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Research paper

Influence of addition of shredded rubber waste on deformability of binder-bound anthropogenic material mixtures

Konrad Walotek[1], Joanna Bzówka[2], Adrian Ciołczyk[3]

Abstract: Construction is one of the industrial sectors responsible for the use of large quantities of natural raw materials. This fact makes it necessary to look for new technologies of producing construction materials based as much as possible on waste materials. Such a solution could have positive effects on the environment and reduce construction costs. This paper presents the results of a study on the deformability of a mix made from anthropogenic waste combined with a hydraulic binder. The presented mixes consist of unburnt coal mining slates (mine waste), shredded rubber waste, silica fly ash and CEM I 42.5 R cement. Samples with two different contents of shredded rubber waste 0% and 10% were made from the mixtures and subjected to destructive compressive strength testing. The strength test was combined with sample deformation measurement performed with the Aramis 3D Video Correlation System. The results presented show the effect of the shredded rubber waste content on the deformability of the sample.

Keywords: closed loop economy, coal mining slate, silica fly ash, rubber waste, deformability, digital image correlation (DIC)

[1]MSc., Eng., Silesian University of Technology, Faculty of Civil Engineering, Akademicka 5, 44-100 Gliwice, Poland, e-mail: Konrad.Walotek@polsl.pl, ORCID: 0000-0001-5170-6941

[2]Prof., DSc., PhD., Eng., Silesian University of Technology, Faculty of Civil Engineering, Akademicka 5, 44-100 Gliwice, Poland, e-mail: Joanna.Bzowka@polsl.pl, ORCID: 0000-0002-1765-7354

[3]PhD., Eng., Silesian University of Technology, Faculty of Civil Engineering, Akademicka 5, 44-100 Gliwice, Poland, e-mail: Adrian.Ciolczyk@polsl.pl, ORCID: 0000-0002-4484-4278

1. Introduction

Construction is an industry with one of the highest demands for natural resources and relatively high CO_2 emissions. It is considered that in the European Union only, the construction sector is responsible for the use of about 25% of extracted natural resources and emissions of about 30% of CO_2 [1]. The field of construction in which this tendency can be noticed most often is the transport construction. This is because in many cases it requires erecting earth structures of considerable dimensions.

These constructions are generally carried out using the virgin soils in the closest vicinity (in order to reduce transport costs). However, this practice is not always feasible due to frequent problems with obtaining satisfactory physical and mechanical parameters of the virgin soil. The virgin soil must meet the requirements for materials used in the construction of earth structures, e.g. embankments. In this situation, contractors are forced to look for other sources of raw materials. The use of good quality aggregates or sands from mines is uneconomical due to their price. The purchase cost of such materials is usually at a fairly low acceptable level, however the total cost including the cost of transportation is already much higher. Therefore, in such situations, waste materials are often sought from industries such as mining or waste from power stations.

In the Upper Silesian Coal Region in Poland, the wastes most often used as a substitute for aggregates or virgin soils are coal mines and power plant waste in the form of fly ash used for improvement of virgin soils or coal waste. Such use of waste fits very well the idea of the Closed Cycle Economy, which is increasingly promoted and aims to protect the environment from negative impacts of human activity [2]. However, the use of coal waste is not always possible due to its high sensitivity to the effects of water and frost, combined with the variability of physical and mechanical parameters over time, as well as depending on the place of collection [3–14]. This makes contractors not very keen to use this material. Therefore, it is important to search for a universal improvement technology for coal mining slate allowing its safe use in a wide range of earthwork applications. This paper presents the results of deformation susceptibility testing of a mixture consisting of coal slate and a binder mixture of rubber waste, silica fly ash and cement.

The mixture presented in this paper contains suitably composed waste materials, allowing to obtain a construction material (for use in road construction and geo-technics) with constant and repeatable parameters. The key issue in the study was to protect the coal mining slate against the influence of water, frost and against fragmentation of the material during compaction. Considering these properties, the most important additive is the addition of rubber waste. In earlier works, the authors [15–19] succeeded in establishing that a 10% addition of rubber waste to the mix reduced the capillary action of water, water absorption, and allowed a greater range of sample deformation in compressive strength tests. It was also demonstrated that the use of rubber waste additives allows the material to perform under cyclic loading at high deformation (1.5 mm for $\varepsilon = 1.9\%$). The purpose of the research presented in this work is to determine the effect of the amount of rubber waste addition on the global vertical deformability of the specimens and the distribution of its deformation on their surface. A precise measurement tool using Aramis 3D digital video image correlation was used for this purpose. Digital Image Correlation (DIC) is a relatively new measurement method, though, it has recently been widely used in many fields of science due to its versatility. For example, tests of carbon-epoxy preimpregnates [20], reinforced concrete beams [21] reinforcement in reinforced concrete elements [22] or mechanical properties of bone tissues [23].

