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NON-CONTACT METHOD FOR MEASURING DEFORMATION IN TESTING SELECTED MATERIALS USED IN ROAD CONSTRUCTION

BEZKONTAKTOWA METODA POMIARU DEFORMACJI W BADANIACH WYBRANYCH MATERIAŁÓW STOSOWANYCH W BUDOWNICTWIE DROGOWYM

STRESZCZENIE. Wysokie wymagania stawiane materiałom stosowanym w budownictwie drogowym powodują konieczność stosowania nowoczesnych metod oceny ich parametrów mechanicznych. Jedną z takich metod jest metoda cyfrowej korelacji obrazu (Digital Image Correlation – DIC). W artykule zaprezentowano możliwości wykorzystania bezkontaktowej metody DIC do pomiaru deformacji w badaniach wybranych cech mechanicznych próbek mieszanki mineralno-asfaltowej oraz kompozytu wykonanego z matrycy polimerowej zbrojonej siatką z włókien szklanych – (fiber reinforced polimer – FRP). W pracy pokazano analizy deformacji całych obserwowanych powierzchni badanych próbek. Stwierdzono też, że pod względem wytrzymałości statycznej na rozciąganie praca taśmy FRP jest podobna do zachowania geosiatek stosowanych do wzmacniania konstrukcji nawierzchni drogowych. Omówione wyniki badań własnych oraz badań opisanych w literaturze potwierdziły przydatność metody DIC w badaniach materiałów stosowanych w inżynierii lądowej.

SŁOWA KLUCZOWE: mieszanki mineralno-asfaltowe, badania cech mechanicznych, metoda cyfrowej korelacji obrazu (DIC), polimer zbrojony włóknami (FRP).

ABSTRACT. High requirements for materials used in road construction make it necessary to use modern methods for assessing the mechanical parameters of these materials. One such method is the Digital Image Correlation (DIC) method. The paper presents the possibilities of using the non-contact DIC method to measure deformation in testing selected mechanical properties of asphalt mixture samples and a composite made of a polymer matrix reinforced with a glass fiber grid (fiber reinforced polymer – FRP). The paper shows deformation analysis of all the observed surfaces of the tested samples. It was found that in terms of static tensile strength, the performance of the FRP tape is similar to the behavior of geogrids used to strengthen road pavement structures. The discussed results of own research and research described in the literature confirmed the usefulness of the DIC method in testing materials used in civil engineering.

KEYWORDS: asphalt mixtures, mechanical properties testing, digital image correlation method (DIC), fiber reinforced polymer (FRP).

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1. INTRODUCTION

High requirements placed on materials used in road construction make it necessary to use modern research methods for assessing the mechanical parameters of these materials. Both contact and non-contact methods for measuring deformation are being developed and used in laboratory and field tests. One of the modern methods that can be used in such research is the non-contact digital image correlation (DIC) method. Its use is particularly important in the context of the possibility of testing a wide group of building materials. It includes traditional asphalt mixtures, mixtures with the addition of recycled materials and the latest materials made of plastics, used, for example, to strengthen the structures of road pavements and bridges.

