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Assessment of the Application of Lumpy Steel Slag as an Aggregate Replacement in Concrete

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Abstract. The need to protect the Earth's resources necessitates pro-ecological activities. One of the aspects of these activities is the rational management of post-production and post-consumer waste. One of the materials whose production significantly pollutes the natural environment is concrete. On the other hand, the analysis of the literature carried out in the work showed that it is a material that can absorb a significant amount of processed waste used as a substitute for cement or aggregate. These are polymer materials of various origins, residues from biomass combustion and, above all, steel slag, which has long been used in construction in various forms. One of the types of this material is lumpy steel slag, which has been used for years mainly in road construction as a replacement for crushed stone in the construction of the road base. The paper presents instrumental tests of the influence of the lump slag content used as a replacement for basalt aggregate on selected parameters of concrete (compressive strength, water absorption, volume density). The research showed that such a modification of the mixture composition does not significantly change the tested parameters. The lump slag can therefore be successfully used in the production of normal and heavy concrete.

Introduction

Waste is inseparable from human industrial activity (post-production waste) and everyday life (post-consumer waste). In the past decades, its recovery, partial or total re-use has not been sufficiently taken into account. The reason for this - apart from the lack of ecological awareness and modernist admiration for industrialization - was the wide availability of fossil resources from shallow deposits or opencast sources. Along with the growing demand for raw materials, the need to exploit deeper and deeper seams and the shrinking sources of their extraction, the use of materials previously considered waste and deposited in landfills occupying more and more areas began to be seriously considered. Waste, especially construction and post-demolition waste, was also often thrown in random places, burned or irresponsibly managed [1]. Analyses of the composition and properties of the waste were conducted, and it was noticed that what was previously considered useless could be useful. It has been noticed that apart from the recovery of raw materials that can be easily reused in the production process (primary or otherwise), especially after processing, they can be used in building construction and road construction. Over the years, the environmental awareness of both governments and societies has grown, leading to the introduction of legislation in many countries, especially in Europe and North America, forcing a continuous increase in activities aimed at protecting the natural environment. Note that the recovery and recycling of materials does not always bring direct economic benefits. Therefore, the ecological context is important here - the reduction of the use of natural resources reduces the burden on the surrounding environment [2]. Also, not all waste material can be reused. For example, asbestos-cement panels or reclaimed road pavement containing tar can be harmful to your health. In this case, the only alternative is wise and safe disposal.

In modern construction, concrete is a material whose production significantly burden the environment. Therefore, many research centers are conducting research on the possibility of using various materials, including waste materials, in the production of concrete [3]. There are two main directions of this search: reducing cement consumption and replacing it with another binding material [4] and the use of waste products as a replacement for aggregate. Recycling materials used as an additive can also advantageously change some parameters of the concrete.

Among the various waste materials, waste polymer materials are of great interest. One of the best-studied waste economies in this area is polyethylene terephthalate, PET [5]. It was used for concrete as a replacement for aggregate or in the form of fibers as dispersed reinforcement [6]. Research was also conducted on the use of recycled polyethylene and polypropylene [7], polystyrene [8], rubber [9] or a thermoplastic elastomer from the production process of car mats [10].

The use of combustion materials is also very popular. These materials can be divided into those coming from production processes and from biomass combustion. The first of these types, which has been used for many years, will be discussed in the next section. As for the residues from biomass combustion, there has been a recent increase in interest in the use of these products. Plant waste, which so far has not been considered for use in construction, can be used as a replacement for cement – here one can mention ashes from rice hulls, oil palm, sugar cane pomace or corn cobs [11] – or even as a replacement for aggregate [12]. In Poland, research was conducted on biomass ash – a mixture of wood and sunflower waste [13].

It should be mentioned that concrete may not only be a material absorbing processed waste, but also a post-consumer waste used, after processing, as a substitute for aggregate in the composition of the concrete mix or in the construction of the road base (Fig. 1).

Fig. 1. *The use of crushed concrete in the construction of the pavement base (photo: Z. Respondek)*

The aim of the article is to assess the legitimacy of the use of waste material on the example of lumpy steel slag for the production of concrete. Therefore, instrumental studies of the impact of the content of processed waste, used as a replacement for basalt aggregate, on selected concrete parameters were performed.

Management of Waste from Combustion in Production Processes

As already mentioned, processed industrial waste, which is a by-product of the combustion process, has been used in construction for many years. Here we can list, among others: silica fume, fly ash and steel slag.

Silica fume (microsilica) is obtained during the production of metallic silicon and ferrosilicon alloys in electric arc furnaces. The use of microsilica has a very positive effect on the increase in concrete strength in the initial period, viscosity, increases resistance to alkali and sulphates and the absorption of $Ca(OH)_2$ in the chemical process. This is due to the large specific surface area of microsilica particles [14].