2. Mixture ingredients

2.1. Unburnt coal mining slate

Coal waste (Fig. 1) in the form of unburned coal-mining slate forms the basis of the mix. They have been used due to their availability in the Upper Silesian Coal Region and very low price. Unburnt coal-mining slates is an aggregate produced during hard coal mining in the Upper Silesian Coal Region. It is estimated that the annual output of this material amounts to approximately 25–30 million tonnes. The aggregate is black-grey in colour and relatively light compared to other aggregates. The structure of the individual grains is made up of thin lamellas and often contains traces of pyrite. Due to their lamellar structure, aggregate grains are sensitive to crushing during mechanical compaction. They are also very sensitive to the effects of water and frost, which manifests itself in the form of grain size degradation under the influence of these factors. The degradation of aggregate grain size results in an increase in the content of fine fractions (sand, silt and clay) at the cost of coarser fractions (gravel or stone). In most cases, this results in a weakening of the strength parameters of the material and the formation of frost heave or increased linear swelling. In addition, the aggregate has a tendency to change its physical and mechanical parameters depending on the length of storage (in particular grain size degradation), which is due to the erosive changes occurring in it after the material is brought to the surface [3–14].

Fig. 1. Unburnt coal mining slate

The particle size distribution of the unburnt coal mining slate used in the tests is shown in the Figure 2.

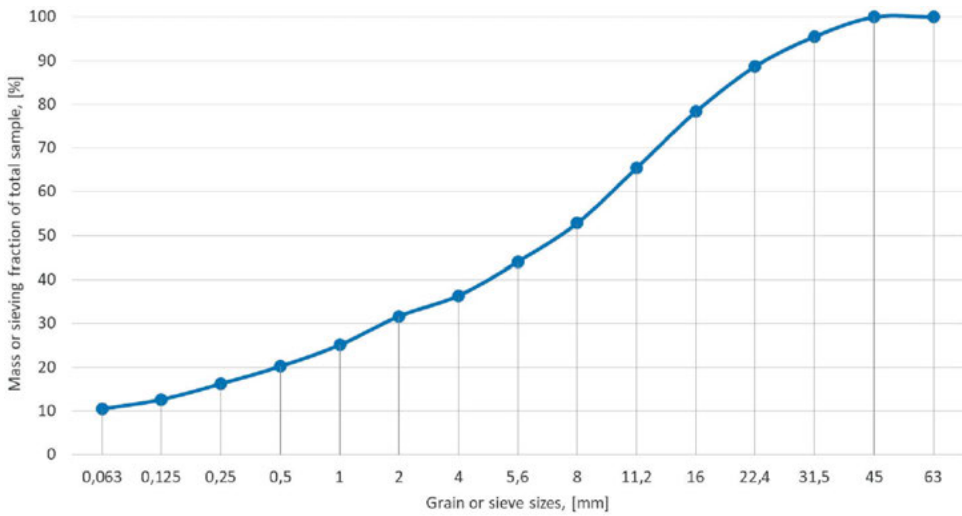

Fig. 2. The particle size distribution of the unburnt coal-mining slate

2.2. Shredded rubber waste

Another waste of anthropogenic origin used in the mixture is shredded rubber waste (Fig. 3) originating from used car tyres, this material is used in many areas of construction, such as geotechnics, asphalt mixtures and as an additive to concrete [24–35].

Fig. 3. Shredded rubber waste

Rubber material of grain size 0/2 mm originating from mechanical shredding of car tyres was used. The particle size distribution of the shredded rubber is presented in the Figure 4.

