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Original Research Article

ANALYSIS OF THE EFFECT OF FIBER ADDITIVES ON THE LOAD-BEARING PROPERTIES OF SANDSTONE AGGREGATE MIXTURES

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A b s t r a c t

The development of road infrastructure requires an increasing use of materials that do not always meet the necessary technical requirements. In road construction, numerous methods for improving the properties of aggregates and soils are known, such as the use of fly ash, blast furnace slag, or lime. However, the amount of these additives, aimed at improving the material's parameters, can account for as much as several dozen percent of the mixture's volume. An innovative solution gaining increasing popularity is the use of fibers as dispersed reinforcement. A small addition of fibers, amounting to only 1–2%, is sufficient to significantly improve the load-bearing capacity and other mechanical properties of the material.
This article presents the impact of using dispersed reinforcement in an aggregate mixture to improve its load-bearing parameters. The study utilized a 0/31.5 mm aggregate mixture enriched with various types of dispersed fibers: carbon, glass, coconut, hemp, basalt, and polypropylene. The analysis included determining the CBR (California Bearing Ratio) and shear strength of the modified material.

Keywords: dispersed fibers, aggregate, CBR index, shear strength, multiple regression

1. INTRODUCTION

The application of a subbase with the appropriate load-bearing class, capable of withstanding loads caused by road traffic, is crucial in road construction. An essential aspect is the proper placement of the subbase within the pavement structure and determining its function—whether it serves as a primary or auxiliary subbase. Aggregates are most commonly used for subbase construction, but due to their insufficient mechanical properties, they often require improvement. To modify the properties of aggregate mixtures, the use of additives such as fly ash, slags, sewage sludge and dispersed fibers is recommended [1–3].

The development of transportation infrastructure focuses on introducing increasingly advanced techniques to enhance the strength properties of aggregates. One popular solution is the addition of

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dispersed reinforcement in the form of fibers, which interact with the soil by absorbing tensile forces and increasing the strength of the modified area [4].

A wide variety of fibers used as dispersed reinforcement is available on the market. These include natural fibers such as hemp, coconut, or basalt, and synthetic fibers, e.g., polypropylene. Natural fibers are biodegradable, whereas synthetic ones, due to their properties, often enrich the reinforced soil with additional features, such as resistance to aggressive environmental factors [5,6]. The potential benefits of introducing dispersed fibers into soil include [4]:

- Improved soil load-bearing capacity,
- Enhanced soil durability,
- Better stabilization,
- Mitigation of local landslides and the ability to secure small slopes,
- Stabilization of the subbase in road construction,
- Reduction of cracks in the soil,
- Increased resistance to dynamic loads,
- Enhanced resistance to adverse chemical and environmental factors.

The use of dispersed fibers enables the creation of a stable, flexible soil that is also easy to green, contributing to ecological balance. These fibers do not affect soil permeability, allowing for continuous plant growth, unlike traditional reinforced concrete or stone reinforcements [5].

This study examines the impact of adding dispersed reinforcement in the form of fibers to aggregate mixtures to improve their load-bearing properties. To assess the effects of the applied additives, a series of preparatory activities were conducted, including sieve analysis and sample compaction using a Proctor apparatus, as well as basic tests such as determining the CBR index and the shear strength of modified samples.

2. DISPERSED REINFORCEMENT

In geotechnics, fibers are widely used and can be categorized into natural fibers, such as coconut, basalt, or hemp fibers, and those specifically manufactured for dispersed reinforcement. The type of fiber determines the dosage required for reinforcing soil or aggregate mixtures.

Carbon fibers consist of stretched carbon structures with a diameter smaller than a human hair. Their production involves the pyrolysis of polyacrylonitrile at 220–250°C for about 50 hours, followed by carbonization at 1000°C and further heating to 3000°C under increased pressure [7]. These fibers significantly improve the load-bearing capacity and structural parameters of soils [8–10]. Key characteristics of carbon fibers include high mechanical strength, non-flammability, chemical resistance, and excellent resistance to tension, creep, and fatigue [11,12]. They are also highly resistant to abrasion, temperature changes, and capable of effectively damping vibrations, making them a particularly attractive solution for geotechnical reinforcement.

