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EVALUATION OF THE INFLUENCE OF RECYCLED GLASS AND CARBON GEOGRIDS ON THE STIFFNESS MODULUS OF ASPHALT CONCRETE

OCENA WPŁYWU RECYKLOWANEJ GEOSIATKI SZKLANEJ I WĘGLOWEJ NA MODUŁ SZTYWNOŚCI BETONU ASFALTOWEGO

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Abstract

The paper presents the findings of a study on the influence of fibers derived from recycled geogrids on the stiffness modulus of asphalt concrete. The preliminary stage of the research involved a survey, which confirmed the escalating issue of reclaimed asphalt pavement (RAP) contamination with glass and carbon geogrid fibers, as well as the limited existing knowledge regarding their impact on asphalt concrete properties. The experimental program encompassed AC16W and AC22W mixtures modified with fibers ranging from 1 cm to 5 cm in length and at concentrations of 0.2% to 1.0% by weight. Analysis of the test results revealed that the application of carbon geogrid fibers did not lead to a significant increase in the stiffness modulus compared to the reference mixtures; conversely, glass fibers exhibited a tendency to reduce it. It was established that excessive fiber length and content lead to a reduction in the stiffness modulus. Based on the analyses, optimal parameters for maintaining high stiffness modulus values were determined: a fiber content of <0.2% and a length of <1 cm, regardless of the mixture's aggregate grading. The results indicate that geogrid recycling may represent an effective and rational approach supporting the circular economy and the development of sustainable asphalt technologies.

Keywords: geogrid recycling, sustainable development, reclaimed asphalt pavement, asphalt mixtures, glass and carbon fibers, experimental design

Streszczenie

W artykule przedstawiono wyniki badań nad wpływem włókien pozyskiwanych z recyklowanych geosiatek na moduł sztywności betonu asfaltowego. Elementem rozpoznawczym były badania ankietowe, które potwierdziły narastający problem zanieczyszczenia destruktu asfaltowego włóknami geosiatek szklanych i węglowych oraz ograniczoną wiedzę na temat ich wpływu na beton asfaltowy. Program badań obejmował mieszanki AC16W i AC22W modyfikowane włóknami o długości 1–5 cm i zawartości 0,2–1,0%. Analiza wyników badań wykazała, że zastosowanie włókien geosiatki węglowej nie powodowało istotnego wzrostu modułu sztywności względem mieszanek referencyjnych, natomiast włókna szklane wykazywały tendencję do jej obniżania. Stwierdzono, że nadmierna długość i udział włókien prowadzą do redukcji modułu sztywności. Na podstawie analiz określono wartości optymalne sprzyjające utrzymaniu wysokiej wartości modułu sztywności: zawartość włókien <0,2% oraz długość <1 cm, niezależnie od rodzaju uziarnienia mieszanki. Uzyskane rezultaty wskazują, że recykling geosiatki może stanowić efektywny i racjonalny kierunek wspierający gospodarkę o obiegu zamkniętym oraz rozwój zrównoważonych technologii asfaltowych.

Słowa kluczowe: recykling geosiatek, zrównoważony rozwój, destrukt asfaltowy, mieszanki mineralno-asfaltowe, włókna szklane i węglowe, plan eksperymentu