Asphalt mixture is the basic material used in the construction of flexible road pavements. Modern pavement design can cover many areas. They may involve, for example, reducing the negative impact on the environment, increasing user safety or increasing the durability of the structure. Proper design and construction of asphalt mixture layers in the pavement structure is of key importance [1]. Moreover, a proper bonding of these layers is necessary [2]. For economic and environmental reasons, the use of selected additives and recycled materials is increasingly sought when building modern road pavements. An example of an additive would be a mixed hydraulic binder. According to Iwański et al., application of such a binder in cold recycling enables the use of reclaimed asphalt pavement material displaying considerable variability in grading [3]. The second important direction of pavement technology development is recycling. Various materials can be used in the recycling process, such as reclaimed asphalt pavement (RAP), rubber from used car tires, plastics or recycled concrete aggregates [4]. RAP is increasingly used in the asphalt mixture production. In-plant and on-site, as well as warm and cold recycling technologies are being developed [3]. Efforts are being made to increase the effectiveness of such technologies. Perhaps in the future, RAP will be the main building material for asphalt layers, and new materials will only be an addition. When designing new and rebuilding existing road pavement structures, knowledge of the static and fatigue mechanical properties of asphalt mixture is required. The most important parameters here are the stiffness modulus, Poisson's ratio and asphalt mixture tensile strength, the values of which depend on the temperature, the method of applying the load and the test scheme used [5]. Stiffness modulus and Poisson's ratio are basic parameters also in analytical and numerical modeling of road structures [6]. These values also depend strongly on the properties of asphalt mixture itself. Sorociak et al. [7] presented the results of asphalt mixture tests made with different contents of RAP. In order to improve the properties of asphalt mixture, a chemical additive was introduced into the granulate to reverse the effects of asphalt aging (rejuvenator). It was reported that the use of a rejuvenator has a positive effect on the properties of the mixture, however, the use of high contents of reclaimed material in asphalt mixture requires further research. Similar research was presented by Chen et al. [8]. It was stated that asphalt mixture made of 100% RAP with the addition of epoxy resin can meet most of the requirements for mixture used for the wearing course. However, low resistance of this mixture to aging caused by UV radiation was noticed. Pouget et al. pointed out the need to evaluate the parameters of asphalt mixture with the addition of RAP recycled several times [9].

Multi-stage laboratory tests are an important element of asphalt mixture design. Regardless of the method used, the values of measured displacements and calculated strains of the sample are important parameters determined in tests [5, 10]. In traditional methods, deformation is measured locally in a selected, fixed direction or several directions. It is not possible to determine the displacement vector for the entire sample surface. The DIC method offers much wider possibilities for deformation measurements. This method was developed in the late twentieth century, and its history and assumptions have been described in the literature [11, 12]. This method is successfully used in the study of various materials and structures [13]. It can also be used in numerical simulations. The literature presents the use of the DIC method in testing asphalt mixture samples of various shapes [14]. It was shown that this method is effective in testing anisotropic and heterogeneous materials which include asphalt mixtures. Roberto et al. [15] reported that the DIC method enables the precise location of the crack initiation area and the analysis of the distribution of irregular strains on the surface of the tested sample. The DIC method is now often used in asphalt mixture testing using the semi-cylindrical bending (SCB) test [16]. Tests carried out using this method made it possible to observe many small cracks occurring near the area of the main crack. Indicating the stages of crack initiation and propagation is important when assessing the fatigue performance of the tested material [17]. Shi et al. presented a numerical analysis of the asphalt mixture model with the addition of RAP [18]. The discrete asphalt mixture model was built based on 3D scanning and discretization software. It was found that shear cracks occurred mainly in the contact area of the RAP grains. Teguedi et al. conducted comparative observations of local deformations occurring in the study of the mechanical properties of cut cylindrical samples prepared from new asphalt mixture and samples made from RAP [19]. It was confirmed that on a macroscopic scale, the addition of RAP increases the asphalt mixture stiffness and compressive strength. On the other hand, the distribution of equivalent strains was analyzed at the microstructure scale of the sample, according to the von Mises hypothesis. For asphalt mixture samples made of 100% RAP, intense concentration of strains around the aggregate grains was observed. This caused cracks in the contact zone between the binder and the aggregate grains. This could be due to the deteriorated properties of the aged binder, with which the aggregate was coated. A more homogeneous strain distribution was observed in the new asphalt mixture. In the case of the mixture with the addition of 40% RAP, the behavior of the asphalt mixture was intermediate between the new mixture and the mixture made entirely of RAP [19].

Accurate research and analysis of asphalt mixture deformations are therefore important. This is also related to the fact that asphalt mixtures with the addition of RAP are increasingly used in the world. According to Willis and Williams [20] the use of RAP in the USA was estimated at 94.6 million tons per year in 2021. This showed an increase in the use of RAP compared to 2009 by approximately 70% [20].

Bridge construction is closely related to the road construction. Bridge structures show various types of damage after years of exploitation. This damage may result in a reduction in the bearing capacity of the structure. Tapes or mats made of fiber reinforced polymer (FRP) are one of the solutions used to strengthen this type of objects. Significant advantages of such materials are high corrosion resistance and low weight [21, 22]. Due to the wide use and composite structure of FRP tapes, research on these materials is important from both a scientific and technical point of view.

