, and foam glass. The most significant DRETM results obtained through experimental measurements and numerical modeling are comprehensively summarized in sufficient detail in publication [3].

Our ongoing efforts aim to identify additional suitable thermal insulation materials that are not derived from natural resources (such as crushed aggregate or gravelly sand) but, at the same time, can provide both protection against climatic factors and, ideally, increased deformation resistance for the entire sub-ballast layers. This is a logical requirement, as the structural composition of the sub-ballast layers must be designed to meet both traffic and non-traffic loading demands.

The first material assessed from this perspective was Liapor concrete, which showed an increase in deformation resistance. However, its thermal insulation properties were insufficient due to its high water absorption, caused by the high permeability of the traditional railway superstructure (ballast) and the structural layers located between the subgrade surface and the ballast. Similarly, specialized rigid boards of extruded polystyrene or foam glass were evaluated. While these materials exhibited good to excellent thermal insulation properties, they had only a minimal impact on increasing the deformation resistance of the sub-ballast layers. A particularly significant material identified through experimental methods as suitable for improving both thermal and deformation resistance of the sub-ballast layers was composite foam concrete. This material has been the subject of several publications, the most notable of which is [4].

In relation to waste plastics and their recycling, the idea emerged to test another material — a mixture of Liapor and plastic that could provide the required properties for the structural composition of the sub-ballast layers, specifically thermal insulation and reinforcement functions. While this material is not entirely of natural origin, its use could contribute, on one hand, to reducing the demand for natural deposits of construction materials and, on the other hand, to the reuse of waste plastics.

Liapor is a lightweight aggregate made from expanded clay, used in construction as a substitute for traditional aggregates, and is widely known in this region under the commercial name *Keramzyt* (in Polish) or *Keramzit* (in Slovak). The virtually spherical granules, available in various sizes, are lightweight yet strong, which suggested that they could contribute to sufficient deformation resistance in the structure. Furthermore, due to their ceramic nature, they are chemically stable and environmentally friendly.

Abroad, compressive strength tests mainly focus on various modifications of concrete mixtures, such as plastic concrete [5], concrete mixtures containing plastic, glass, rubber aggregates [6], or waste glass [7] and the shapes or sizes of the tested samples [8-9]. According to publication [6], the compressive strength of a concrete mixture decreases as the plastic or rubber content increases (determined compressive strength values range from approximately 2 to 7 MPa, depending on the percentage of plastic or rubber in the mixture) and, conversely, increases with a higher glass content (determined compressive strength values range from approximately 6 to 11 MPa, depending on the percentage of glass in the mixture). The compressive strength of the reference sample (a mixture without recycled material) was approximately 16 MPa.

Similarly, samples of concrete mixed with plastic waste [10-12] or concrete mixed with Liapor, fly ash, or hollow ceramic spheres [13] were tested. Based on the findings of study [10], it was recommended that processed HDPE powder material could be used as an additive in conventional and high-strength concretes at a volume of 0.5% of the cement weight without reducing their compressive strength. The study tested M25 and M50 grade concretes.

Study [13] examined the properties of lightweight geopolymers, using polystyrene (GPP), Liapor (GPL), or hollow ceramic microspheres (GPM) as fillers. The best compressive strength was achieved with the GPM filler — approximately 27 MPa (GPL – approximately 14 MPa and GPP – approximately 12 MPa). In terms of flexural strength, the best results were achieved with GPP — approximately 2.1 MPa (GPL and GPM – approximately 1.5 MPa). The publication [14] presents a novel method for evaluating compressive strength, while publication [15] discusses the impact of the hydration process on the resulting compressive strength of concrete samples.

Compressive strength tests were also conducted on samples made of lightweight concrete, where expanded glass granulate, fly ash, and Liapor were used as fillers [16-17], as well as on samples of foam concrete [18-20]. In study [16], all lightweight aggregate concretes had a density of less than 1000 $kg \cdot m^{-3}$, with compressive strength values ranging from 16 to 25 MPa. The thermal conductivity coefficient of all tested materials was below 0.35 $W \cdot m^{-1} \cdot K^{-1}$.