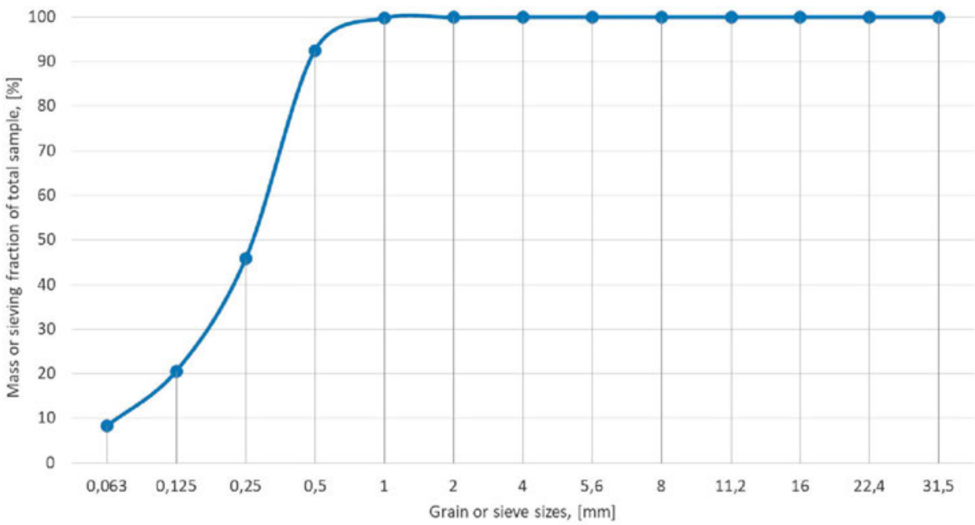

Fig. 4. The particle size distribution of the shredded rubber

The purpose of using shredded rubber waste in the mix was to create cushioning for the aggregate grains during compaction, so as to reduce the effect of degradation of its grain size and to protect the aggregate against the negative influence of water. According to [15–19], it was found that the addition of rubber waste in such a mix makes it possible to reduce the height of capillary action and the absorbability of the bound material, resulting in an increase of resistance of the material to the effects of water by partially isolating it. During strength tests, it was observed that the material, despite the formation of stiff hydraulic bonds (resulting from the use of cement additive), exhibited increased global vertical deformability with increasing rubber waste content. The addition of rubber waste increased the range of elastic deformation observed and changed the fracture mechanics of the samples without rubber waste addition to failure mechanics similar to that observed in steel tensile strength tests, adding the flow of the material in the stress range similar to the compressive strength of the material [15–19].

2.3. Silica fly ash

Silica fly ash from a power plant was used in the mix. The purpose of this additive is to grain the resulting mixture in order to obtain the tightest possible surrounding of larger coal-mining slate grains with a rubber-ash-cement mortar. Fly ash is also used to improve the strength parameters of the bound materials.

Silica fly ash (V), from the combustion of hard coal, was used in the research. It belongs to the group of low-active fly ashes (CaO content between 3.5 and 7.0%). The particle size distribution of the silica fly ash is presented in the Figure 5.

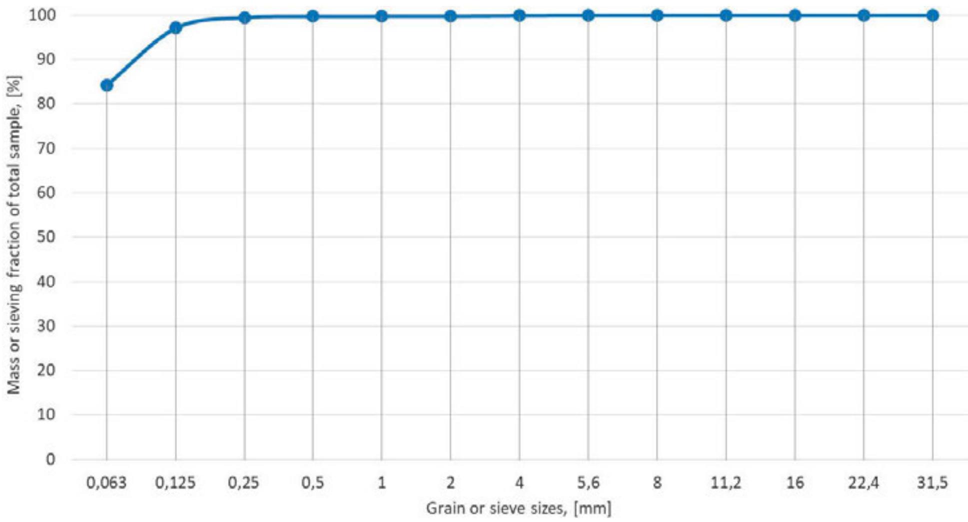

Fig. 5. Particle size distribution of the silica fly ash (V)

2.4. Cement CEM I

The last component of the mix is CEM I 42.5 R cement used to form hydraulic bonds and to obtain strength parameters. CEM I 42.5 R cement, that does not contain pozzolanic and metallurgical additives, was used in order to eliminate their influence on the test results.

3. Research plan

3.1. Research objective

This paper presents the results of testing the influence of the size of the rubber waste addition on the global vertical deformability of the material. An Aramis 3D scanning apparatus (Fig. 6) and a testing machine were used for this purpose.

The Aramis 3D scanning system allows real-time observation and measurement of deformations occurring on the surface of an object based on virtual points. These virtual points are tracked by the device on the basis of a contrasting gradient painted on the surface of the tested sample (Fig. 7a) or through marker points (Fig. 7b). The Aramis 3D system is also compatible with strength testing machines, which allows for accurate correlation of deformations and stresses in the tested object.

In order to determine the effect of the amount of rubber additive on the global vertical deformability of the specimens, two mixtures were prepared with 0% and 10% rubber additive content. The prepared samples were subjected to strength tests along with surface deformation measurements using the Aramis 3D system.

