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Research paper

Selected issues concerning the use of Shredded Rubber Waste (SRW) in binder-bound mixtures

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Abstract: This paper presents the results of a composite consisting mainly of industrial waste bound by a hydraulic binder. The composite consists of unburnt coal-mining slate, shredded rubber waste (SRW), fly ash and CEM I cement. The purpose of using the above components was to protect the unburnt coal-mining slate from the negative effects of water, which causes degradation of the aggregate grain size and significantly affects the load-bearing capacity of the aggregate. This was achieved through the use of a binder consisting of shredded waste rubber, fly ash and cement, which imparts hydrophobic properties to the composite. The composite is to be used in road pavement construction and earthworks as a substitute for standard materials. This paper focuses on testing the effects of 5, 10 and 15% additions of shredded rubber waste (SRW) on the physical and mechanical parameters of the composite, mainly compressive strength, water absorption by mass, capillary rise and deformability under cyclic loading. The composite was tested under cyclic loading conditions using a measurement system based on digital image correlation (DIC), with which the deformations occurring on the surface of the test specimens were determined. The results obtained showed the influence of shredded rubber waste additives on the decrease in compression strength (after 7 and 28 days of specimen care), mass water absorption and capillary rise, as well as an increase in the deformability of the composite under destructive loading and cyclic loading.

Keywords: industrial waste, mining waste, rubber waste, DIC

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1. Introduction

Construction is an industry sector with a very high demand for natural resources. This trend seems to be increasing in recent years, China being an example, which consumed around 6.6 Gt of cement between 2011 and 2013, where, by comparison, the US consumed 4.5 Gt in the 20th century [1]. In addition to the demand for mineral binders, the construction industry also uses very large quantities of natural aggregates. In France, there was an increase in natural aggregates production from 331 Mt to 429 Mt in 2016/2017 [2]. In the context of dwindling mineral resources, these figures necessitate the search for other alternative sources of aggregates or mineral binders. An effective response to this problem is the Closed Circuit Economy (CCE) system [3]. Under this idea, waste from one sector or product of an industry would serve as production raw materials in another sector, creating a closed loop. The European Union Directive 2008/98/EC, is a first step in this direction. More and more countries around the world are trying to use waste to produce mineral aggregates or binders in line with CCE:

- Use of construction rubble for aggregate production [2];
- Use of fluidized bed ash for the production of bentonite binders [4];
- Use of gold mining waste to produce bricks [5];
- Use of rubber waste for soil reinforcement [6].

As a result of the significant development of coal mining, the Upper Silesian Coal Region is rich in mining waste accompanying hard coal. These wastes are generated during preparatory work and mining and processing operations. According to the Road and Bridge Research Institute [7], more than 1.5 billion tonnes of post-coal waste is deposited in Upper Silesia, and approximately 37 million tonnes are extracted annually [8]. Such a large amount of material requires finding a way to dispose of it or use it in industry.

Mining waste consists of various types of rocky and non-rocky soils and may include [7, 9–13]:

- Clay shales;
- Mudstones;
- Carbonaceous shales;
- Sandstones;
- Pebbles;
- Mules;
- Siderite;
- Spherosiderites;
- Coal crumbs.

As the petrographic composition of the barren rock varies so much, it will show large differences in physical and mechanical parameters depending on its place of origin. In addition, as the barren rock is only subjected to natural erosion processes after extraction, it is very sensitive to the effects of water and frost, which cause degradation of the aggregate grain size. As a result of these changes, the waste rock may decrease its load-bearing properties by reducing the skeleton consisting of coarser aggregate fractions and may begin to exhibit heaving characteristics as a result of a significant accumulation of powdery-silty fractions. [7, 14–18].

The above characteristics mean that any use of waste rock in the construction industry requires a number of laboratory tests, particularly long-term tests in which sensitivity to water and frost is checked. This causes considerable reluctance to use this waste among contractors, despite its attractive price and very high availability in Upper Silesia.

Post-coal waste is mainly used for:

- Embankment construction [7, 19–22];
- Macro levelling of human-degraded land [23, 24];
- The erection of hydraulic structures [14, 15, 25, 26];
- As an additive in the manufacture of low volume units and cements [23, 27].

