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Influence of Cement Amount and Rubber Threads on Fatigue of Cement Bound base Course

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Evaluation of cement-stabilized material for use as a pavement bearing course (CBC) is primarily conducted through testing its compressive strength. However, the pavement structure is exposed to cyclic loading induced by traffic, making it susceptible to material fatigue. CBC, as the stiffest course of the pavement structure, is particularly sensitive to the effects of fatigue. Fatigue testing for this material is unconventional and not standardized, and the testing of this property is challenging due to the brittle structure of CBC. Within this study, the fatigue sensitivity of CBC was examined using a test standard designed for the evaluation of asphalt materials, as both materials are subjected to the same type of loading. Three mixtures of CBC with varying cement content and two quantities of waste rubber threads were investigated. Generally, fibers are incorporated into cement composites to enhance strength and serve as micro-reinforcement, while the use of rubber threads aims to increase the mixture's resistance to traffic loading. In addition to fatigue sensitivity, the mechanical characteristics and interdependence of individual parameters of these mixtures were determined. Apart from utilizing rubber as recycled material to enhance mixture resistance, this study emphasizes the necessity of conducting additional tests to ensure the quality of cement-stabilized aggregate mixtures for use in pavement base layers.

Keywords: *cement stabilized base course, dynamic load, critical stress, rubber threads*

Introduction

Load-bearing capacity of high-volume roads is usually ensured by the incorporation of cement-stabilized base course (CBC) as a bearing course in the pavement structure. The conditions of compressive strength are prescribed by normative documents as an assessment of the quality of the CBC. The pavement structures are subjected to cycling loading, which, due to a large number of repetitions, can lead to the formation of fractures in the CBC (Zvonarić & Dimter 2022). The fracture mechanism occurs due to induction of tensile stresses within this layer. Since the fractures do not occur due to compressive stresses, it is necessary to evaluate the quality of the CBC through other mechanical properties. Furthermore, the properties of materials exposed to the cycling loading are examined using static methods for testing mechanical properties. These findings indicate the need to consider other methods that focus on properties relevant to the fracture mechanism, which are tensile stress and cyclic testing.

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In addition to a more accurate assessment of the quality of the CBC through conducting tests on various mechanical properties of this material, the service life of the CBC can also be influenced by using materials that will positively affect the tensile strength of this mixture. Certain potential for a positive effect on the tensile strength of the CBC mixtures lies in rubber threads. It is known that waste materials in the form of fibers are used as micro-reinforcement in composite materials. The rubber threads, besides their elongated form, also possess elastic properties that could inhibit the absorbed load causing the tensile stress. With that in mind, aim of this research was to gain more knowledge on CBC behavior when subjected to cyclic load. Scope of this research was to upgrade existing knowledge on rubberized CBC and to upgrade existing testing procedures for fatigue behavior of CBC layers.

Literature Review

Problems of environment preservation and reuse and recycling of waste materials that would otherwise be landfilled has been at the forefront of scientific research for the last few decades but even more in this day and age. One of the currently existing problems is finding ways to reuse and recycle end of life tires, as it is estimated that annual influx of those tires is around one billion, out of which only roughly 50% are currently recycled (Azunna et al. 2024, Rigotti & Dorigato 2022). Main problems of their landfilling are that they are not biodegradable, can leach toxic chemicals into environment, are flammable and can cause great fires and also are a breeding ground for mosquitos and different vermin (Mohajerani et al. 2022, Rigotti & Dorigato 2022). Due to increasing stockpiling of end of life tyres, solution for its recycling and reuse trough construction industry is being increasingly considered and researched (Rigotti & Dorigato 2022). Majority of research on this issue deals with application of crumb rubber of different particle sizes as possible alternative aggregate in concrete industry (Bušić et al. 2018, Jalal et al. 2019). Furthermore, recent research also deals with application of crumb rubber in asphalt mixtures, as road construction is part of the construction industry that uses largest volume of natural resources. Research on the reuse of waste tires in lower pavement courses, of larger thickness, such as cement bound courses (CBC) is still quite sparse and mostly done determining only mechanical properties under static loading (Farhan et al. 2020, Farhan et al. 2016b, Sun et al. 2020, Zvonarić et al. 2021, Zvonarić et al. 2022). Effect of repeated cyclic loading that would better simulate traffic loads experienced by pavements, as well as usage of rubber threads instead of crumb rubber is yet to be determined.

It has previously been shown that application of crumb rubber effects various CBC properties, starting even with its compaction properties (Zvonarić et al. 2021). Addition of rubber in CBC results with lower optimal moisture content (OMC) and maximum dry density (MDD) during compaction due to its hydrophobic nature, rough surface, low density and ability to absorb some of compaction energy (Zvonarić et al. 2021, Zvonarić et al. 2022). Furthermore, waster rubber has a substantial effect on the mechanical properties of CBC mixtures as shown by Farhan et al. (2020), Farhan et al. (2016a), Farhan et al. (2016b), Farhan et al. (2018), Zvonarić et al. (2024). In few researches, Farhan et al. (2020, 2016b, 2016a), and Farhan et al. (2015) found that addition of crumb rubber in CBC resulted in reduction of such mechanical properties as unconfined compressive strength (UCS), indirect tensile strength (ITS), flexural strength, static and dynamic modulus of elasticity. However, according to the same group of authors, addition of crumb rubber simultaneously caused improvement in energy absorption capacity of such mixtures or its toughness. Similar results on effect of crumb rubber in CBC in terms of UCS, ITS and elastic moduli were also found by other authors (Barišić et al. 2021, Zvonarić et al. 2021, Zvonarić et al. 2021, Zvonarić et al. 2024). The reason for this decline in mechanical properties is mostly found in lower stiffness of rubber particle that act as a void in stiff cement matrix and worse adherence of cement paste to rubber particle than to natural aggregate. However, most of these researches were done with crumb rubber, with similar aggregate shape as natural aggregate, just rougher surface. Incorporation of rubber threads, that by its elongated particle shape should act as micro-reinforcement of cement bound materials, is not yet researched enough, especially when repeated dynamic loads are considered.