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1. INTRODUCTION

In European Union countries, more than 2.1 billion tones, of waste are generated annually, of which as much as 36% is accounted for by construction and demolition waste, encompassing materials such as concrete, ceramics, wood, glass, metals, and polymers [1]. An additional 26% is attributed to mining and quarrying waste, while the combined share of municipal, industrial, agricultural, service-related, and hazardous waste constitutes the remainder of the waste stream. In this context, waste generated by construction activities represents the largest share and remains one of the most critical areas for the development of the Circular Economy and the European Green Deal [2, 3]. In 2022, 14.8 million tones, of reclaimed asphalt pavement (RAP) were recovered in Germany, with as much as 87% being reused in the production of new asphalt mixtures [4]. In Poland, by contrast, reclaimed asphalt pavement is extensively utilized for road shoulder stabilization, which, as researchers point out, does not fully exploit its inherent potential [5]. Meanwhile, in accordance with the principles of the Circular Economy, waste should be treated as a secondary raw material and retained within the economic cycle for as long as possible [6]. In road engineering, reclaimed asphalt pavement (RAP) is a typical secondary waste material generated during the milling of pavement surfaces [7]. A critical problem that has been escalating in recent years is the presence of geogrid fragments within reclaimed asphalt pavement (RAP). Geogrids employed for the reinforcement of asphalt layers are manufactured from glass or carbon fibers, which are classified as synthetic, chemically stable, and inorganic materials [8]. In light of the guidelines [9] the permissible content of foreign matter – including synthetic materials – in reclaimed asphalt (RAP) is limited to <0.1% by mass [9,10]. Exceeding this threshold classifies the reclaimed asphalt as contaminated and precludes its use in the production of asphalt mixtures. Contamination of RAP with geogrid fibers is becoming increasingly prevalent, as glass and carbon geogrids are currently widely employed in maintenance treatments for flexible pavements [7, 11]. Geogrid fragmentation occurs during the milling process, and the resulting residues are incorporated into the reclaimed asphalt (RAP), presenting both technological and environmental challenges. Although geogrids are chemically inert and do not release hazardous substances [8], they are classified as foreign matter from the standpoint of technical standards. Their presence may restrict the recycling potential of RAP and pose a risk of secondary waste generation [10]. It is paradoxical that virgin glass, carbon, and synthetic fibers – in dosages of up to 4% by mass of the asphalt mixture – are described in both literature and road engineering practice as legitimate reinforcing additives [12-14], that improve, among other properties, rutting resistance, stiffness, and fatigue life [15-20]. Conversely, in the case of fibers derived from geogrid recycling, the situation is reversed; despite their similar mechanical properties, they are treated as contaminants that degrade the quality of the reclaimed asphalt [10]. However, international research findings indicate that post-service geogrid residues can be fully functional. Studies conducted by S&P Clever Reinforcement GmbH confirmed that fragmented glass geogrids retain desirable properties during the milling process and can be reintroduced into asphalt mixtures in compliance with German regulations [21, 22]. Furthermore, it has been demonstrated that their presence does not adversely affect rutting resistance [22]. In Poland, however, the issue of geogrid recycling remains largely unexplored; available industry data [5] indicate that while 80% of companies declare the use of RAP, the stringent limit on synthetic material contamination (<0.1%) significantly hampers its full utilization [10]. Against the background of these technological conditions and the existing research gaps regarding the impact of recycled geogrids on asphalt mixture properties, this study evaluates the influence of glass and carbon geogrid fibers derived from RAP on the stiffness modulus of asphalt concrete. The analysis was focused on identifying the optimal ranges for fiber content and length that allow for the retention of the favorable mechanical properties of the AC. Thus, the study verified the validity of treating recycled geogrid exclusively as technological contamination, considering its potential role as a structural modifier for asphalt concrete. This issue aligns with the strategic objective of rational secondary raw material management in road engineering.

2. METHODS AND MATERIALS

2.1. Geogrid

The study utilized virgin fibers obtained from glass and carbon geogrids, characterized by a tensile strength in both longitudinal and transverse directions exceeding 100 kN/m. These materials are commonly employed as reinforcement in asphalt pavement layers and bituminous overlays. Both geogrid types comply with the requirements of the PN-EN 15381 standard [23], which enables their full application in road engineering

Fig. 1. Virgin geogrid fiber after the simulated aging process in a Los Angeles machine

and provides a basis for analyzing their potential for reuse in the recycling process. The selection of these specific geogrids for the research was based on an assessment of RAP contamination and the results of a research survey [7], which confirmed the dominance of glass and carbon fibers as primary contaminants in reclaimed asphalt pavement. To replicate the real-world conditions of geogrid occurrence in RAP as closely as possible, the fibers underwent pre-treatment and a length-based selection process. Furthermore, the fibers were subjected to a simulated aging process in a Los Angeles (LA) machine (Fig. 1), where a cycle of 1,500 revolutions was performed for each 1 kg batch of geogrid fibers.