Fly ash is a fine-grained fraction of ashes produced during the combustion of solid fuels. Currently, they are the most commonly used waste materials used as a partial replacement for Portland cement because its properties are similar to those of Portland clinker (pozzolanic activity). However, due to the insufficient content of calcium hydroxide in the chemical composition, they cannot function as a hydraulic binder on their own. Fly ash as a partial replacement for cement initially reduces the compressive strength of concrete, but after about 90 days, an increase in this strength is observed in relation to the base concrete [15].

Steel slag (blast furnace slag) can be used in several forms.

Granulated steel slag is obtained by rapidly cooling molten slag. A granular material with a glassy amorphous structure and hydraulic properties is obtained. This material is used as an additive to Portland cement (slag cement). Also, cooling, but with a smaller amount of water, results in the production of pumice slag – this material has the form of larger lumps with a porous-spongy amorphous structure. After mechanical processing in crushers and division into fractions, light aggregate is obtained, used primarily for the production of bricks and blocks [16].

Lumpy steel slag is a slag slowly cooled with air, which, after solidification, is crushed and separated into fractions. For many years, this material has been used instead of natural stone, mainly in road construction, because its physical properties are equivalent to those of aggregates obtained from natural rocks. In the context of the use of blast furnace slag for heavy concretes and reinforced concrete, this material initially raised doubts – there was a concern that the reinforcement would corrode as a result of the sulfur contained in it. Currently, it is assumed that there is no concern about the negative impact of this aggregate when the sulfur content, converted into SO_3, does not exceed 2 wt.%. It should be added that all metallurgical waste may have a different chemical composition, therefore each time there is a need to research the possible negative impact of these materials on human health and the environment [17].

Methodology of research

Instrumental tests of concrete were carried out at the Faculty of Civil Engineering of the Czestochowa University of Technology. The tests were preceded by the design of the base concrete for the assumed grade C30 / 37:

- Portland cement CEM I 42,5 R (Górażdże) – 296 kg/m^3,
- water - 160 kg/m^3,
- sand - 836 kg/m^3,
- basalt aggregate 2-8 mm - 836 kg/m^3,
- basalt aggregate 8-16 mm - 836 kg/m^3.

Two sets of five series of 15×15×15 cm cubic samples were made: base concrete and four series in which 8-16 mm basalt aggregate was replaced with lumpy steel slag in the amount of: 25, 50, 75 and 100 wt.%. Each series consisted of 3 samples.

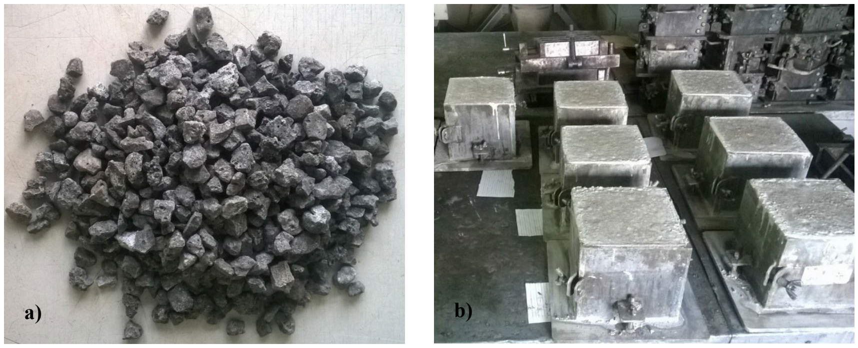

Fig.2. *Test preparation: a) 8-16 mm lumpy steel slag used, b) samples after demolding (photo: A Harwat)*

The slag used for the test was imported from one of the Ukrainian smelters. The 8-16 mm fraction was used (Fig. 2a). The research program included:

- compressive strength after 28 days,
- water absorption after 28 days,
- volume density.

One of the prepared sets of samples was used to determine the compressive strength, the other - for water absorption and volume density. Preparation of samples (Fig. 2b) and execution of the test were carried out according to the procedures included in the standards of the series "EN 12390 Testing hardened concrete". In order to finally select the quantitative composition of the materials used, a trial preparation was made for each series and the amount of water was adjusted due to the improvement of the workability of the mixture. Stachement 2050 superplasticizer was also used. ToniTechnik 2030 test machine (Berlin, Germany) was used for the compressive strength test.

Results

The test results are shown in Figures 3-5. In all graphs, the solid line represents the average value of three samples, while the dashed line shows the minimum and maximum value of a given parameter obtained for individual samples from each series. Table 1 illustrates the percentage change in the average values of the tested parameters in relation to the base concrete.

The compressive strength test shows that the content of 25 wt.% of slag as a replacement for basalt aggregate results in a slight increase in compressive strength. Higher slag content causes a slight deterioration of this parameter. However, these fluctuations do not affect the change of concrete grade. Determined according to EN 206 “Concrete. Specification, performance, production and conformity” is in any case C30/37. With regard to the water absorption, fluctuations of several percent were also observed. The worst parameters were obtained for the series of 50 wt.%, best for 100 wt.%. According to the literature recommendations [18], the water absorption of concrete should not exceed 5% for concretes exposed to the external environment and 9% for concrete protected against this effect. Score 4.98 for 100 wt.% is therefore near the limit value.