Publication [21] even presented results where microorganisms (fungi) were used in the production of foam concrete mixtures. However, the author is not aware of any study that examines the properties of a Liapor and plastic mixture.

2 Materials and Methods

The issue of recycling waste plastics is a subject of long-term research focus at the University of Bielsko-Biała, specifically at the Faculty of Materials, Civil, and Environmental Engineering. As part of the research conducted at this department, various test samples were produced using a mixture of molten plastic and gravel (Fig. 1).

Fig. 1: Samples produced at the University of Bielsko-Biała from a mixture of melted plastic and gravel.

This part of the paper focuses on the production method of the samples, where gravel in the proposed mixture was replaced with a thermal insulation material — specifically Liapor (expanded clay). It also describes the procedure for determining the compressive strength of the tested (cube-shaped) samples.

2.1 Test samples

Every test sample was produced in a ventilated chamber, where approximately 1 liter of Liapor (*Keramzit*) fraction 8/16 mm was heated on a sufficiently large sheet (Figure 2, left). Crushed expanded polystyrene (EPS) beads (Figure 2, center) were then added. These beads melted onto the Liapor and gradually bonded together. The ratio of Liapor to EPS was approximately 1:1. To increase the tensile strength of the tested material, polyester fibers (Figure 2, right) were also incorporated into the mixture. The ratio of EPS to polyester fibers was approximately 2:1.

Fig. 2: Components of the test mixture: Liapor fraction 8/16 mm (left), EPS beads (center), and polyester fibers (right).

After preparing a sufficient amount of the mixture, it was gradually placed into a cube mold with dimensions of 100x100x100 mm (Figure 3, left), and compacted continuously using a tamper. The final form of the sample after curing is presented in Figure 3, right.

Fig. 3: Filling the mold for sample production (left) and the created test sample (right).

2.2 Determination of compressive strength

The determination of compressive strength was carried out by applying compressive force to the three prepared test samples, monitoring the material's resistance to crushing, and assessing its ability to recover after the application of a specific compressive load. The objective of the test was to determine the maximum stress the sample could endure for a given duration under loading. The test typically continued until the sample experienced destruction (e.g., fracture or cracking).

The TVM 30KN70N measurement setup was used for the test. This motorized testing stand is designed to measure tensile or compressive forces within a range of 0–30 kN. It is equipped with an integrated *Sauter* force gauge that records the force applied to the sample during measurement, with a resolution of 1 N. A *Sylvac* dial indicator, with a resolution of 0.001 mm, is mounted on the stand's frame to measure the deformation of the sample by recording the displacement of the movable base relative to the fixed base.

The TVM stand operates as a mechanical force stand powered by an electric motor with a gearbox, which converts the motor's rotational motion into the translational motion of a threaded rod, thereby moving the base. The motor includes a frequency converter, allowing adjustment of the motor's rotational speed and, consequently, the displacement speed. The measuring system is categorized as a controlled displacement line, with a displacement speed adjustable between 1 and 70 mm/min. The stand frame consists of rigid guide rods to which both bases are secured (Figure 4).