Rubber waste, particularly from used car tyres, is another material that is difficult to reuse due to the irreversible processes that accompany the vulcanisation of the fresh rubber compound. Current uses of rubber waste are mainly based on its use in geotechnics [28, 29], concretes [30] and mineral and asphalt mixtures [31, 32]. The increasing number of internal combustion vehicles on the road is leading to an increasing production of car tyres. According to Lo Presti [31] and Alfayez et al. [33] approximately 1.4 billion tyres are sold each year and a comparable amount becomes waste in the form of used car tyres. This waste is not considered as a hazardous or risky material with proper treatment, storage and transport. In addition, they are non-toxic, resistant to mould, moisture and show high resistance to bacteria. However, due to their resistance to biodegradation and the effects of organic solvents, these materials are heavy burden on the environment. Therefore, a number of pieces of legislation have emerged to standardise ways of dealing with used car tyres, including [34]:

- Directive 1999/31/EC (Landfill Directive) – a European Union directive introducing a ban on the landfilling of whole used car tyres from July 2003 and, from July 2006, also of shredded tyres [34, 35];
- Directive 200/53/EC (End-of-life Vehicle Directive) – a European Union directive defining the end-of-life treatment of vehicles [34, 35].

The biggest problem with the reuse of rubber waste is the irreversible nature of the vulcanisation process for fresh rubber compounds. As a result, it is not possible to convert waste rubber into a usable product for its original purpose. It is estimated that a 1% addition of shredded rubber waste to the production of car tyres results in a reduction in their durability of approximately 1% [31]. Therefore, rubber waste is most often recycled [36, 37] by the following methods:

- Energetic;
- Product;
- Raw material;
- Material.

Product and material recycling of rubber waste is most commonly used in the construction industry. Depending on the degree of processing, rubber waste is used in:

- Geotechnics (lightweight embankment fill, ground improvement, slope stability improvement, retaining wall construction, drainage and cut-off layers, road culverts) [28, 29, 38–41];
- Technologies for the production of mineral and asphalt mixtures [28, 29, 33, 42, 43];
- Production of lightweight concretes [30, 34, 35, 44–56].

The results of research into the use of shredded rubber waste as an additive to concretes indicate that it causes a reduction in compressive strength, but improves frost resistance parameters, deformability, hydrophobicity and makes it possible to eliminate the phenomenon of brittle fracture occurring at the failure of classic concrete samples.

Based on unburnt coal mining slate and shredded rubber waste, the article proposes a composite mix to be used for road pavement layers. The mixture, consisting mainly of industrial waste, fits perfectly into the idea of a Closed Economy and aims to exploit the positive properties of the materials used. The presented mixture was used to improve the physical and mechanical parameters of unburnt coal mining slate (bed rock), and in particular to increase the water resistance of the shale. The purpose of using mixtures in road construction is primarily:

- Increasing the durability of binder-bonded shale mixtures, which, due to the high water sensitivity of the aggregate, can degrade over long periods of time. The use of shredded rubber waste in the mixtures is expected to create an insulating layer in the cement-asphalt-rubber matrix, hindering the penetration of water deep into the material;
- Reduction of water absorption in the mixture. The addition of shredded rubber waste (a material that is non-absorbent of water at temperatures below 100°C) is intended to reduce the overall absorbency of the composite and, through changes in the pore microstructure, lead to a reduction in capillary action forces and, as a result, a reduction in the capillary suction of water;
- Improving bearing capacity by creating hydraulic bonds. The use of the cement additive is intended to produce a mixture with stable strength parameters.

2. Materials and methods

2.1. Materials

The unburnt coal-mining slate which was used in the tests had a grain size of 0/63 mm (with an overburden content of 9.81%) and came from the decarburisation of waste rock carried out by the HALDEX company. Fig. 1 show the grain size curve of the aggregate used. Due to the influence of water on the grain size degradation of the unburnt coal-mining slate, the grain size curves were determined using the 'dry' and 'wet' methods.

According to PN-EN ISO 14688-1:2006 [57] the unburnt coal mining slate consisted of 1.44% fine fraction, 17.49% sand fraction, 71.26% gravel fraction and 9.81% stone fraction when dry sieve analysis was performed, and 9.25% fine fraction, 15.82% sand fraction and 74.93% gravel fraction when wet sieve analysis was performed. For aggregate used, there was a tendency for the larger aggregate grains to disintegrate when exposed to water.

The following additives were applied to the unburnt coal-mining slate:

- Shredded rubber waste;
- Silica fly ash;
- Cement CEM I 42.5.