This procedure was intended to reflect the long-term service life of the geogrid within the pavement structure and the mechanical degradation occurring during the milling of the bituminous layers. Three fiber lengths were employed in the study: 1 cm (micro), and 3 cm and 5 cm (macro), which allowed for a comprehensive analysis of the influence of both fiber dimensions and type on the properties of the asphalt concrete. The laboratory aging and the selection of fiber dimensions made it possible to obtain a material that closely resembles the one found in actual reclaimed asphalt pavement (RAP) after the milling process. The fibers prepared in this manner were then incorporated into the asphalt mixtures, enabling an assessment of their impact on the mechanical and physical properties of the asphalt concrete in the context of the sustainable utilization of geogrids in the recycling process.

2.2. Asphalt Concrete Design

The design of the asphalt mixtures was preceded by a qualitative analysis of all components, including mineral aggregates, reclaimed asphalt pavement (RAP), the binder used, and the addition of glass and carbon geogrid fibers. The assessment was conducted in accordance with the material requirements specified in the guidelines and standards for asphalt mixture production [10, 24-27]. The composition of the mineral mixture was designed using the grading envelope method, which ensured an aggregate gradation meeting the criteria [9] for mixtures intended for the binder course [9]. The grading curves for the AC 16W KR3-4 and AC 22W KR3-4 mixtures are presented in Figures 2a and 2b.

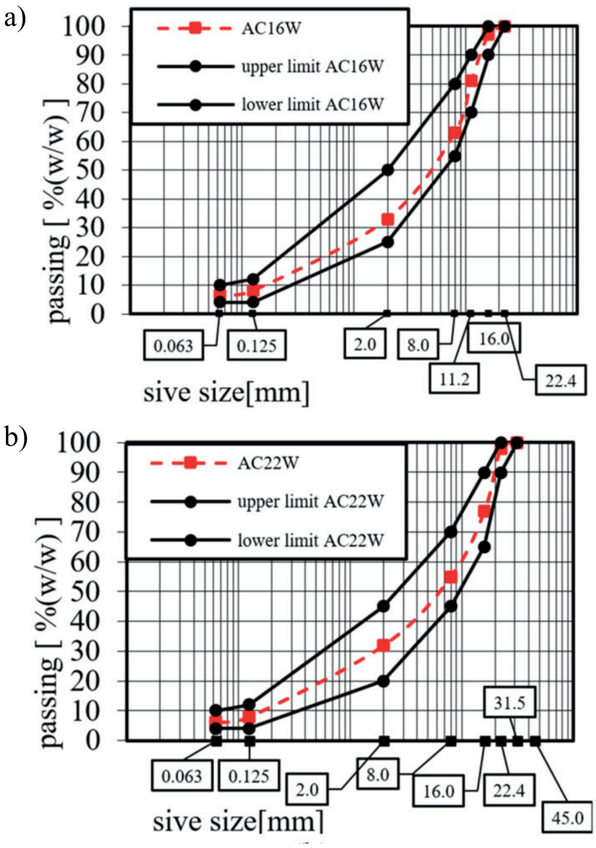

Fig. 2. Grading curves of the asphalt concrete (AC) mineral mixture: a) AC 16W KR3-4, b) AC 22W KR3-4

The composition of the asphalt mixtures is presented in Table 1.

Table 1. Percentage share of mineral and asphalt mixture components for AC 16W and AC 22W

Material	Description (Rock, Binder, Additive)	AC 16W 35/50 KR 3-4 Content [%] (m/m) mma	AC 22W 35/50 KR 3-4 Content [%] (m/m) mma
11.2 RAP 0/8*	Reclaimed Asphalt Pavement	19.3*	-
22.4 RAP 0/16**	Reclaimed Asphalt Pavement	-	19.3**
Aggregate 16/22 mm	Dolomite	-	21.2
Aggregate 8/16 mm	Dolomite	35.6	19.3
Aggregate 2/8 mm	Dolomite	20.2	15.5
Aggregate 0/2 mm	Dolomite	20.2	20.3
Limestone filler	Limestone	1.0	1.0
Bitumen 35/50	Paving grade bitumen	3.7	3.4
Adhesion agent	Adhesion agent	0.1	0.1
Total bitumen content	-	4.6	4.4

The asphalt mixture compositions designed in this manner ensured the stability of the mix and enabled an unambiguous assessment of the impact of recycled geogrid fibers on the properties of the asphalt concrete.