Glass fibers, known for their high strength and corrosion resistance, are produced by melting silica, soda ash, and lime, which are then drawn into thin glass threads. Coating these fibers with polymers or epoxy resin further enhances their strength properties [13]. Glass fibers demonstrate tensile strength up to 3.5 GPa and chemical resistance to acids, bases, and solvents. They are also thermally resistant, electrically insulating, and resistant to atmospheric corrosion and biological factors [14–16]. These properties make them widely applicable in geotechnical projects requiring durable reinforcement.

Fig. 1. Carbon fibers

Fig. 2. Glass fibers

Coconut fiber, a natural material, is often used as dispersed reinforcement in concrete or for stabilizing soil. Its primary advantage is its ability to bind soil particles, preventing their displacement and improving load-bearing capacity. This reduces the likelihood of settlement and cracking of the terrain [17]. Additionally, coconut fiber is effective in protecting slopes and embankments against climatic erosion, while its biodegradable and environmentally friendly nature makes it a preferred material in sustainable construction [18,19].

Hemp fibers are commonly employed as dispersed reinforcement in concrete, improving its strength properties, and in soil applications, they are used for slope stabilization. They also enrich the substrate with nutrients, including nitrogen, during the repair of slopes [20]. Hemp fibers exhibit a tensile strength of approximately 900 MPa and possess the ability to self-seal cracks upon exposure to moisture, thereby minimizing the extent of structural damage [21]. Their ecological sustainability further enhances their appeal in environmentally conscious construction projects.

Fig. 3. Coconut fibers

Fig. 4. Hemp fibers

Basalt fibers are produced by melting basalt at temperatures of 1500–1700°C and forming it into fibers. These fibers are notable for their high mechanical strength, resistance to chemical agents, UV radiation, and high temperatures [22]. Additionally, their production process is energy-efficient, making them environmentally friendly. Basalt fibers find application in concrete reinforcement, thermal and acoustic insulation, and as components in fire-resistant textiles [23].

Polypropylene fibers are synthesized through the polymerization of propylene, followed by stabilization and cutting into fibers. They are lightweight and exhibit tensile strengths ranging from 300 to 760 MPa. They are also highly resistant to chemical corrosion [24,25]. However, their limited adhesion properties compared to other fibers can reduce their effectiveness in specific geotechnical applications. Nonetheless, they remain a cost-effective and efficient alternative for many reinforcement purposes.


Fig. 5. Basalt fibers


Fig. 6. Polypropylene fibers

The application of dispersed fibers in geotechnics provides significant benefits, such as improved load-bearing capacity, stability, and durability of soils and construction materials. The selection of fiber type depends on the specific technical, environmental, and economic requirements of a project, enabling optimal adaptation to soil conditions and structural loads while incorporating sustainable practices.

3. SCOPE OF RESEARCH

To analyze the impact of dispersed fiber additives on aggregate mixtures, a series of tests were conducted in accordance with the applicable standards. All tests were performed at the certified *Laboratory for Testing the Properties of Rocks and Stone Products* at AGH University of Science and Technology.

The first step involved determining the aggregate gradation through sieve analysis, which was conducted to assess the quality of the aggregate mixture used in the study. In accordance with the recommendations of the PN-EN 933-1 standard, a set of sieves was used, with the largest opening size of 40 mm and the smallest permissible size of 0.063 mm, as specified in the standard. The results of the sieve analysis are presented in Figure 7 and Table 1.