This paper presents the use of a modern, non-contact DIC method to measure displacements and determine strain tensors in tests of two selected building materials. Deformation analysis in mechanical properties tests was carried out for asphalt mixture samples and FRP composite samples. The assumptions of the method, the method of sample preparation and the results of selected laboratory tests were presented. The main aim of the research was the analysis and assessment of the overall surface behavior of the tested samples.

2. OWN LABORATORY TESTS

2.1. DIGITAL IMAGE CORRELATION METHOD (DIC)

The DIC method is included in the group of optical, non-interferometric methods. It enables measurements of surface deformations of various materials and elements. A correlation is created between subsequent images of the tested element subjected to load. The image is recorded as a set of small, square sub-areas (facets) located around the points of the virtual grid. These facets are used in the image correlation algorithm. The size of facets depends on the geometry of the tested surface, the type of analysis and the quality of the stochastic pattern visible on the surface of the tested sample.

The correlation algorithm allows you to determine the coordinate transformation of points in the analyzed area. Using the parameters of displacement (a_0, a_4), elongation (a_1, a_6), shear (a_2, a_5) and distortion (a_3, a_7) the transformation coordinates (u, v) can be calculated according to equation (1) [23, 24]:

$$u(a_0, a_1, a_2, a_3, x, y) = a_0 + a_1 x + a_2 y + a_3 xy$$
$$v(a_4, a_5, a_6, a_7, x, y) = a_4 + a_5 x + a_6 y + a_7 xy. \quad (1)$$

The parameters taken into account in the transformation algorithm are presented graphically in Fig. 1 [23, 24].

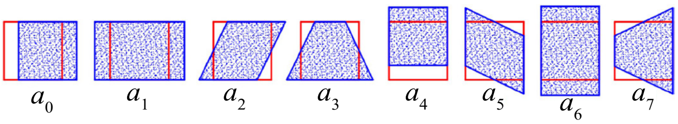

Fig. 1. Graphical illustration of the parameters used in the DIC transformation algorithm

The research procedure consisted of several stages. The first is to prepare the setup and laboratory samples. These steps are described below. The next step is to calibrate the DIC system. This process was performed using specialized calibration plates. The dimensions of the plates were adapted to the size of the tested samples. The system calibration was performed automatically using the Zhang algorithm [25]. The calibration quality was assessed by the calibration residuum. The calibration plate is shown in Fig. 2.

In the next stage, laboratory tests of asphalt mixture samples were carried out. During the test, subsequent photos of the tested surface were taken. The deformation analysis was performed using Istra 4D software, which uses the previously described transformation algorithm [26]. At the post-processing stage, displacement maps and strain tensor elements were determined for the entire surface of the tested sample. Moreover, the software allowed solving the issue of principal strains and principal directions.

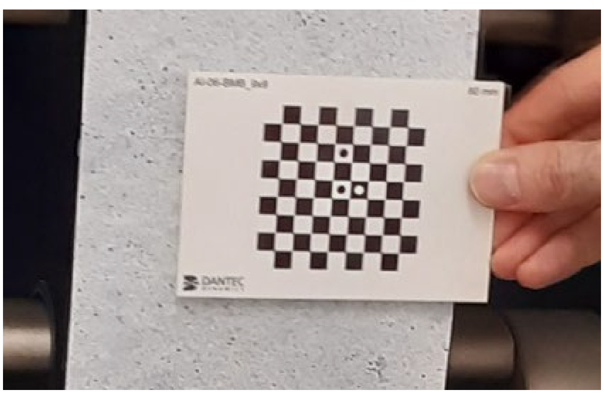

Fig. 2. DIC system calibration plate

2.2. TEST PROCEDURES AND PARAMETERS

Asphalt mixture laboratory tests were carried out using the indirect tensile method according to the PN-EN 12697-23 standard [27]. A series of five cylindrical samples were used to test the asphalt mixture performance. A constant deformation speed of 50 ± 2 mm/min was used. The tests determined the indirect tensile strength (ITS) of asphalt mixture samples according to equation (2) [27]:

$$ITS = \frac{2P}{\pi DH}, \quad (2)$$

where:

P – breaking load (kN),

D – sample diameter (mm),

H – sample height (mm).