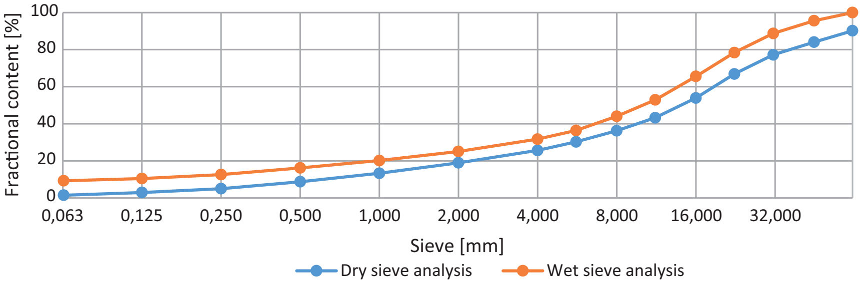

Fig. 1. Grain size curves for unburnt coal-mining slate

The shredded rubber waste, came from the mechanical shredding of passenger car tyres. Their purpose in the mix was to protect the grains of unburnt coal mining slate from the grain-degrading effects of water. The grain size of the shredded rubber waste is shown in Fig. 2.

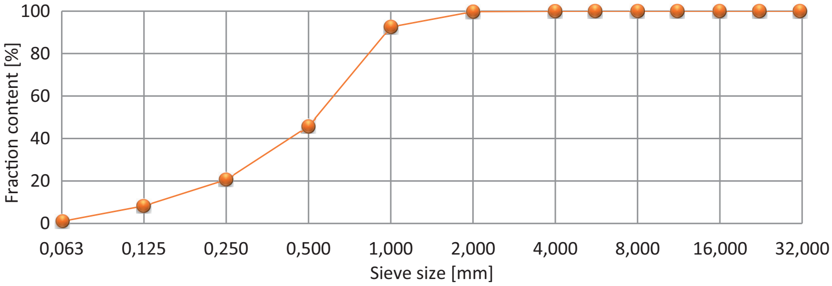

Fig. 2. Grain size curve of shredded rubber waste

The rubber waste used consisted of 1.07% fine fraction, 98.67% sand fraction and 0.26% gravel fraction.

Silica fly ash was used to granulate the mix in order to make the prepared mix as compact as possible. This is a prerequisite for the effective use of the shredded rubber waste in the cement and ash matrix. Fig. 3 shows the grain size curve of the fly ash used.

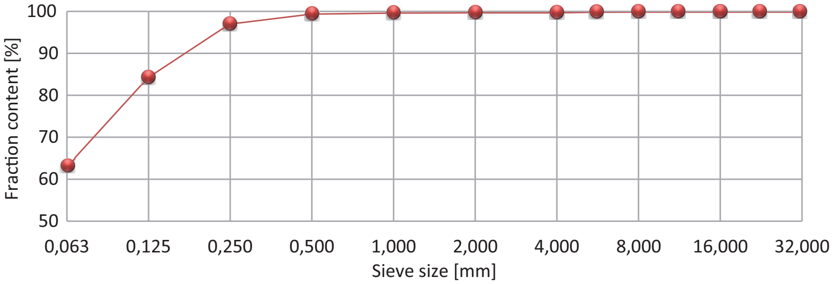

Fig. 3. Grain size curve of silica fly ash

The silica fly ash used consisted of 63.24% fine fraction and 36.76% sand fraction. CEM I 42.5 cement was used to form hydraulic bonds in the mix and to give the mix its strength parameters.

2.2. Preparation of the mixture

The presented mixture was developed on the basis of soil stabilisation preparation according to WT-5 [58], Polish guidelines for bound road construction layers. The additions of shredded rubber waste, fly ash and cement were determined as a percentage of the dry weight of the aggregate, and the whole was mixed and compacted at the optimum moisture content determined by the Proctor II method.

Due to the low bulk density of the shredded rubber waste, relative to the other components, which causes the components to segregate when water is added to the mixture, a suitable mixing procedure was required to achieve a homogeneous mixture.

The procedure for preparing the mixture is as follows:

- Drying of all ingredients to a constant mass at 105°C;
- Weighting the contents of the individual ingredients into separate vessels;
- Mixing together shredded rubber waste, fly ash and CEM I 42.5 cement;
- Adding to the mixture of shredded rubber waste, fly ash and cement about half of the water content needed to achieve optimum moisture content and mixing until a homogeneous mass is obtained;
- The above mixture is then added to the unburnt coal mining slate with continuous stirring. Stirring is carried out until the mixture becomes homogeneous, but no longer than 5 minutes in order not to break up the aggregate grains too much;
- Once a homogeneous mass is obtained, the remaining water content is gradually added and stirred until homogeneous (no more than 2 minutes).