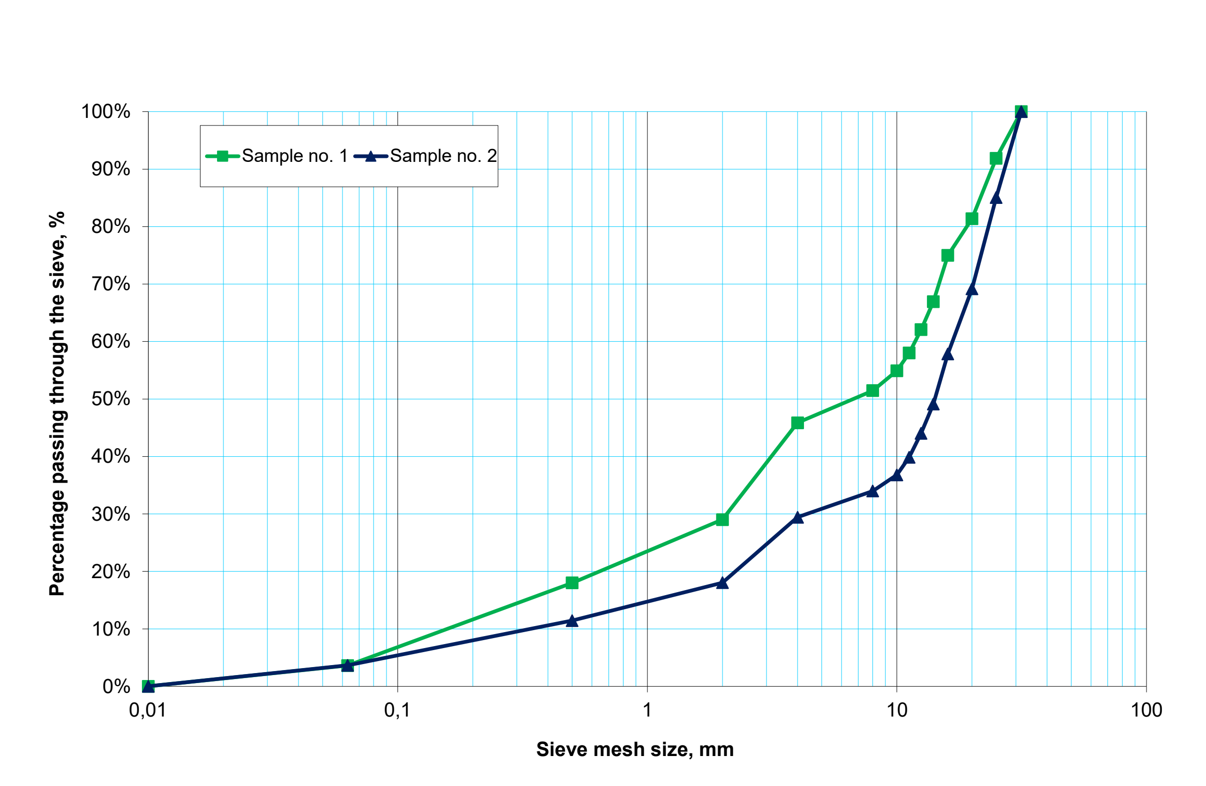

Fig. 7. Grain Size Distribution Curve for Sandstone Aggregate

Table 1. Grain Size Parameters of Sandstone Aggregate

Parameter		Simple no. 1	Simple no. 2
Effective diameter	d_{10} [mm]	1.0598	1.6158
	d_{50} [mm]	9.4248	16.3523
	d_{60} [mm]	13.2248	20.9930
Coefficient of uniformity	U [-]	12.48	12.99

The determination of the optimal moisture content of the tested aggregate mixture was carried out in accordance with the PN-EN 13286-2 standard. Samples with their natural moisture content and structure were used for this purpose. The mixtures were placed in a large cylinder in three layers, with each layer compacted using a light rammer, striking the sample 55 times. The rammer's drop height was 320 ± 1 mm, and the specific compaction energy was 0.59 J/cm³. During the test, five samples with varying moisture levels were prepared. This approach allowed for the determination of the moisture level at which the maximum compaction of the material was achieved. The optimal moisture content for the entire 0-31.5 mm mixture, considering the grain composition, was found to be 4.2%.

The California Bearing Ratio (CBR) tests were conducted in accordance with the PN-EN 13286-47 standard. Two samples were prepared for the aggregate mixture without additives, and two for each type of fiber reinforcement, added in the amount of 1.5% of the sample mass. In all cases, while adding dispersed reinforcement to the aggregate, water was gradually introduced to achieve a moisture content close to the optimal level. The tests were conducted on samples weighing approximately 5 kg each. The samples were placed in a CBR test cylinder and compacted using a Proctor apparatus. Subsequently, a plunger with a diameter of 50 mm was pressed into the sample, and the force required to penetrate the plunger to depths of 2.5 mm and 5.0 mm was recorded. The plunger was applied at a constant speed of 1.25 mm/min.

Fig. 8. CBR Testing Press

The shear strength test was conducted in accordance with the PKN-CEN ISO/TS 17892-10 standard using a direct shear apparatus. This method involves placing a soil sample in a shear box, applying a normal force, and shearing the sample along a horizontal plane at a constant rate, as determined by the apparatus construction.

Seven samples were prepared for testing. The first sample consisted of an aggregate mixture without additives, to which water was added to achieve the optimal moisture content of 8.2% for fractions smaller than 10 mm. For the remaining six samples, fibers were incorporated in addition to the appropriate amount of water.