The FRP tape was tested in accordance with the EN ISO 10319 standard [28], using the wide-width tensile test. A set of three samples was tested. A constant deformation speed of 1 mm/min was used. The tests were carried out at a temperature of 22 ± 1°C. Before testing, the samples were conditioned at a set temperature for a minimum of 4 hours.

2.3. SAMPLES PREPARATION

Asphalt concrete AC16W with road bitumen was used in asphalt mixture testing [29, 30]. The components of asphalt mixture are shown in Table 1.

Table 1. Components of the asphalt mixture used

Component	Grain size [mm] (bitumen type)	Type of rock	Content [%] (m/m)
Coarse aggregate	8/16	dolomite	34.9
Coarse aggregate	2/8	dolomite	28.1
Fine aggregate	0/2	granite	28.6
Filler	≤0,063	limestone	3.8
Bitumen	35/50	–	4.6

Asphalt mixture samples with a diameter of 150 ± 3 mm were prepared in the laboratory from a new mixture [31]. The bulk density was 2.398 g/cm³. The air voids content was equal to 5.1%, which met the requirements set out

Fig. 3. Preparation of samples for DIC method testing: a) asphalt mixture sample surface painted white; b) randomly plotted black speckles; c) painted FRP sample

in WT-2 guidelines for this type of mixture [29, 30]. The average thickness of the samples was 55 ± 2 mm.

In testing the strength of the FRP composite, a tape made of polyurethane resin reinforced with a grid made of glass fibers was used [22, 32]. The tape used was 12 cm wide and long enough to insert it in the grips of the testing machine.

The use of the DIC method needed special preparation of the observed surfaces. This required a random arrangement of black speckles visible on a white background. Therefore, the sample surfaces were painted with white paint. Then black speckles were randomly placed on the prepared surfaces. After preparation, the FRP tape took the form of a white polymer sheet with black speckles and an invisible glass fiber grid embedded inside. The stages of painting the asphalt mixture sample and the prepared FRP sample are shown in Fig. 3.

2.4. LABORATORY TESTING STAND

The research was carried out at a specially prepared laboratory stand. The main element of the testing stand was a servo-hydraulic MTS Landmark testing machine. The accuracy class of force measurement in this machine is 0.5. Static and cyclic loads can be generated here.

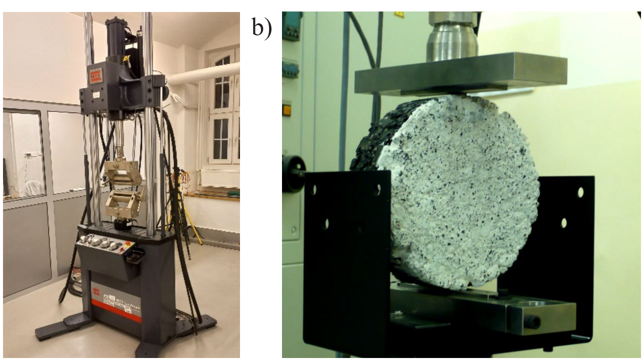

Fig. 4. Laboratory testing stand: a) general view; b) asphalt mixture sample prepared for indirect tensile test using DIC method

The second element of the stand was a non-contact system for measuring deformation of the tested samples using the DIC method. The Q-400 system from Dantec-Dynamics was used in the research [26]. The system consists of cameras, lighting and a system controller connected to the computer. A view of the testing stand is shown in Fig. 4.

3. RESULTS AND DISCUSSION

3.1. ASPHALT MIXTURE TEST RESULTS

In the first stage, the load-vertical displacement curves generated during the ITS test were compiled and the surfaces of the tested samples were visually assessed. Typical cracks development with increasing load was found. These cracks appeared in the vertical direction of the sample, perpendicular to the direction of the principal strains. According to the PN-EN 12697-23 standard [27], the failure type was defined as a main crack resulting from the combination of many small cracks concentrated near the vertical diameter. An example of the load-vertical displacement curve and a view of vertical cracks on the sample surface are shown in Fig. 5.

The results of asphalt mixture indirect tensile strength tests according to PN-EN 12697-23 [27] are presented in Table. 2. The obtained results showed correct values consistent with the results presented in the literature.