2.3. Preparation of samples

The test samples were compacted in 80 × 80 mm cylindrical moulds using a hand-held lightweight rammer (2.5 kg). Compaction was carried out in two layers of 15 tamping strokes per layer. Due to the dimensions of the mould, the aggregate used to prepare the samples was sifted to a grain size of 0/16 mm. Table 1 shows the recipes for the prepared mixtures.

Table 1. Percentage of additives determined in relation to dry weight of unburnt coal-mining slate

Prescription	Shredded rubber waste [%]	Fly ash [%]	Cement CEM I 42.5 [%]
G0	0	5	5
G5	5	5	5
G10	10	5	5
G15	15	5	5

The samples were compacted at optimum moisture content; graphs of the dependence of maximum bulk density on moisture content are shown in Fig. 4.

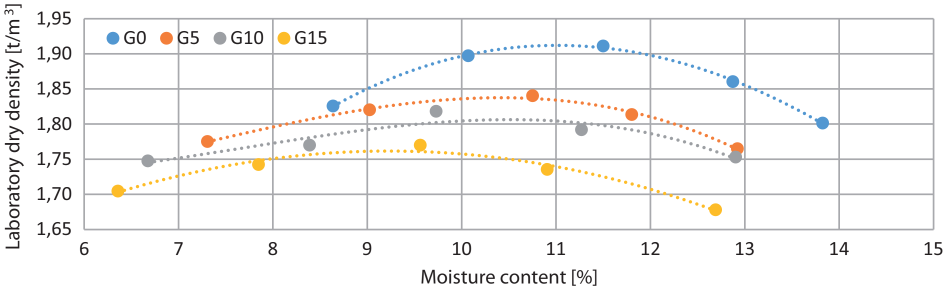

Fig. 4. Plot of laboratory dry density vs. moisture content for unburnt coal-mining slate mixtures

3. Test methods

3.1. Test procedure

The following tests were carried out on the prepared samples:
- Water capillary action test;
- Water absorption test by weight;
- Compressive strength testing after 7 and 28 days of specimen conditioning;
- Test under cyclic load conditions performed after 28 days of specimen conditioning, the test was carried out with the use of the DIC system ARAMIS 3D, which allows to measure strains occurring on the specimen surface.

Each test was conducted on group of 5 specimens made according to the prescriptions of table 1. on the basis of unburnt coal mining slate:

Procedures for performing the tests
- Compressive strength testing after 7 and 28 days of specimen care according to PN-S-06103:1997 [59];
- Testing the height of capillary action-own method:
  - the test carried out on at least 3 samples for each prescription,
  - 80 × 80 mm cylindrical specimens were air-dried to a minimum of half of the water content used during compaction,
  - the samples shall be weighed and determined,
  - then place the samples in a flat-bottomed dish and add water so that the immersion of the samples is 20 mm,
  - after 10 minutes of suction, take a first measurement of the suction height from the moisture trace on the side of the sample,
  - the next measurements were carried out 30, 60, 90..., 1440 minutes after placing the samples in water;
- Water absorption test according to PN-B-06250:1980 [60];
- Test under cyclic load conditions according to do 3.2 point.

3.2. Test under cyclic load conditions with the use of DIC ARAMIS 3D system

Cyclic loading tests were conducted on the prepared samples after 28 days of curing. The test procedure was modelled on the cyclic CBR test [61]. The procedure for performing the test was as follows:

- At the end of the treatment period the sample was placed in the testing machine;
- The specimen was preloaded with a force of approximately 1.5 kN in order to align the contact surfaces of the specimen and to compensate for play in the compression fixtures;
- The specimen was subjected to 20 cycles of loading and unloading or until failure at a speed of 1.27 mm/min;
- During cyclic loading and unloading of the specimen, the compressive force and de-formation of the specimen were continuously monitored;
- Each of the loading and unloading cycles consisted of (Fig. 5):
  - forcing a deformation of 1.5 mm on the specimen,
  - relieving the specimen to a compressive force not exceeding 0.1 kN.