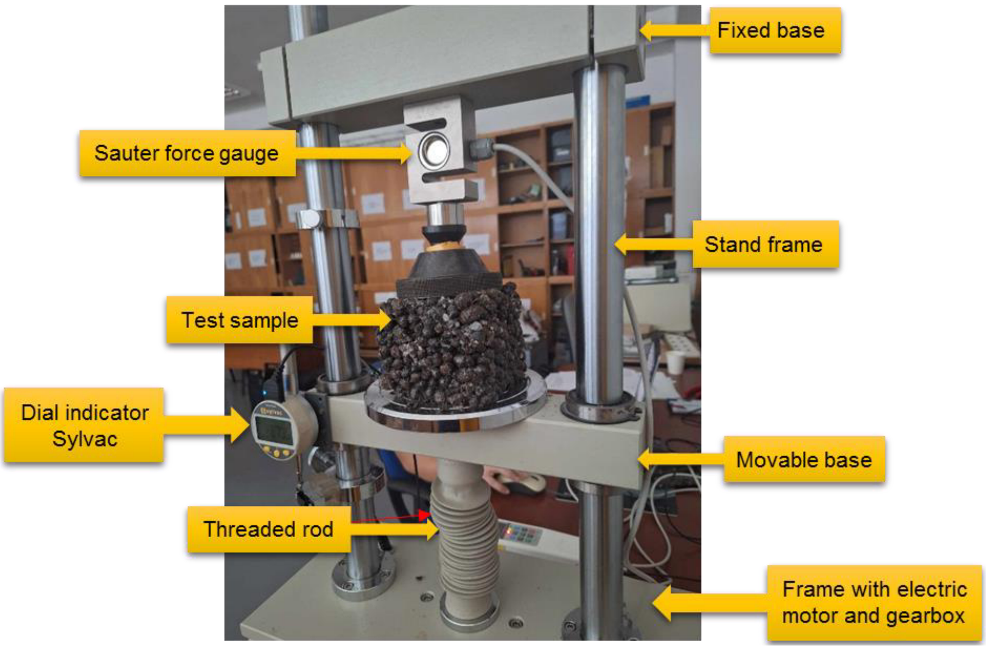

Fig. 4: Setup for determining the compressive strength of the sample.

The measuring stand is equipped with an automatic shut-off mechanism controlled by force (activated upon reaching a specified force) and deformation (triggered upon reaching a specified deformation). The measuring devices—the force gauge and dial indicator—are connected to a control PC, where the measured values are synchronously recorded in real-time. Both devices operate with a sampling frequency of 10 Hz.

The recorded force and deformation data can be readily converted into stress and strain by taking into account the geometry of the tested sample. Given the uniaxial nature of the load — in this case, uniaxial compression — stress σ [Pa] and strain ε [-] can be expressed using the following well-known relationships:

$$\sigma = \frac{F}{A}, \tag{1}$$

$$\varepsilon = \frac{\Delta l}{l}, \tag{2}$$

where F [N] is the directly measured force, *A* [m²] is the cross-sectional area of the test sample, *l* [m] is the original height of the sample, and Δ*l* [m] is the directly measured displacement of the base or the deformation of the sample. From Hooke's law for uniaxial stress, we can subsequently determine the instantaneous modulus of elasticity *E* [Pa] using the following relationship:

$$E = \sigma \cdot \varepsilon, \tag{3}$$

Using these calculated values, a stress-strain curve can be constructed from the test, and the instantaneous modulus of elasticity can be determined for each measured value.

3 Results

The preparation of each test sample, along with the equipment used for conducting the compressive strength test, was detailed in Chapter 2. The compressive strength measurement was carried out until the complete destruction (collapse) of the sample – see Figure 5.

Fig. 5: Demonstration of sample collapse during the compressive strength test.

An example of a graphical overview of the results from the conducted compressive strength test, documenting the maximum achieved compressive strength value from the three tested samples, is demonstrated in Figure 6. Specifically, the left side of Figure 6 displays the working diagram, and the right side of Figure 6 presents the curve showing the progression of the modulus of elasticity.