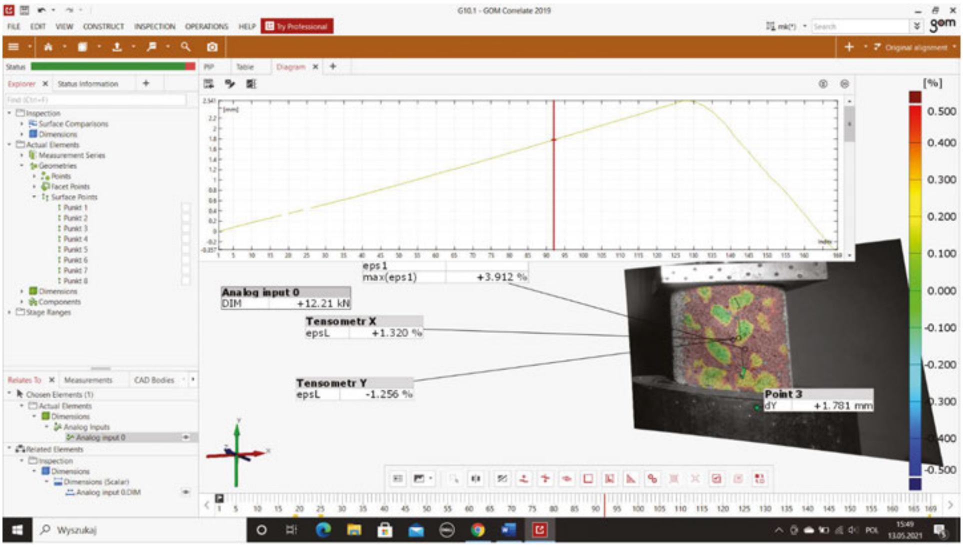

Fig. 6. Aramis 3D system interface

a) b)

Fig. 7. a) Contrasting gradient painted on the surface of the sample; b) Marker points

3.2. Test procedure

Two mixtures were prepared for the tests according to the recipes presented in Table 1. From each recipe, 5 samples were prepared for tests, compacted at the optimum moisture content (determined according to Proctor method 2) in a cylindrical mould of dimensions 80 × 80 mm.

The optimum moisture content of the G0 mixture was equal to 11.2%, and the G10 mixture – 10.1%. The results of the optimum moisture content of the mixtures are presented in the Figure 8.

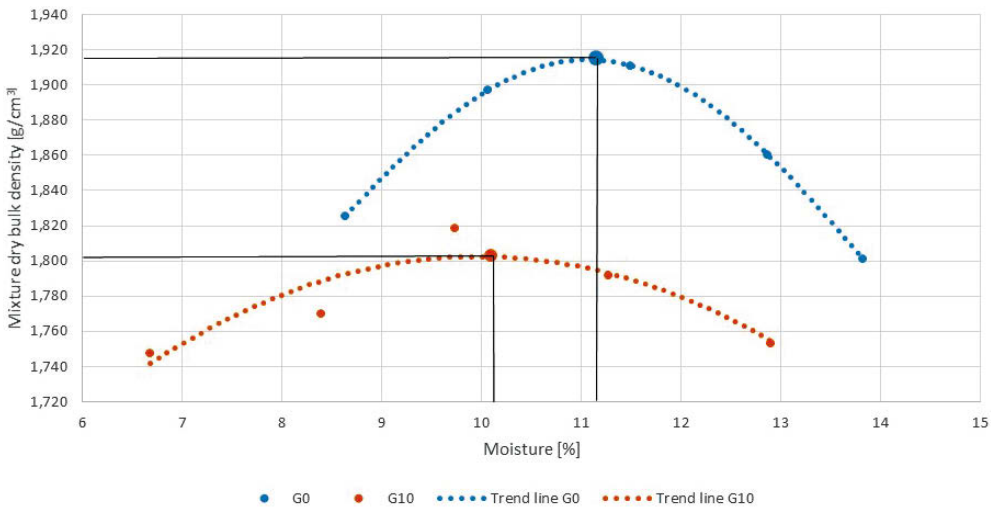

Fig. 8. Results of the optimum moisture content and the dry bulk density of G0 and G10 mixtures

Due to the limited diameter of the cylinder, coal mining slate of grain size 0/16 mm was used. The mixture was compacted in 2 layers with 15 light tamping strokes per layer, which corresponds to the compaction energy for Proctor methods 1 and 2.

Table 1. The recipes of the mixtures used for the research

Recipe	Unburnt coal-mining slate 0/16 mm [%]	Shredded rubber waste 0/2 mm [%]	Silica fly ash [%]	CEM I 42.5 R [%]	Water content* [%]
G0	90	0	5	5	11.2
G10	80	10	5	5	10.1

*The amount of the added water in relation to the dry weight of the other ingredients

The prepared specimens were subjected to care and strength testing after 28 days, in accordance with [36]. The specimens were treated by storing them in air-humid conditions (in water-soaked sand or under conditions of protection against drying out) for 14 days and another 14 days of storage under conditions of full immersion in water at 20°C. The strength test took place in a testing machine with a maximum load of 50 kN, at a compression speed of 12.0 mm/min [36]. The testing machine was coupled with the Aramis 3D system (Fig. 9).

Fig. 9. Test stand with the Aramis 3D system

4. Research findings

4.1. Stress-deformation relationship test

Figure 10 shows the deformation – stress relationship for G0 and G10 specimens. The stresses and deformation values were read from the testing press and the Aramis measuring system. The deformations readings correspond to the maximum force applied to the specimen, read as movement of the lower plate of the testing machine. Trend lines in the form of 3rd degree polynomials were fitted to the created point clouds. The coefficient of determination R^2 is 0.95 for G0 series specimens and 0.93 for G10 series specimens.