Table 2. Results of asphalt mixture indirect tensile strength tests

Sample number	ITS
1	0.63
2	0.78
3	0.61
4	0.71
5	0.63
Mean value [MPa]	0.67
Standard deviation [MPa]	0.07
Coefficient of variation [%]	11

The key stage of the work included the analysis of the

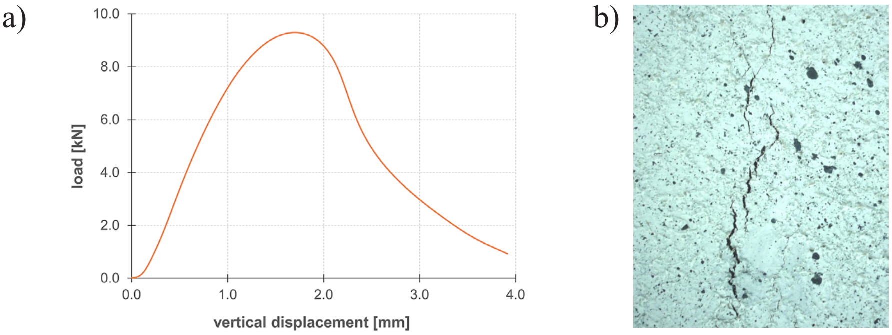

Fig. 5. a) load-vertical displacement curve from the ITS test; b) vertical cracks visible on the surface of the tested sample

entire surface of the tested samples using the DIC method. At the beginning, the discretization (virtual grid) parameters were determined for the analyzed area. Then, using the algorithm described above, displacement vectors were determined on the sample surface. Examples of the results of these stages are shown in Fig. 6.

Then, the distributions of horizontal displacements were analyzed for selected stages of sample loading. In the next step, strain tensors, principal strains and their directions were determined. Determining displacements and strains at any point and for any direction allows for the analysis of local changes in material properties and the impact of material heterogeneity. This is particularly important in the case of materials where local concentrations of strains and stresses may occur. These concentrations may be caused, for example, by non-uniform contact conditions between composite material components with different properties. Selected results are shown in Fig. 7 and 8.

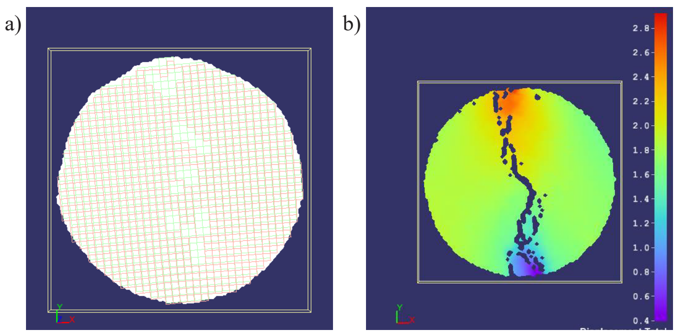

Fig. 6. a) virtual grid on the surface of the tested sample after loading; b) values of the displacement vector on the sample surface at the final stage of the test [mm]

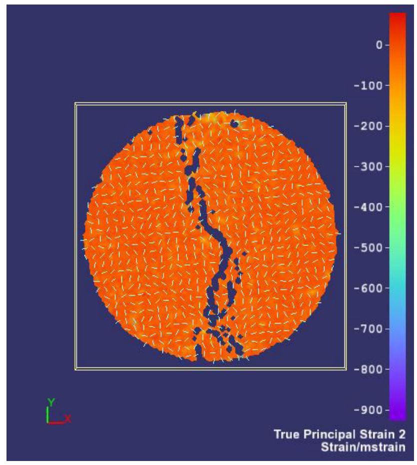

Fig. 8. Minimum principal strains and their directions on the sample surface

The obtained results show the variability of horizontal displacements on the analyzed sample surface for various stages of test (increase in the load value). This leads to the important conclusion that when measuring displacement using an extensometer, its location may affect the test result. Fig. 8 shows the distribution of minimum principal strains and their directions in the final phase of crack formation. These types of results can be used to analyze the influence of the material structure on crack formation and propagation.