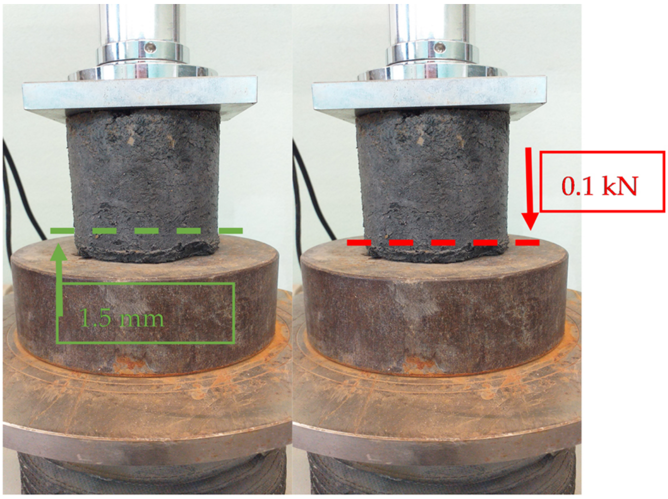

Fig. 5. Scheme of a single cycle of loading and unloading the specimen (own photo)

The test measured the global deformation of the specimen, read as absolute displacement values of the moving shelf of the testing machine. The measurement was performed continuously throughout the test. In addition, an ARAMIS 3D DIC system (HUB 150 mm) was used to precisely determine the deformations and strains occurring on the specimen surface. Gird of virtual strain gauges placed on the sample surface is shown in the Fig. 6.

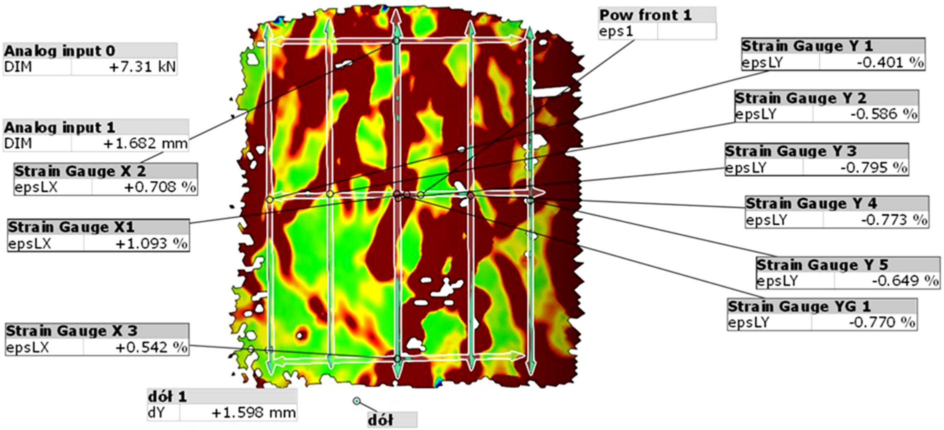

Fig. 6. Example of setting up the strain gauge grid on the specimen surface

4. Research results

Figure 7 shows the heights of capillary suction of water obtained by the samples with varying shredded rubber waste content. The control samples in which no shredded rubber waste was used in the formulation reached a maximum capillary suction height equal to that of the sample. The use of SRW additives reduced the height of capillary suction. The lowest values were obtained for an additive equal to 10%, while higher additives increase the parameter.

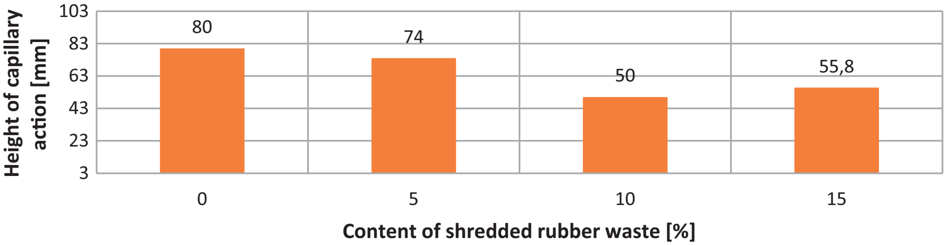

Fig. 7. Diagram of the dependence of capillary suction on the content of shredded rubber waste

In the water absorbability test (Fig. 8), the effect of the shredded rubber waste content showed a similar trend to the capillary rise test. Additions of 10% SRW obtained the lowest absorbability values, while a higher addition increased the parameter to values similar to those obtained by the control samples.