From the fitted trend lines it can be seen that the averaged compressive strength of the G0 series specimens is approximately 3.21 MPa at a deformation of 1.37 mm (ε = 1.71% at a specimen height of 80 mm). For specimens of the G10 series, the averaged compressive strength is about 2.11 MPa at a deformation of 1.86 mm (ε = 2.3%). Based on the values presented, it can be determined that the 10% addition of rubber fines reduces the compressive strength of the material by approximately 34% and increases the maximum global vertical deformability by 35% compared to the G0 series specimens.

In addition to influencing the global vertical deformability and the maximum compressive strength, the rubber compound also affects the failure mechanics of the specimen. In the case of the G0 series specimens, we are dealing with quasi-brittle fracture mechanics. When these specimens reach their maximum strength, they lose this strength very quickly as a result of the resulting scratches. They maintain strength above 90% of their maximum value in the deformation range of 1.05 mm to 1.65 mm, which gives an interval of 0.6 mm.

In the case of the G10 series specimens, which contain a 10% addition of rubber waste, the flow zone of the material is extended. This means that after reaching its maximum strength, the sample does not lose strength that quickly. They maintain a strength of more than 90% of their maximum value in the deformation range of 1.35 mm to 2.35 mm, which gives an interval of 1.0 mm.

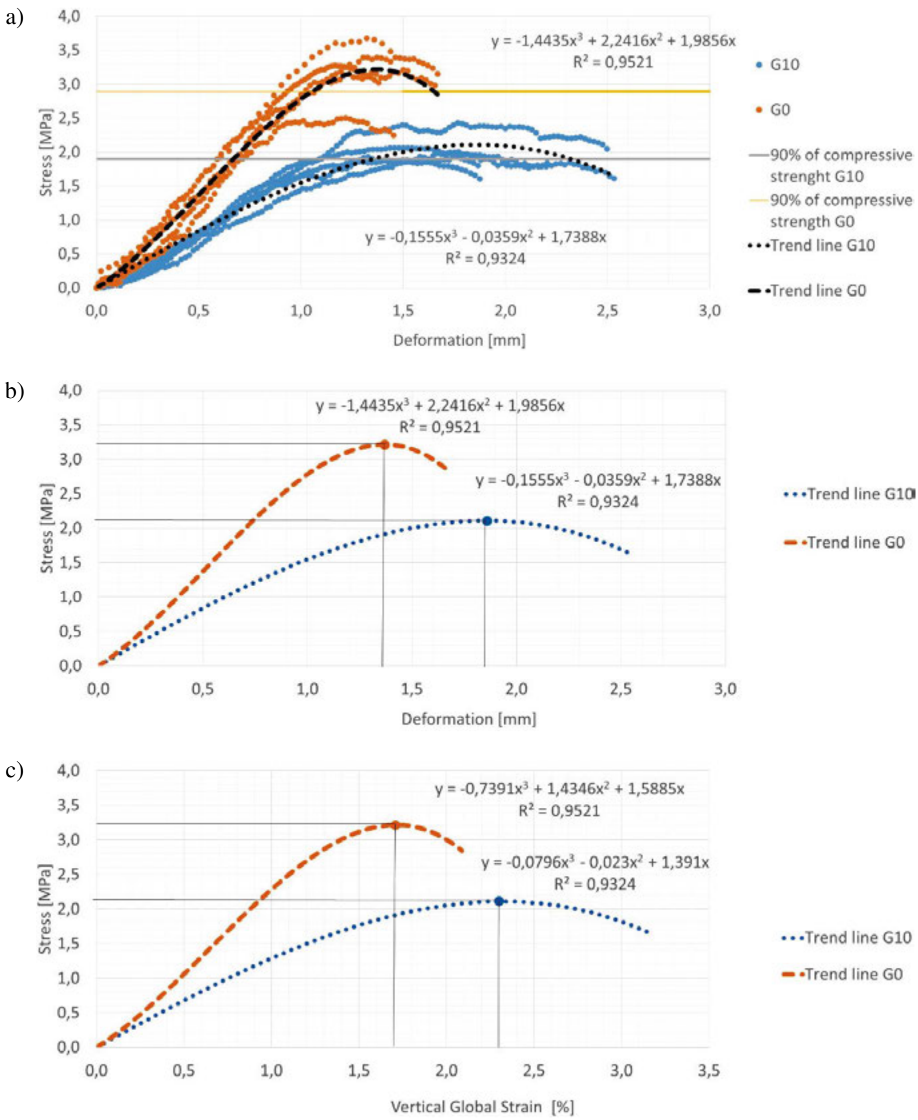

Fig. 10. a) Stress – deformation relationship for samples of the G0 and G10 series; b) Isolated trend lines of the stress – deformation relationship for samples of the G0 and G10 series; c) Isolated trend lines of the stress – strain relationship for samples of the G0 and G10 series

4.2. Comparison of surface deformation distribution

The Figures 12, 13 show the distribution of the major strains on the surface of the test specimens, at 50%, 75% and 100% of the maximum applied stresses. Explanation of the major strains map for the Figures 12, 13 is shown in the Figure 11. The major strains are those produced in the direction of the greatest deformations.