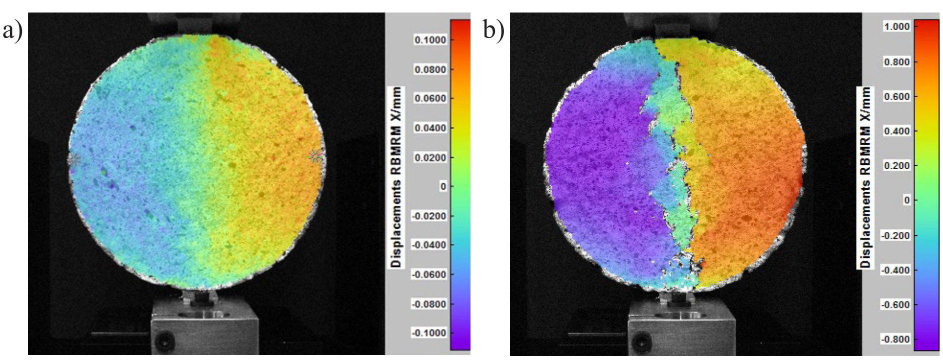

Fig. 7. a) horizontal displacements on the sample surface in the initial phase of the test [mm]; b) horizontal displacements on the sample surface in the final phase of the test [mm] [33]

3.2. FRP COMPOSITE TEST RESULTS

In the first stage, the applied load-nominal strain curves of the tested FRP samples were determined. The observed performance of the composite was similar to that shown by geogrids used to strengthen road pavement structures [24]. The glass fiber grid ribs were broken successively, creating a characteristic jagged load-strain plot in the final stage of the tests. A high average tensile strength value of approximately 50 kN/m was achieved. An example of the applied load-nominal strain curve is shown in Fig. 9.

Then the displacement vectors were determined. During the tensile test, an almost uniform deformation was found in the horizontal cross-section of the sample. The

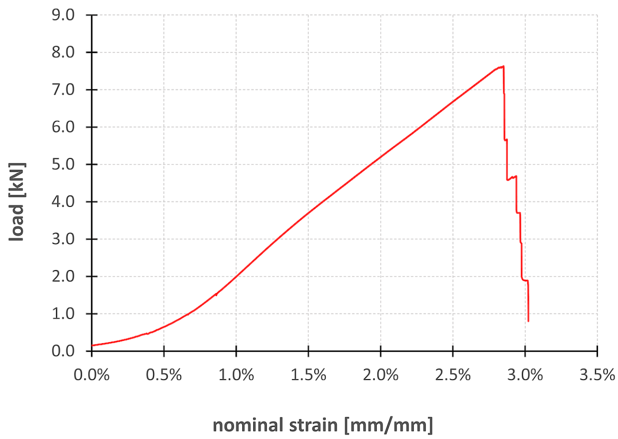

Fig. 9. Load-nominal strain curve of the tested FRP tape

distributions of the displacement vector values for the selected load level are shown in Fig. 10b.

The next stage of work included the calculation of strain tensors and the determination of the principal strains and principal directions. Strain tensor maps show the heterogeneous nature of the sample performance. The grid ribs deform in a different way than the polyurethane matrix. The strain tensors are shown in Fig. 11. The red places show the local concentration of strains on the matrix surface and the places where the glass fibers break. Generally, the directions of principal strains on the

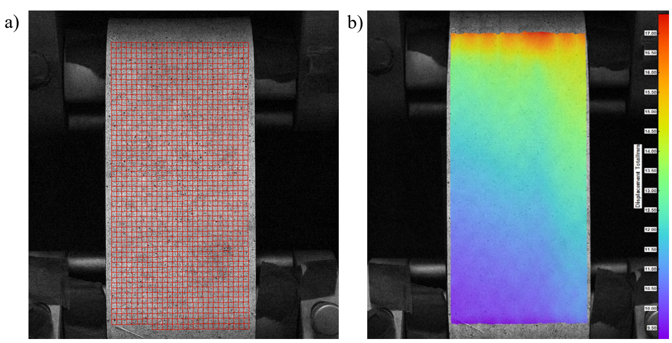

Fig. 10. a) facets/virtual discretization of the DIC method;
b) distribution of total displacement on the sample surface [mm]