4. RESULTS OF CBR AND SHEAR STRENGHT TESTS

The California Bearing Ratio (CBR) test was conducted on 14 samples of sandstone aggregate mixture, including two baseline samples (without additives) and 12 samples with various types of fiber reinforcement. According to standard requirements, the highest CBR value from the two measurements taken for each sample was used for analysis.

The results for the fiber-reinforced samples are presented in Figure 9. Compared to the baseline sample, the addition of basalt fibers significantly increased the CBR. For a plunger penetration of 2.5 mm, the CBR value increased by 27.736% (sample 2.2), while for a penetration of 5.0 mm, it increased by 17.347% (sample 2.2). Samples with coconut fibers also exhibited an improvement in bearing capacity, though to a lesser extent. At 2.5 mm penetration, the CBR increased by 12.906% (sample 3.1), while at 5.0 mm penetration, it rose by 8.635% (sample 3.2). In samples containing glass fibers, the CBR values were similar to those of the baseline samples. At a penetration of 2.5 mm, the CBR increased slightly by 3.659% (sample 4.2), whereas at 5.0 mm penetration, a decrease of 1.302% was observed (sample 4.2). The inclusion of carbon fibers enhanced the CBR compared to the baseline. At 2.5 mm penetration, the CBR increased by 11.565% (sample 5.1), whereas at 5.0 mm, the increase was only 3.807% (sample 5.2). Hemp fibers led to a moderate increase in the CBR compared to the baseline samples. At 2.5 mm penetration, the CBR rose by 8.918% (sample 6.1), and at 5.0 mm penetration, it increased by 10.850% (sample 6.2). For samples with polypropylene fibers, the CBR values remained close to those of the baseline samples. At 2.5 mm penetration, the CBR increased slightly by 3.619% (sample 7.2), whereas at 5.0 mm penetration, a decrease of 1.369% was recorded (sample 7.2).

Among all tested fibers, the highest improvement in CBR was observed with the addition of basalt fibers. In contrast, the smallest increase—or even a decrease in some cases—was noted in samples with glass and polypropylene fibers.