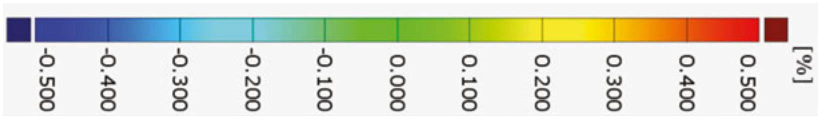

Fig. 11. Explanation of the major strains map for Figs. 12, 13

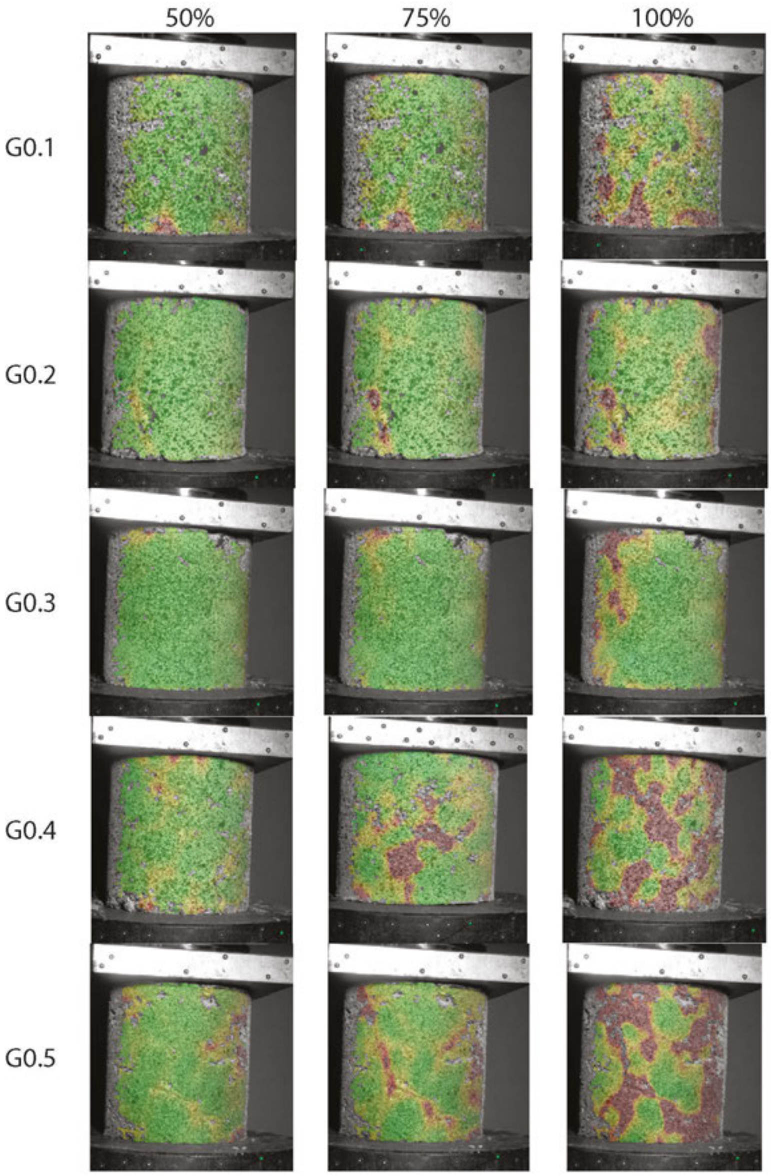

Fig. 12. Distribution of major strains on the surface of G0 series specimens at 50%, 75% and 100% of the maximum stress values