2.3. Experimental Design

The starting point for developing the experiment was determining the appropriate sampling method, which would allow for an unambiguous assessment of the impact of recycled geogrid fibers on the properties of the asphalt concrete. The research was based on a design incorporating diverse qualitative and quantitative input variables. Four independent variables were included in the experiment: two quantitative (fiber length and fiber content) and two qualitative (mixture type: AC 16W / AC 22W; and geogrid type: glass/carbon). The ranges for the quantitative variables were established at three levels, selected based on the research survey [7], and available literature concerning the impact of dispersed fibers-particularly glass and carbon-on the properties of hot-mix asphalt (HMA) [14]. The qualitative variables were introduced at two levels, covering the geogrids most commonly used in road construction and mixtures intended for the binder course, where the highest stress gradients in the pavement structure are typically observed. The adopted levels of the input variables are presented in Table 2.

Table 2. Input variables and their levels in the experimental design

Quantitative Variable	Levels	Qualitative Variable	Levels
Geogrid content, %	0.2; 0.6; 1.0	Geogrid type	Carbon; Glass
Geogrid length, cm	1; 3; 5	Asphalt mixture type	AC 16W; AC 22W

To analyze the impact of geogrid fibers on the properties of asphalt concrete, a final plan comprising 11 variable combinations was developed (Table 3), enabling the fulfillment of the adopted criteria while maintaining testing efficiency. The number of replicates for each configuration was determined in accordance with the requirements of the relevant testing standards [28-31].

Table 3. Experimental matrix

No.	Geogrid Type	Asphalt mixture Type	Fiber content [%]	Fiber length [cm]
1.	glass	AC 16W	0.2	1
2.	glass	AC 16W	0.6	3
3.	glass	AC 16W	1.0	5
4.	glass	AC 22W	0.2	1
5.	glass	AC 22W	1.0	5
6.	carbon	AC 16W	0.2	1
7.	carbon	AC 16W	0.6	3
8.	carbon	AC 16W	1.0	5
9.	carbon	AC 22W	0.2	1
10.	carbon	AC 22W	0.6	3
11.	carbon	AC 22W	1.0	5

To facilitate further evaluation of the fiber-reinforced mixtures, the individual test series were coded according to the following system:

- G16021-1 – AC 16W KR3-4 mixture (16) with glass fibers (G), a fiber content of 0.2% (02), a fiber length of 1 cm (1), and the experimental design sequence number (-1);

- C16021-6 – AC 16W KR3-4 mixture (16) with carbon fibers (C), a fiber content of 0.2% (02), a fiber length of 1 cm (1), and the experimental design sequence number (-6);
- G22021-4 – AC 22W KR3-4 mixture (22) with glass fibers (G), a fiber content of 0.2% (02), a fiber length of 1 cm (1), and the experimental design sequence number (-4);
- C22105-11 – AC 22W KR3-4 mixture (22) with carbon fibers (C), a fiber content of 1.0% (10), a fiber length of 5 cm (5), and the experimental design sequence number (-11).

2.4. Physical and Mechanical Properties of Asphalt Concrete

To assess the impact of recycled glass and carbon geogrid fibers on the properties of the asphalt concrete, a comprehensive suite of standardized tests was first conducted to verify the compliance of the mixtures with the requirements of the relevant standards and guidelines [9, 26]. The scope of the asphalt mixture analysis included the evaluation of physical, mechanical, and volumetric properties. These parameters, along with their respective test codes and normative references, are summarized in Table 4.

Table 4. Tested parameters of the asphalt concrete

No.	Tested Property	Test Standard
1.	Air void content (V_a)	PN-EN 12697-8 [31]
2.	Water sensitivity (ITSR)	PN-EN 12697-12 [30], annex 1 for WT-2 p. I
3.	Resistance to permanent deformation (WTS_{AIR}), mm/1000 cycles, small device, method B, in air, 60°C, 10 000 cycles,	PN-EN 12697-22 [31]
4.	Resistance to permanent deformation (PRD_{AIR}), mm/1000 cycles, small device, method B, in air, 60°C, 10 000 cycles	PN-EN 12697-22 [31]
5.	Stiffness modulus (IT-CY)	PN-EN 12697-26 [28]