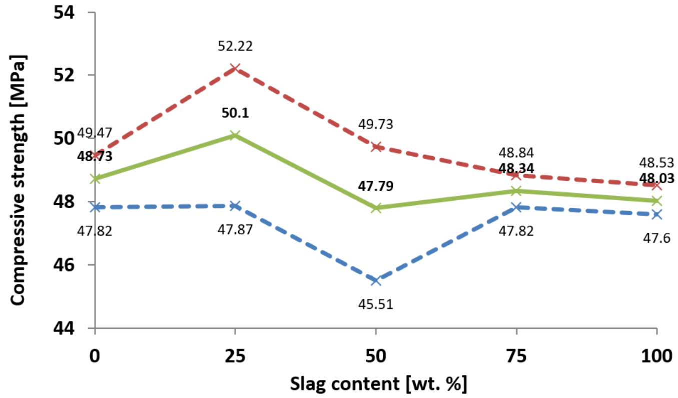

Fig.3. *The influence of slag content on the compressive strength of concrete [own research].*

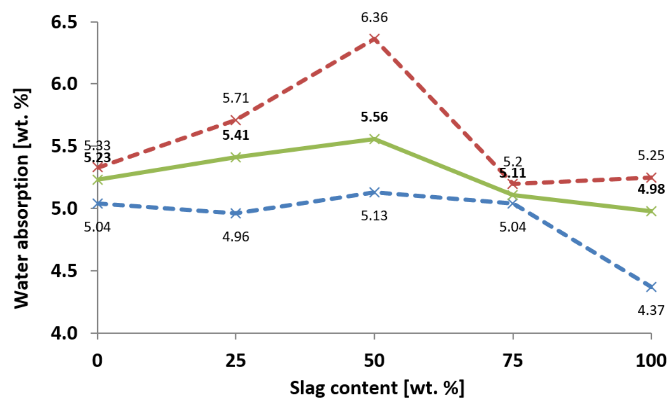

Fig.4. *The influence of slag content on the water absorption of concrete [own research].*

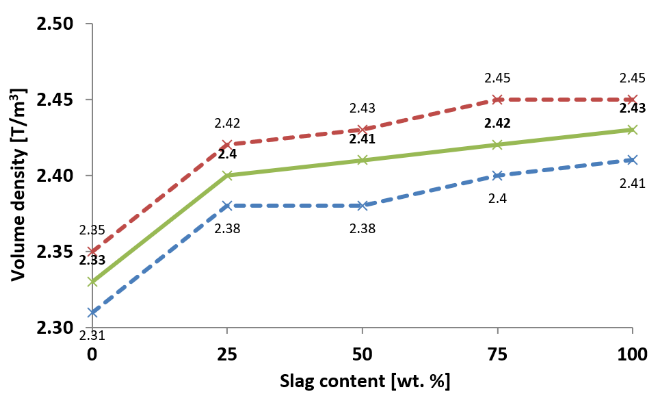

Fig.5. *The influence of slag content on the volume density of concrete [own research].*

Table 1. *Percentage change of the tested parameters (average values) in relation to the base concrete [own research]*

Parameter	Slag content			
	25 wt. %	50 wt. %	75 wt. %	100 wt. %
Compressive strength	2.8%	-1.9%	-0.8%	-1.4%
Water absorption	3.4%	6.3%	-2.3%	-4.8%
Volume density	3.0%	3.4%	3.9%	4.3%

The tests also showed an increase in the slag content, resulting in an increase to 4.3 wt.%, the concrete volume density in relation to the base concrete with basalt aggregate.

Conclusions

The literature analysis carried out in the article showed a wide spectrum of waste materials that can be used as a component of concrete. This use is limited, first of all, by the harmful effects on human health. The condition for the proper use of waste as a replacement for cement or aggregate in concrete is the prior processing of this waste and carrying out tests confirming or disproving the legitimacy of using such modified materials in construction. The instrumental tests of concrete with the content of lump slag carried out in the work are an example of such an action.

In common understanding, slag concrete is associated with a cheaper and worse type of concrete. For example, the commonly used slag concrete blocks are characterized by high water absorption, reduced strength and often insufficient durability. The conducted research has shown that lumpy steel slag, commonly used as a replacement for aggregate in the road-base layers, can be successfully used as a substitute for basalt aggregate in classic concrete.

The compressive strength of the modified concrete is not more than 2% worse than that of the base concrete. The aggregate replacement does not change the concrete grade.

The water absorption of concrete when replacing basalt aggregate with processed waste of the same fraction does not differ significantly from the parameters of the base concrete. All series show water absorption at the limit of applicability for concrete exposed to moisture.

The aggregate replacement increases the volume density of the concrete, although all series should be classified as normal concrete. It seems possible, however, that with the appropriate design of the mixture composition, heavy concrete (specific gravity above 2.6 T/m^3) can be achieved with the content of lumpy slag. Such a composite can be used, for example, as ballast concrete.

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