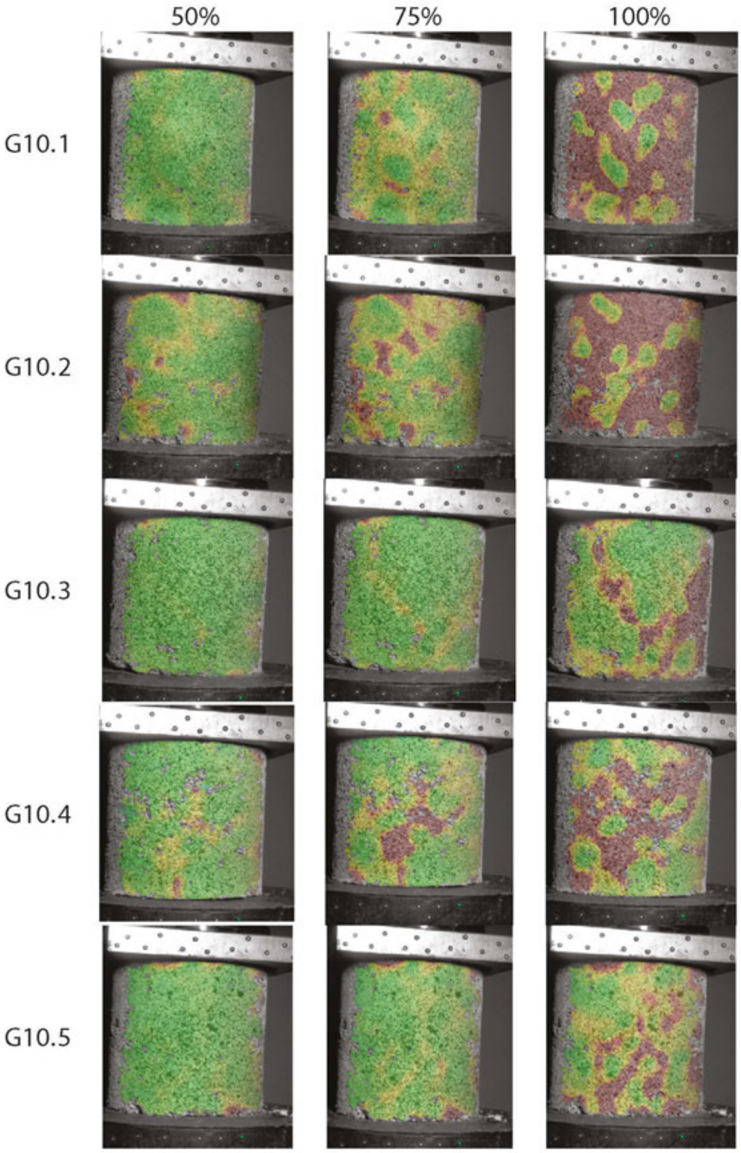

Fig. 13. Distribution of major strains on the surface of G10 series specimens at 50%, 75% and 100% of the maximum stress values

In the case of the observation of the surface major strains of the G0 series specimens at 50% of the maximum applied stress, no major strains were observed apart from a few local phenomena. At a stress equal to 100% of the maximum applied stress, areas of significant major strains can be observed, which are an extension of the local phenomena observed at 50% of the maximum applied stress. However, the most significant phenomenon observed here is the

Table 2. Stress and deformation values for individual specimens of the G0 series from Aramis 3D system

Sample	~50%		~75%		100%	
	Stress [MPa]	Deformation [mm]	Stress [MPa]	Deformation [mm]	Stress [MPa]	Deformation [mm]
G0.1	1.92	0.611	2.69	0.832	3.67	1.322
G0.2	1.30	0.461	1.90	0.715	2.49	1.198
G0.3	1.67	0.622	2.58	0.835	3.27	1.168
G0.4	1.79	0.672	2.58	0.920	3.39	1.321
G0.5	1.65	0.516	2.45	0.782	3.21	1.501
G0$_{av}$	**1.67**	**0.576**	**2.44**	**0.817**	**3.21**	**1.302**

Table 3. Stress and deformation values for individual specimens of the G10 series from Aramis 3D system

Sample	~50%		~75%		100%	
	Stress [MPa]	Deformation [mm]	Stress [MPa]	Deformation [mm]	Stress [MPa]	Deformation [mm]
G10.1	1.28	0.712	1.84	0.991	2.43	1.781
G10.2	1.03	0.629	1.49	0.867	2.00	1.793
G103	1.00	0.595	1.55	0.866	2.06	1.483
G10.4	0.98	0.705	1.46	1.043	1.96	1.803
G10.5	0.94	0.568	1.41	0.820	1.88	1.411
G10$_{av}$	**1.05**	**0.642**	**1.55**	**0.917**	**2.07**	**1.654**

non-uniform distribution of major strains across the surface of the specimen. This is because in this case there are only accumulations of areas of very high major strains, i.e. areas where cracks are formed that cause the specimen to fail and areas where the specimen is not deformed at all or only very slightly.

When observing the major strains of the surfaces of the G10 series specimens at a load equal to 50% of the maximum stress values, we do not observe any major strains apart from a few local phenomena, similar to the G0 series. At a load equal to 100% of the set stress values, we can observe areas of significant major strains. However, unlike the G0 series specimens, in this case we are dealing with larger areas of large major strains, which are more uniformly distributed over the surface of the specimen.

Figure 14 shows the course of the lateral strain – deformation relationship. The lateral strains were measured using virtual strain gauges, introduced in the Aramis 3D system software, placed at the mid-height of the specimen.