The completion of the basic tests enabled the transition to the main research stage, which involved determining the stiffness modulus (S_m) using the Indirect Tension Test on Cylindrical specimens (IT-CY). This was conducted in accordance with the test procedure described in PN-EN 12697-26, Annex C [28]. The target horizontal displacement was 5 μm ±2 μm, and the load rise time was 124 ms ±4 ms. The stiffness modulus was calculated according to the relationship shown in Equation (1), while the Poisson's ratio was determined based on the analytical relationship given in Equation (2):

$$S_m = \frac{F \cdot (\nu + 0.27)}{z \cdot h} \tag{1}$$

$$\nu = 3.59 \cdot \frac{z}{\Delta V} - 0.27 \tag{2}$$

where:

S_m – stiffness modulus of the specimen [MPa],
F – peak load applied to the specimen [N],
ν – temperature-dependent Poisson's ratio,
z – amplitude of the horizontal displacement of the specimen under loading [mm],
h – specimen thickness [mm],
ΔV – maximum vertical displacement of the specimen (corresponding to the peak horizontal displacement) [mm].

The specimens were prepared by compacting the asphalt mixture using a Marshall impact compactor, with 75 blows applied to each face (2 × 75) [32]. Immediately prior to testing, the specimens were conditioned for a minimum of 4 hours at the test temperature to ensure full thermal equilibrium throughout the material cross-section. Measurements were performed along two mutually perpendicular diameters.

3. RESULTS AND DISCUSSION

The evaluation of the impact of recycled geogrid on the properties of asphalt concrete is a highly complex issue, arising from the multidimensional nature of the interactions between the asphalt mixture composition and the parameters of the recycled geogrid fibers. As part of the preliminary research characterization, the basic properties of the asphalt mixtures were evaluated to determine their baseline state. The scope of the testing included air void content (Va), water sensitivity (ITSR), and resistance to permanent deformation, expressed by the WTS_{AIR} and PRD_{AIR} parameters (small device, Method B, in air, 60°C, 10,000 cycles). In this study, these basic test results, presented in Table 5, serve as an interpretative background for the in-depth analysis focused on the stiffness modulus (S_m), which is the key parameter characterizing the influence of the recycled geogrid on the mechanical behavior of the asphalt concrete.

Table 5. Basic test results of the asphalt mixtures

Mix code	V_a [% (v/v)]	ITSR [%]	WTS_{AIR}	PRD_{AIR}
G16021-1	2.4	78	0.07	5.6
G16063-2	3.9	108	0.08	6.8
G16105-3	4.3	102	0.07	6.5
G22021-4	5.4	79	0.06	5.5
G22105-5	6.0	103	0.07	7.5
C16021-6	4.1	105	0.06	5.8
C16063-7	5.2	97	0.05	6.6
C16105-8	7.3	97	0.09	8.5
C22021-9	5.7	95	0.06	5.5
C22063-10	6.4	100	0.07	6.2
C22105-11	7.8	101	0.07	6.5

The primary objective of the analyses was a detailed evaluation of the asphalt mixtures containing geogrid fibers, with a particular focus on the stress and strain distribution within the asphalt concrete intended for the binder course. To this end, special attention was paid to the stiffness modulus determined by the Indirect Tension Test on Cylindrical specimens (IT-CY), as an indicator sensitive to both changes in the mixture composition and the characteristics of the applied fibers. The stiffness modulus tests were conducted at five temperature levels: −10°C, 5°C, 13°C, 25°C and 50°C, in accordance with the requirements of PN-EN 12697-26 [28]. The obtained modulus values, presented in Figure 3, were subjected to aggregation and statistical analysis, taking into account the influence of the geogrid type, fiber content, and the type of asphalt mixture.

The use of a full temperature range allowed for determining the actual susceptibility of the material to service loads. The generalized stiffness moduli for glass and carbon geogrids, determined using the IT-CY method, showed an unambiguous dependence on the test temperature. As the temperature increased, a significant reduction in S_m values was observed, which is typical for thermoplastic materials where the susceptibility of the asphalt binder plays a dominant role in deformation. The highest values were recorded at −10°C, while the minimum values were found at 50°C, confirming the mixtures' transition to a state significantly more susceptible to permanent deformation. The statistical dispersion of the results increased significantly as the temperature decreased, indicating a stronger interaction between the asphalt binder and the presence of recycled fibers at low temperatures. Consequently, the obtained stiffness modulus values were the result of the cumulative influence of the test temperature. To illustrate the