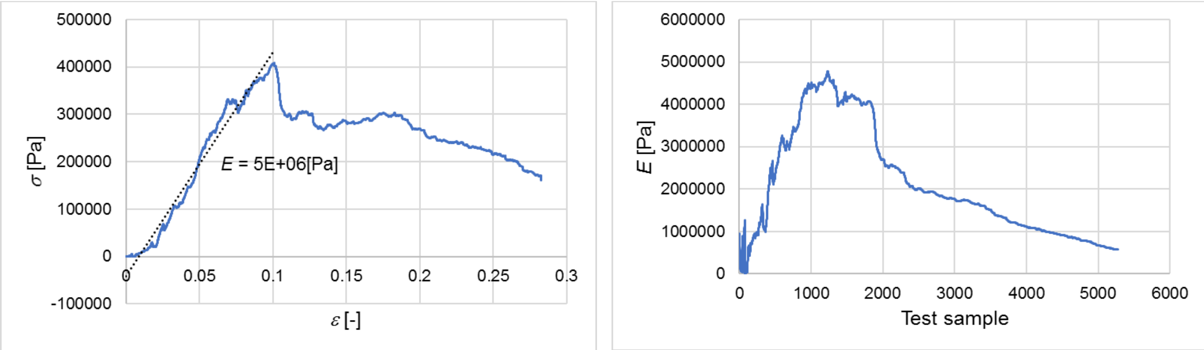

Fig. 6: An example of a graphical overview of the results from the compressive strength test of the tested sample – the working diagram (left) and the curve showing the progression of the modulus of elasticity (right).

The working diagrams indicate that the maximum stress the sample can withstand is approximately 0.40 MPa, after which it collapses. For comparison, this is only 0.1 MPa higher than the value that a plate made of extruded polystyrene (Styrodur 2800 C) can resist. The application of such a plate in the structural composition of the sub-ballast layers was evaluated in previous research [22] and showed only a negligible effect on increasing its deformation resistance. Ideally, the plastic-Liapor mix sample should achieve a compressive strength of at least 1.0 MPa for it to contribute meaningfully to improving the deformation resistance of the sub-ballast layers. For comparison, a composite foam concrete sample with a density of 600 $kg \cdot m^{-3}$, which was also evaluated in earlier research and published results, e.g., in [4], reached a compressive strength of approximately 2.0 MPa. This strength had a significant impact on increasing the deformation resistance of the proposed modified structural composition of the sub-ballast layers.

3 Conclusion

The search for new methods of artificial material production and the recycling of used materials is a crucial part of modern construction, aiming to ensure sustainable development in all, especially technologically advanced, countries. As natural material resources are continuously depleting and the demand for high-quality construction remains high, replacing them with alternatives , whether non-natural materials or new natural construction material deposits, has become an inevitable necessity.

This article presents the results obtained from samples from a mixture of plastic and Liapor, considered for use in the structural composition of sub-ballast layers. The application of this mixture aims, on one hand, to reduce the demand for natural materials (such as sand, gravel, or crushed aggregate), and on the other hand, to make use of recycled plastic materials. However, as demonstrated in the experimental measurements presented in Chapter 2, the created sample of the plastic and Liapor mixture exhibits relatively low compressive strength (approximately 0.40 MPa). Therefore, it would have only a minimal impact on increasing the deformation resistance of the sub-ballast layers, particularly in the sub-ballast upper surface, which is crucial for evaluating the deformation resistance of traditional track structures with a ballast bed. This level is a crucial point for assessing the design of the railway track with a conventional superstructure, known as a ballast track bed, in terms of deformation resistance. Given the results of the experimental measurements (low compressive strength), it was decided that further tests (flexural strength, impact resistance, durability, and long-term stability) are irrelevant. A new mix design ratio is required, or possibly a modification of the production process of the mixture, and if better results are achieved from the compressive strength test, it would be meaningful to conduct additional tests.

The proposed mixture of plastic and Liapor, specified in section 2.1, could thus be applied to the structural composition of the sub-ballast layers solely for the purpose of increasing its thermal resistance, which is expected to be relatively high. The porous structure and ceramic nature of Liapor guarantee excellent thermal insulation and accumulation properties, with a thermal conductivity coefficient (λ) ranging from 0.09 $W \cdot m^{-1} \cdot K^{-1}$. This value of thermal conductivity is considered very low, indicating the potential for achieving a relatively high thermal resistance in the layer containing Liapor.

Since our research primarily focuses on materials that would provide both thermal insulation and reinforcement (such as composite foam concrete) within the sub-ballast layers, this mixture does not meet those requirements. Therefore, our future research will focus on modifying the mixture—by adjusting the material composition and the ratio of individual components—or modifying the manufacturing process to definitively assess whether the mixture meets at least the minimum criteria or cost-effectiveness in terms of deformation resistance. It is assumed that the thermal insulating effectiveness of this mixed material could ultimately prove to be sufficient.

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