It can be seen from Fig. 9 that the addition of shredded rubber waste causes a reduction in the compressive strength of the specimens. However, for the additives 5 and 10% SRW, no significant differences were noted in their effect on the strength of the specimens tested.

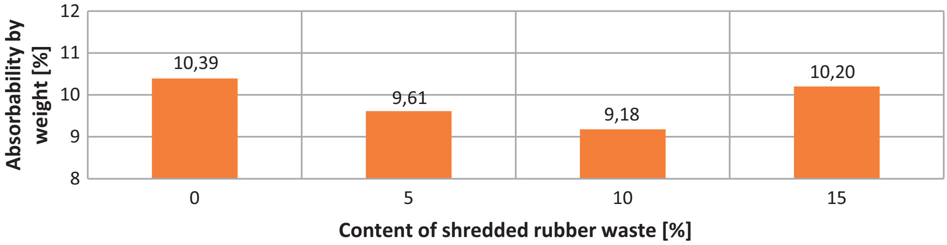

Fig. 8. Plot of the dependence of bulk absorbability on the content of shredded rubber waste

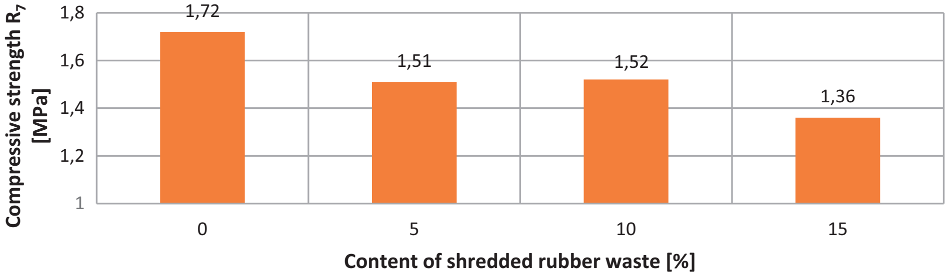

Fig. 9. Plot of the dependence of the compressive strength after 7 days of specimen care on the content of shredded rubber waste

When tested after 28 days of specimen conditioning (Fig. 10), the SRW additives again cause a decrease in compressive strength. A similar trend to the test after 7 days can also be seen, to slight differences in the effect of SRW additives equal to 5 and 10%. Samples with these SRW contents recorded very similar compressive strength values.

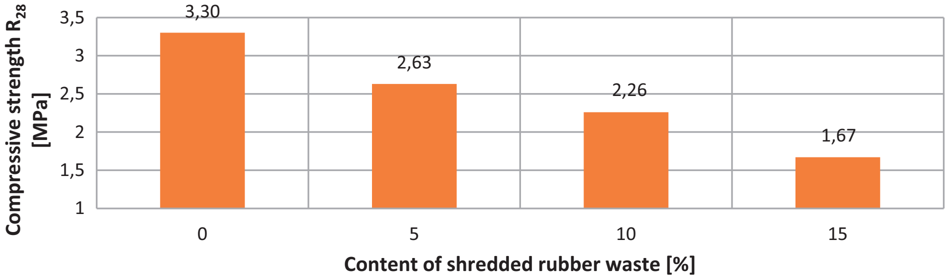

Fig. 10. Plot of the dependence of the compressive strength after 28 days of specimen care on the shredded rubber waste content

In the compressive strength test, in addition to controlling the failure stress of the specimen, the maximum strains occurring at the maximum failure stress were also measured. These data are shown in Figs. 11 (test after 7 days of specimen care) and 12 (test after 28 days of specimen care). In the case of the test after 7 days of specimen conditioning, an

SRW content of less or equal than 5% does not present a significant effect on the maximum deformation of the specimens. The addition of 10% SRW or higher causes a significant increase in the maximum deformation of the specimens.