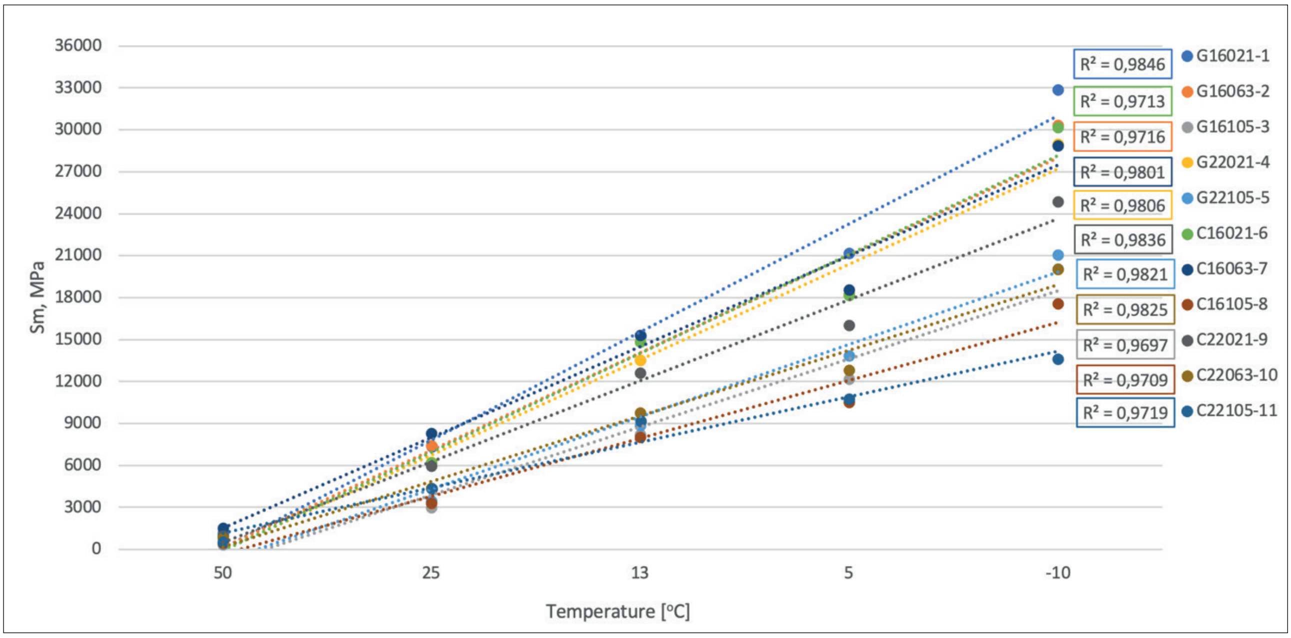

Fig. 3. Results of the stiffness modulus S_m (IT-CY) versus temperature

nature of the changes in the S_m parameter, it was aggregated with respect to individual temperature levels (Fig. 4).

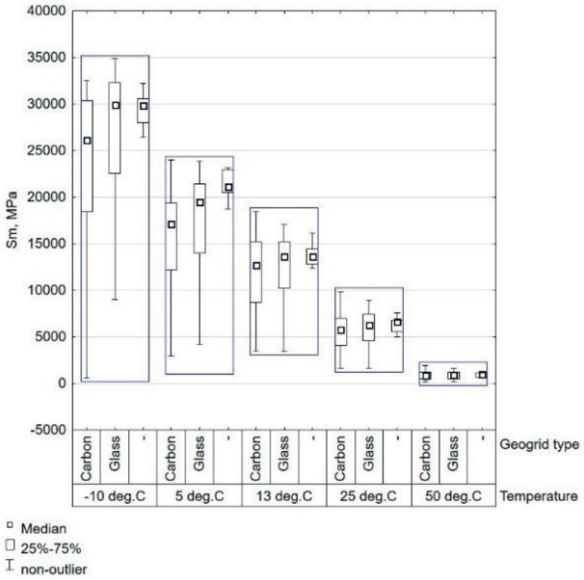

Fig. 4. Stiffness modulus S_m versus temperature categorized by geogrid material type