In the case of specimens of the G0 series, failure (maximum deformation of 1.37 mm) occurred at values of lateral strains reaching approximately 0.9%. In the case of G10 series specimens, failure (reaching the maximum deformation of 1.86 mm) occurred at lateral strains of approximately 1.7%. This represents an increase in maximum lateral strain measured at

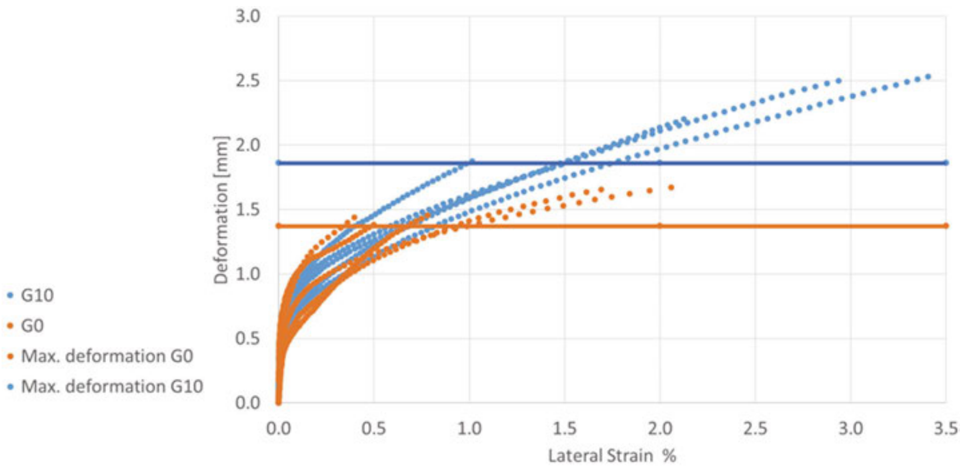

Fig. 14. Lateral strain – deformation relations for specimens of G0 and G10 series

failure of 88% compared to specimens of the G0 series. This may indicate the greater importance of local accumulation of major strains in the case of G0 series specimens, for which the increase in major strains over a limited area led to scratching of the specimen, resulting in failure at lower values of deformation and lateral strains. For G10 series specimens, major strains propagated across the surface of the specimen, resulting in higher values of lateral strains and, consequently, higher maximum specimen deformations.

This phenomenon is indicative of the effect of the addition of rubber waste on increasing the uniformity of stress distribution in the specimen, so that as deformation increases, an increasing area of the specimen is drawn into cooperation. This can also be explained by the change in failure mechanics of the specimens with the addition of rubber waste. The G0 series specimens failed as a quasi-brittle fracture because the resulting deformations were cumulative over a very narrow area leading to crack formation that significantly reduced the strength of the material. In the case of the G10 series specimens, the resulting deformations propagated over a much larger area, resulting in a much later crack formation causing a significant reduction in the strength of the material.

5. Summary

Based on the above results, the following conclusions can be drawn:

- the 10% addition of shredded rubber changes the damage mechanics of the sample into quasi-brittle fracture by adding the material flow zone,
- the addition of shredded rubber reduces the compressive strength, however, it is so small (from 3.21 to 2.11 MPa) that both mixtures still fall within the same strength class $C_{1.5/2.0}$,
- the 10% addition of shredded rubber reduces the compressive strength of the material but increases the range of its maximum deformation by approx. 35%,

– the use of shredded rubber extends the range of deformation in which the samples maintain at least 90% of the maximum stresses without damage from 0.6 to 1.0 mm. In the case of road surfaces, this means at least several years of extending the durability of the surface,
– the addition of shredded rubber affects the uniformity of deformations distribution on the sample surface. With the addition of rubber dust, deformations appearing on the surface of the sample can propagate over its surface. Thus, delaying the formation of scratches leads to the sample destruction.

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Wpływ dodatku rozdrobnionych odpadów gumowych na odkształcalność mieszanek materiałów antropogenicznych związanych spoiwem

Słowa kluczowe: gospodarka o obiegu zamkniętym, łupek przywęglowy nieprzepalony, odpady gumowe, popiół lotny krzemionkowy, odkształcalność, cyfrowa korelacja obrazu (DIC – Digital Image Correlation)

Streszczenie:

Budownictwo jest jednym z sektorów przemysłu odpowiedzialnym za wykorzystanie znacznych ilości surowców naturalnych. Fakt ten sprawia, iż należałoby szukać nowych technologii wytwarzania materiałów budowlanych bazując w jak największym stopniu na materiałach odpadowych. Takie rozwiązanie niesie ze sobą pozytywne skutki dla środowiska naturalnego oraz wpływa na obniżenie kosztów budowy. W pracy przedstawiono wyniki badań odkształcalności mieszanki wykonanej z odpadów antropogenicznych połączonych spoiwem hydraulicznym. Poddane badaniom mieszanki składają się z łupków przywęglowych nieprzepalonych (odpady kopalniane), rozdrobnionych odpadów gumowych, popiołu lotnego krzemionkowego oraz cementu CEM I 42,5 R. Z mieszanek wybrano próbki o zawartości rozdrobnionych odpadów gumowych 0% i 10% oraz poddano je niszczącemu badaniu wytrzymałości na ściskanie. Badania wytrzymałościowe były połączone z pomiarami deformacji próbki wykonanymi za pomocą systemu korelacji obrazu Aramis 3D. Wyniki badań pokazują wpływ zawartości rozdrobnionych odpadów gumowych na odkształcalność mieszanek.

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