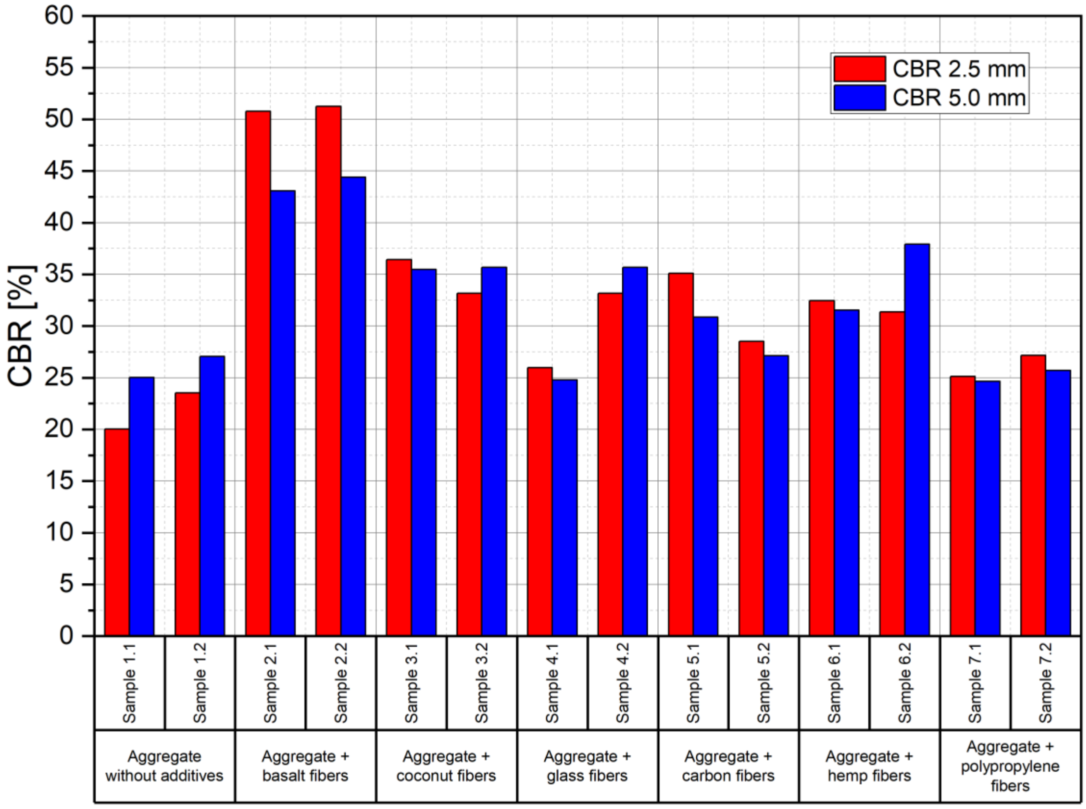

Fig. 9. The CBR index value for samples with fiber additives

The results of the shear strength test for aggregate samples with fiber additives are presented in Figure 10 (cohesion values) and Figure 11 (internal friction angle values). The baseline sample, i.e., the

0/31.5 mm aggregate mixture without dispersed fiber additives, exhibited an internal friction angle of 47.02° and cohesion of c=6.89 kPa.

The addition of basalt fibers to the mixture resulted in an internal friction angle of 34.59°, indicating a decrease of 26.5%, while cohesion increased to 62.09 kPa, representing an increase of 801% compared to the baseline sample. Another sample containing coconut fibers exhibited an internal friction angle of 41.64°, a decrease of 11.5%, and cohesion of 38.25 kPa, an increase of 455% relative to the baseline. The sample with glass fiber additives showed an internal friction angle of 45.14°, a decrease of 4.00%, and cohesion of 18.51 kPa, which represents a 169% increase compared to the baseline.

The sample with carbon fiber additives had an internal friction angle of 43.95°, a decrease of 6.54%, and cohesion of 18.14 kPa, marking an increase of 163% relative to the baseline. When hemp fibers were added to the sample, the internal friction angle was 44.38°, a decrease of 5.62%, while cohesion rose to 15.41 kPa, an increase of 123.8% compared to the baseline. Finally, the addition of polypropylene fibers to the 0/31.5 mm mixture resulted in an internal friction angle of 45.66°, a decrease of 2.89% compared to the baseline, while cohesion increased to 18.07 kPa, representing a 162% increase.

Analyzing the above results, it is evident that the addition of dispersed fibers to the 0/31.5 mm aggregate mixture improves the cohesion of the tested samples, whereas the internal friction angle often decreased. The most significant improvement in cohesion was observed with the addition of basalt fibers, where cohesion increased more than eightfold compared to the baseline sample. Conversely, the most substantial decrease in the internal friction angle was recorded for the sample containing glass fibers.

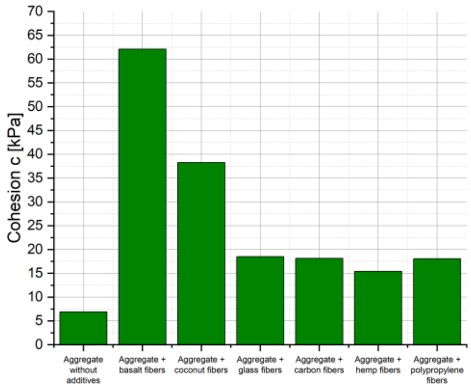

Fig. 10. The cohesion value for samples with fiber additives

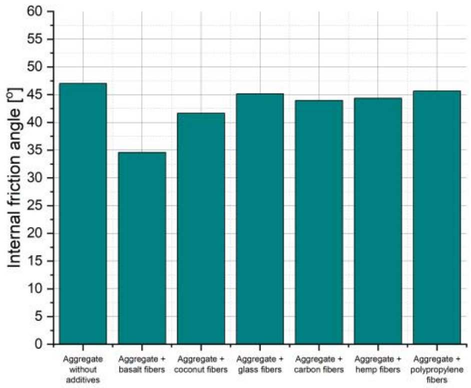

Fig. 11. The internal friction angle for samples with fiber additives

5. DISCUSSION

The influence of fiber additives on the load-bearing properties of aggregate mixtures is evident from the results presented in the previous section. However, a key issue remains determining the extent to which different types of fibers affect the CBR value and how precisely this influence can be estimated. To address this, multiple regression analysis was employed, allowing for the formulation of an equation incorporating multiple parameters.