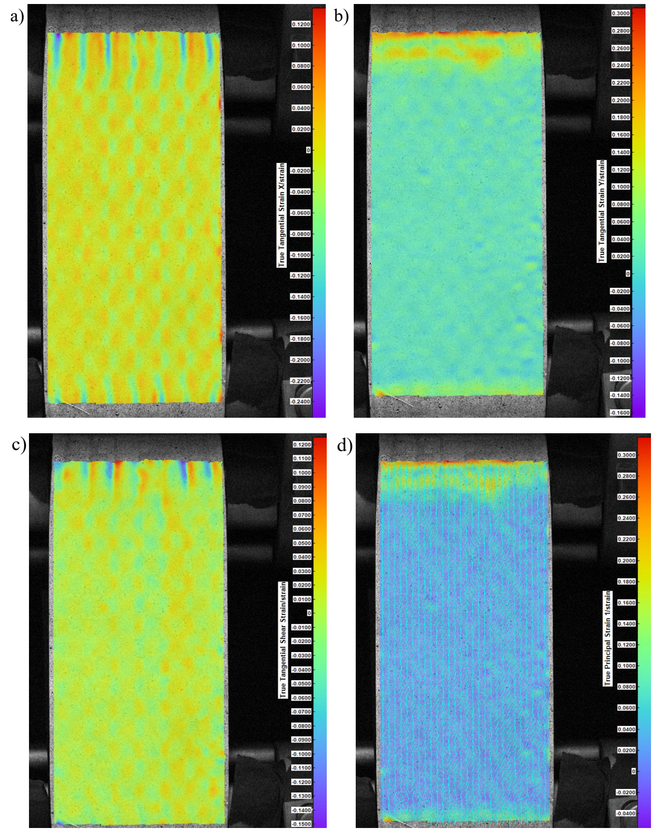

Fig. 11. The maps of the strain tensor components (true strain) a) ε_{xx} (horizontal direction); b) ε_{yy} (vertical direction); c) ε_{xy}, d) distribution of the maximum true principal strains and the principal directions (blue lines)

surface of the sample are almost vertical in accordance with the direction of the applied tensile load (Fig. 11d).

Figure 12 shows the variability of the true principal strains for the measurement base located in the vertical symmetry axis of the sample. The strains show that in the vertical direction there is tension and in the horizontal direction compression is observed, which is consistent with current knowledge. The wavy strain diagram shows the influence of following ribs and polyurethane matrix. The average ratio of the true principal strain 2 (minimum) to the true principal strain 1 (maximum) is about 0.57.

4. CONCLUSIONS

The paper presents the use of a non-contact method of measuring deformation in testing samples of two selected materials used in transport construction. The results of the conducted research yield the following conclusions:

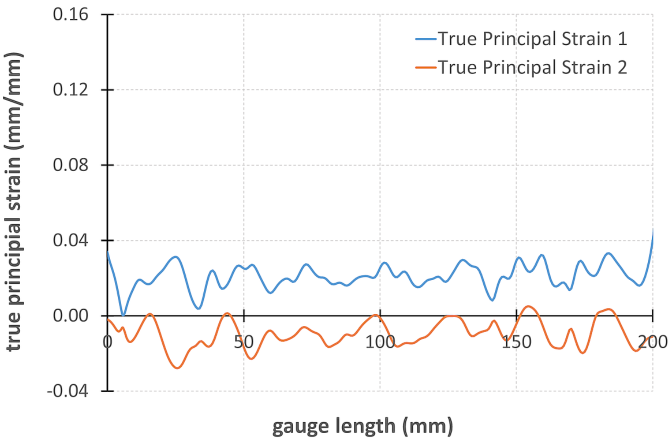

Fig. 12. The graph of the true principal strains variation in along the gauge length for maximum load

- the DIC method is one of the modern methods enabling the determination of displacements and strains on the sample surface during strength tests, at various stages of fracture,
- the method used enables measurement and analysis of the entire observed surface of the tested sample, along with the identification of key areas in the fracture process, which is not possible when using traditional contact measurement methods,
- post-processing calculations enable the determination and analysis of strain tensors, the values of principal strains and principal directions for the entire surface of the tested sample,
- in the static tensile test, the load-strain curve of the FRP tape is qualitatively similar to the performance of geogrids used to strengthen road pavement structures,
- the DIC method is an effective tool in testing both asphalt mixtures and modern FRP composites.

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