The results indicated that the application of carbon fibers had a stabilizing effect and, in most cases, led to a slight increase in S_m values. However, compared to the reference mixtures, the presence of the carbon geogrid did not cause a significant increase in the stiffness modulus S_m. At the same time, the carbon fiber-reinforced system exhibited lower variability of results than analogous compositions based on glass geogrid. This suggests that carbon fibers more effectively transfer and distribute stresses within the asphalt matrix, particularly at intermediate and high temperatures. A different trend was observed for mixtures containing glass geogrid, where a decrease in the stiffness modulus was noted in some systems. This confirms that glass geogrid does not provide the same level of reinforcement as carbon fibers introduced at the same dosages. It was observed that increasing the aggregate size of the asphalt mixture from 16 mm to 22 mm resulted in a reduction of the stiffness modulus, which was also evident in combinations with an excessive geogrid dosage (>0.2%). The overall median stiffness modulus determined for all mixtures at 13°C (Fig. 5) was 13.187 MPa, which is higher than the value of 10.300 MPa specified for road structures in the Catalogue of Typical Flexible and Semi-Rigid Pavement Structures [11].

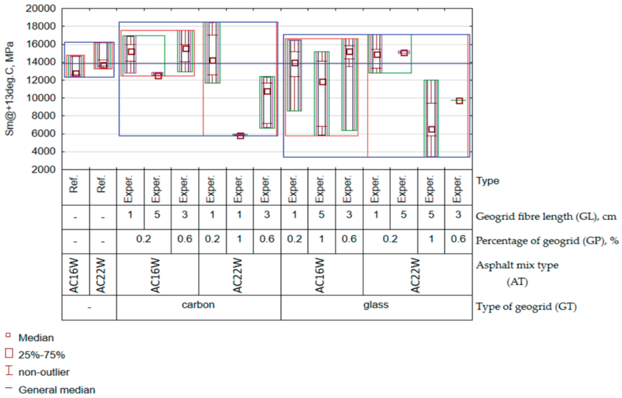

Fig. 5. Variation of the stiffness modulus S_m at 13°C

Obtaining slightly higher stiffness modulus values indicates a significant potential for increasing the pavement structure's resistance to permanent deformation, particularly in zones subjected to heavy traffic loads.

4. CONCLUSIONS

The conducted research and analyses led to the following detailed conclusions:

- The results of the analyses clearly indicate the need for in-depth studies regarding the presence of geosynthetic materials in Reclaimed Asphalt Pavement (RAP). The current permissible contamination limit of < 0.1% significantly restricts the practical utilization of RAP containing geogrid fragments. Simultaneously, the obtained results demonstrate that properly identified and classified RAP with recycled geogrid additives can positively influence asphalt concrete parameters, emphasizing the importance of precise identification of the feedstock material.
- The research demonstrated that the application of carbon geogrid fibers does not lead to a significant increase in the stiffness modulus (S_m) compared to the reference mixtures, whereas the presence of glass fibers in many combinations resulted in a reduction of stiffness. This underscores the necessity of distinguishing the geogrid material type during the suitability assessment of reclaimed asphalt.
- In line with the thermoplastic characteristics of asphalt materials, S_m values decreased as temperature increased, with the greatest dispersion observed at low temperatures. This suggests a dominant contribution of the interactions between the asphalt binder and the recycled geogrid fibers.

- The overall median S_m obtained for all results at 13°C (13.187 MPa) slightly exceeded the catalog value for AC mixtures (10.300 MPa). This confirms the beneficial potential of recycled geogrid in reducing the susceptibility of the pavement structure to permanent deformation. Furthermore, no significant degradation of stiffness was observed in mixtures containing recycled glass geogrid fibers.
- Analysis of the stiffness modulus S_m revealed that the most significant decrease in the modulus occurred with an increase in fiber length and percentage content, which was particularly evident at test temperatures of 13°C and 5°C. This indicates that an excessive amount of fibers may weaken the structural matrix of the asphalt mixture, especially within the range of low and moderate service temperatures.
- The results of the analyses clearly indicated that the optimal values for ensuring high stiffness S_m are: fiber content <0.2% and fiber length <1 cm, regardless of the aggregate gradation (AC 16W or AC 22W).
- A controlled amount of recycled geogrid fibers can provide an effective means of improving selected mechanical parameters, especially stiffness at higher service temperatures, while maintaining stability within the temperature range relevant to European climate conditions.

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