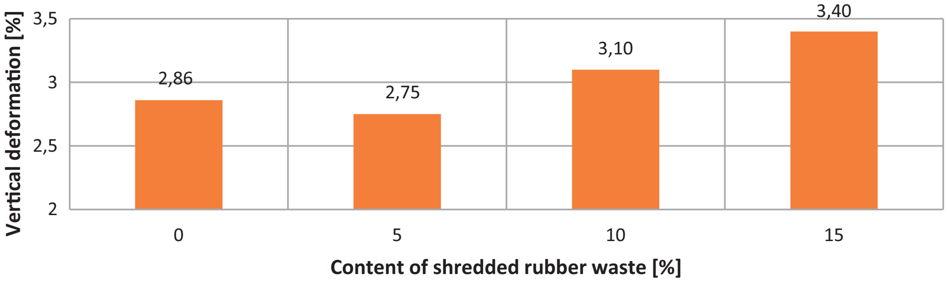

Fig. 11. Plot of the dependence of strain readings at specimen failure on the content of shredded rubber waste after 7 days of specimen care

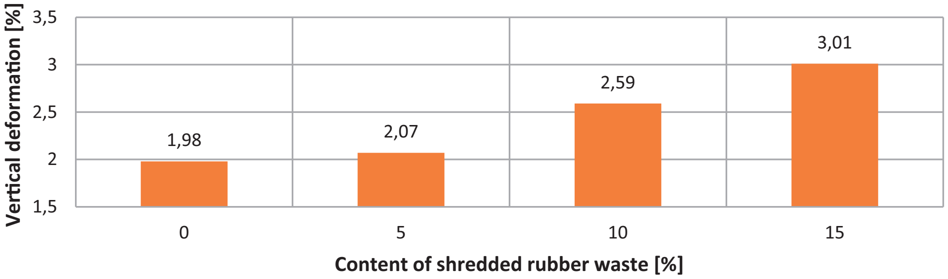

Fig. 12. Plot of the dependence of strain readings at specimen failure on the content of shredded rubber waste after 28 days of specimen care

In a test performed after 28 days of specimen care, a direct effect of the SRW content on the magnitude of the maximum deformations can be seen. They increase by approximately 0.5% for every 5% of SRW addition. Only in the case of the control specimens and the specimens with 5% SRW content, no effect on deformability is observed.

Figure 13 shows the values of vertical deformation (positive part of the vertical axis) and vertical strain (negative part of the vertical axis) obtained for the individual mixtures during successive loading cycles. Analysing the vertical deformation values, it can be seen that as the SRW content increases, the magnitude of the recorded minimum deformations, which in this case can be regarded as plastic deformations, decreases. This has the effect of enlarging the range of elastic deformations in which the mixtures operate as the SRW content increases. The SRW content also influences the reduction of the elastic deformation range in subsequent loading cycles (especially the first 6) as it increases, because the G0 control mixture reduces its elastic deformation range much more rapidly compared to mixtures containing SRW. Measurements of the deformation occurring on the surface of the test specimens made with the ARAMIS 3D DIC system confirm the effect of the SRW additives on the increase in the elastic working range of the material and the rate of its reduction. The effect of the reduction in the elastic strain readings is due to the influence of SRW on the form of deformability of the material under load and has been described in more detail by the authors in [62].

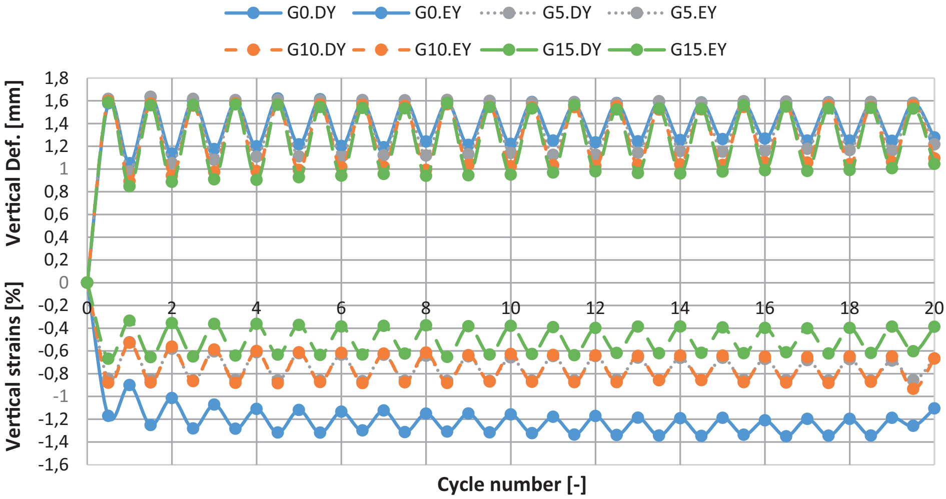

Fig. 13. Graph of vertical deformations and vertical strains in successive load cycles