Based on the CBR values obtained from a series of tests with different fiber additives, a multiple regression analysis was conducted. Two parameters were used to predict the CBR value: penetration depth (as specified in the standard, either 2.5 mm or 5.0 mm) and the fiber density provided by the manufacturer. For the sample without fiber additives, the fiber density was assumed to be zero. As a result of the analysis, the following equation was derived (5.1):

$$CBR = 3.921 \cdot P + 3.602 \cdot \rho + 0.411 \cdot c \tag{5.1}$$

where:
P – penetration depth (2.5 mm or 5.0 mm),
ρ – fiber density [g/cm³]
c – cohesion [kPa].

The presented data summarizes the results of a multiple regression analysis, highlighting that the model has been executed effectively, as evidenced by the quality and significance of the obtained results. The regression coefficients, along with their associated metrics, demonstrate a strong and meaningful relationship between the independent variables and the dependent variable, particularly for the variables with statistically significant results.

For the variable representing penetration (P), the coefficient of 3.921241 indicates a strong positive effect on the dependent variable. This relationship is highly significant, as reflected by the very low P-value of 0.000002 and a high t-statistic of 6.145094. Additionally, the 95% confidence interval for this coefficient, ranging from 2.607030 to 5.235451, excludes zero, further confirming its significance. Importantly, the R^2 value of 0.953 demonstrates that 95.3% of the variability in the dependent variable is explained by this predictor, underscoring the reliability of the model in capturing this effect.

The variable related to fiber density (ρ) also shows a positive coefficient of 3.601690, suggesting its contribution to the dependent variable. Although the P-value of 0.072687 is slightly above the conventional threshold of 0.05, indicating marginal statistical significance, the results still suggest a meaningful trend. The wider confidence interval, which ranges from -0.356932 to 7.560311, indicates a need for further investigation to confirm its precise role in the model.

Cohesion (c) emerges as another key variable, with a coefficient of 0.411316 that indicates a smaller yet positive contribution to the dependent variable. The statistical significance of this relationship is evident from the P-value of 0.000553 and a t-statistic of 3.957095. The 95% confidence interval, ranging from 0.197240 to 0.625393, excludes zero, providing robust support for the inclusion of this variable in the model.

Overall, the regression analysis demonstrates strong performance, with statistically significant results for key variables and high explanatory power, as reflected in the R^2 values. The results indicate that the model effectively captures the relationships between the predictors and the dependent variable, providing a solid foundation for interpreting the impact of penetration, fiber density, and cohesion on the studied phenomenon.

Table 2. Statistical data of multiple regression

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	R^2
P (penetration)	3.921241	0.638109	6.145094	0.000002	2.607030	5.235451	0.953
ρ (fiber density)	3.601690	1.922091	1.873839	0.072687	-0.356932	7.560311	
c (cohesion)	0.411316	0.103944	3.957095	0.000553	0.197240	0.625393	

The graphs from the multiple regression analysis emphasize the statistical significance and effectiveness of the study. Residual distributions and fitted line comparisons highlight the accuracy and reliability of the regression model in representing the relationships between the dependent and independent variables.

Residual distribution plots show that the residuals are symmetrically distributed around the zero line for both key variables, indicating the absence of systematic errors or biases in the model. This random scatter supports the assumption of normality and suggests that the regression model effectively captures the variation in the data.

The fitted line plots further demonstrate the model's robustness. Observed values align closely with predicted values, reinforcing the reliability of the regression coefficients and the overall model. The minimal deviation between observed and predicted data underscores the model's ability to explain a significant portion of the variability in the dependent variable.

In summary, the results provide strong evidence for the statistical validity of the regression analysis. The alignment of residuals and predicted data confirms that the model is not only statistically significant but also practical for describing and predicting relationships in the analyzed dataset.