5. Discussion and conclusions

The presented results allow concluding that the optimum content of SRW in terms of the presented parameters is an addition of 10%. It allows to obtain the lowest values of mass absorptivity of water and capillary action height, which are very important due to high sensitivity of unburnt coal-mining slate to its influence. At this content, a relatively small reduction in compressive strength is also achieved, which makes it possible to meet the requirements for binder-bound pavement construction layers. Increasing the extent to which a material works in the elastic range can have a positive effect on its fatigue life, where, in the case of road pavements, fatigue work is the primary mode of pavement failure. In this case, standard tests dedicated to BSM (Bitumen Stabilised Material) or MAM (Mineral Asphalt Mixture) mixtures would have to be performed, among others, a four-point bending beam test, in order to be able to determine the direct influence of SRW content on fatigue life. A final aspect of the data obtained from the presented studies is the effect of SRW on the amount of strain at failure of the material. However, in this case, due to the unusual performance characteristics of the composite, it is difficult to say whether this will have a positive or negative effect on the work of the pavement structure, and this requires test loading tests carried out on a package of road pavement construction layers using the SFRC mix.

Summarising the presented research results, it can be concluded that SRW additives cause:

- Reduction in capillary suction, lowest suction is achieved for 10% SRW allowance;
- Reduction in the bulk absorbability of the samples. The lowest wettability values are obtained for SRW 10% additive;
- Reduction in compressive strength (after 7 and 28 days of specimen care), with no significant difference observed between the effects of additives 5 and 10%;
- Increase in the maximum deformability of the specimens at failure. This effect is only apparent for an addition of SRW higher or equal than 10% in the short-term test. In the long-term strength test, the additives cause an increase in deformability of 0.5% for every 5% SRW.

The results show that SRW additives have a positive effect on the values of the absorbability and capillary suction parameters, but unfortunately cause a reduction in compressive strength.

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Wybrane zagadnienia dotyczące wykorzystania rozdrobnionych odpadów gumowych w mieszankach związanych spoiwem

Słowa kluczowe: odpady przemysłowe, odpady górnicze, odpady gumowe, system pomiarowy DIC

Streszczenie:

W pracy przedstawiono wyniki badań kompozytu składającego się głównie z odpadów przemysłowych, związanych spoiwem hydraulicznym. W skład mieszanki wchodzą: łupek przywęglowy nieprzepalony, rozdrobnione odpady gumowe, popiół lotny oraz cement CEM I. Celem zastosowania powyższych składników było zabezpieczenie łupka przywęglowego nieprzepalonego przed negatywnym wpływem wody, który powoduję degradację uziarnienia kruszywa, co znacząco wpływa na nośność kruszywa. Osiągnięto to poprzez zastosowanie spoiwa składającego się z rozdrobnionych odpadów gumowych popiołu lotnego oraz cementu, które powoduje nadanie kompozytowi właściwości hydrofobowych. Mieszanka może być wykorzystana w konstrukcji nawierzchni drogowej oraz w robotach ziemnych, jako substytut standardowo wykorzystywanych materiałów. W artykule skupiono się na badaniach wpływu 5, 10 oraz 15% dodatków rozdrobnionych odpadów gumowych na parametry fizykomechaniczne kompozytu, głównie wytrzymałość na ściskanie, nasiąkliwość masową, podciąganie kapilarne wody oraz odkształcalność pod wpływem cyklicznego obciążenia. W ramach testów kompozytu w warunkach cyklicznego obciążenia został wykorzystany system pomiarowy opierający się na cyfrowej korelacji obrazu (DIC), za pomocą którego określono odkształcenia zachodzące na powierzchni badanych próbek. Uzyskane wyniki badań pozwoliły stwierdzić wpływ dodatków rozdrobnionych odpadów gumowych na zmniejszenie się wytrzymałości na ściskanie (po 7 oraz 28 dniach pielęgnacji próbek), nasiąkliwości masowej i wysokości podciągania kapilarnego oraz podwyższenie odkształcalności kompozytu pod wpływem obciążeń niszczących, jak i obciążenia cyklicznego. Zaprezentowany kompozyt ze względu na swój skład, w którym wykorzystuje się głównie odpady przemysłowe dobrze wpisuje się w gospodarkę o obiegu zamkniętym oraz pozwala na znalezienie nowego sposobu wykorzystania odpadów górniczych, których utylizacja ciągle stanowi problem w Zagłębiu Górnośląskim.

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