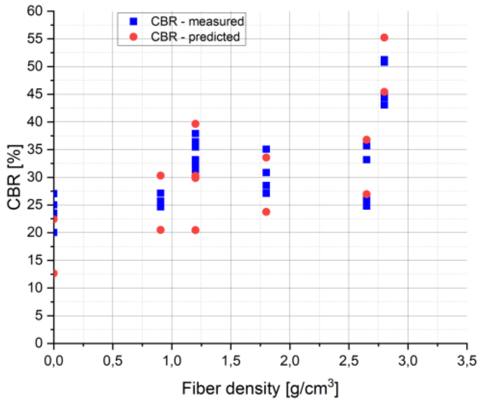

Fig. 13. CBR index values measured and predicted as a function of fiber density

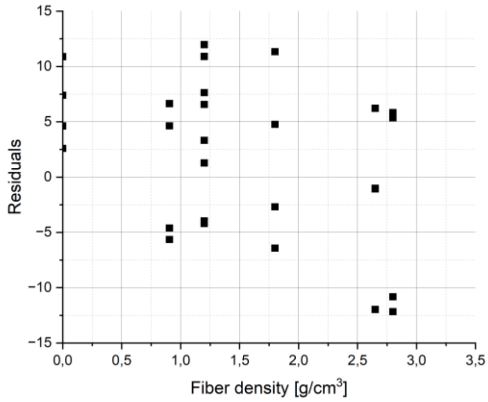

Fig. 14. Residual distribution as a function of fiber density

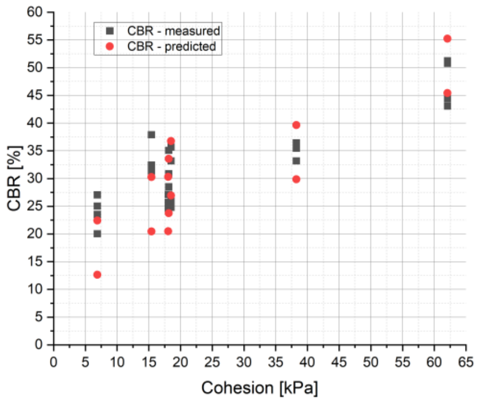

Fig. 15. CBR index values measured and predicted as a function of cohesion

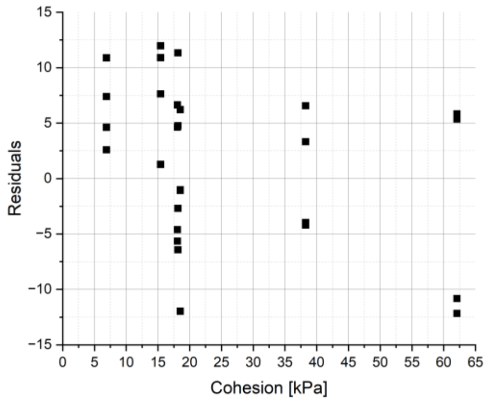

Fig. 16. Residual distribution as a function of cohesion

6. SUMMARY

This study investigates the impact of dispersed fiber additives on the load-bearing properties of sandstone aggregate mixtures, commonly used in road construction. A variety of fibers, including natural (coconut, hemp, basalt) and synthetic (carbon, glass, polypropylene), were
tested to assess their effects on the California Bearing Ratio (CBR) and shear strength of the mixtures.

The findings show that incorporating fibers significantly improves certain mechanical properties of the aggregates. Among the fibers tested, basalt exhibited the most substantial improvement in CBR values, particularly at lower penetration depths, making it highly effective in enhancing load-bearing capacity. Coconut and carbon fibers provided moderate improvements, presenting cost-effective alternatives for road construction projects, while glass and polypropylene fibers had a marginal or mixed effect on performance.

The addition of fibers generally increased cohesion, a key parameter for stability, although it often reduced the internal friction angle of the mixtures. The regression analysis highlighted the significance of penetration depth, fiber density, and cohesion as predictors of CBR values, with an R^2 value of 95.3%, indicating strong model accuracy and reliability in predicting the relationship between these variables.
From a practical standpoint, the research emphasizes that basalt fibers are particularly suitable for applications requiring high cohesion and enhanced load-bearing properties. Coconut and carbon fibers offer viable, eco-friendly alternatives for projects with moderate performance requirements. The use of natural fibers like coconut and hemp aligns with sustainable construction practices due to their biodegradability and environmental benefits, while basalt fibers contribute to ecological goals through their energy-efficient production processes. Although glass and polypropylene fibers showed lower impacts on CBR, they remain relevant for applications focused on resistance to chemical and environmental factors.

Overall, incorporating dispersed fibers into aggregate mixtures provides significant benefits in terms of subbase stability, crack prevention, and resistance to dynamic loads. These improvements contribute to the development of durable, flexible, and environmentally conscious road infrastructure, paving the way for more efficient and sustainable construction practices. This study lays a strong foundation for the wider adoption of fiber additives in geotechnical engineering, offering valuable insights for optimizing material performance in road construction.

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