Behavior of road materials under repeated loading and its fatigue life is one of the most important indexes of road durability. Simple static test that are prescribed by norms and different highway agencies are not sufficient to determine this behavior, especially when new (i.e., less known) and alternative materials are incorporated into mixtures for different road courses. This is especially the case for cement stabilized courses as they are prone to fatigue cracking under repeated traffic loading that is far lower than it tensile strength (Lv et al. 2019a, Lv et al. 2021). However, repetition of low tensile stresses and strains that occur in the lower zone of such course, due to traffic load bending transferred from asphalt layers, can lead to loss of bond between aggregate and low amounts of binder and microcrack formation. And again, with repeated loading this microcracks will expand and lead to fatigue cracking of such pavement layer (Lv et al. 2019).

Therefore, it is necessary to determine how CBC material composition and content of different less known alternative materials, such as waste rubber particles, affects the behavior under repeated loading, mainly fatigue performance of the mixture. However, that is not an easy task as those kinds of testing take long time, require complex experiment settings, have many influencing factors which results with problems in efficiency and quality of the test and therefore high data deviation (Tang et al. 2020, Zhao et al. 2021). When CBC is concerned there is no prescribed unified testing method for determining fatigue of these mixtures. The resistance of material under cyclic load is often evaluated as number of loads repetition applied until failure under fatigue occurs (Pacheco-Torres et al. 2018). Non-uniformity between the specimen shapes and sizes, testing setup and means of inducing the cyclic loads are the cause of large discreetness of fatigue test results. The fatigue testing itself can be done through repeated compression, tensile or bending test, triaxial tension and compression test, while loads itself can be applied as uniaxial loads, radial loads, or two, three or four point bending loads (Lv et al. 2021). Most commonly cylindrical samples are used with testing setup for indirect tensile strength or beam samples in testing mode through flexural bending, while also semi-cylindrical specimens were used in available literature (Dong et al. 2021, Lv et al.

2019, Zhao et al. 2021). Also, different frequency of applying cyclic stress on samples can be found, but most often a frequency of 10 Hz is used as it corresponds to driving speed of 60 to 80km/h (Dong et al. 2021, Tang et al. 2020, Zhang et al. 2022). There is also a question of specimen curing time, testing temperatures, loading rate, stress levels that are being applied and mode i.e. in compression, tension or both, as it was shown that all of this factors affect the achieved results (Lv et al. 8AD, Tang et al. 2020, Zhao et al. 2021). However, some researchers have developed fatigue models of cement bound courses according to the results of UCS, ITS and flexural tensile test for various specimen age and cement content (Xie et al. 2018) or according to the different stress ratios and loading modes (Lv et al. 2019). But these models have been developed for specific mixtures, not including different potential alternative materials that can be used in CBC and that can greatly affect the behavior of such mixtures under repeated loading. For instance, Ma et al. (2015) found that fatigue life of cement stabilized aggregate can be greatly improved (up to 4.2 times) with the addition of polypropylene filament fibers as reinforcement.

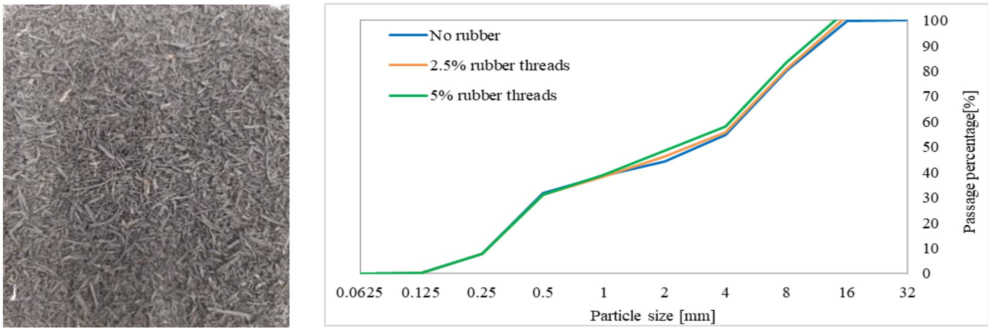
In general, application of waste rubber, particularly in form of rubber threads, has not been well researched, even more so when its effect on durability under repeated loading or mixtures fatigue life is concerned. In rare papers where both rubber (but in crumb form) and cyclic testing were used (Farhan et al. 2020), it was shown that crumb rubber increased fatigue life in flexural testing, especially in lower stress ratios, due to increase in toughness of such mixtures. The effect of adding rubber crumbs to more rigid material was more evaluated for concrete mixtures. Authors Pacheco-Torres et al. (Pacheco-Torres et al. 2018) report through own work and literature review, that addition of rubber to concrete mixtures can have beneficial effect on fatigue life compared to reference mixtures. According to them rubber particles increase flexibility of concrete and also delay fragile rupture by absorbing part of energy, due to which additional energy is needed to break the specimen (Pacheco-Torres et al. 2018). But they also emphasize the lack of standard test for determining fatigue of materials to be used in pavements, and therefore used its own testing method on prismatic beams.

Due to the noticeable absence of appropriate and applicable method or norm for fatigue testing of CBC and knowledge on its performance when rubber threads are incorporated in the mixture this preliminary research was carried out. For testing methodology and sample size was used as it prescribed in norm for cyclic testing of asphalt sample, as both materials when applied as pavement courses are subjected to the same traffic loads. Additionally, results of this test are compared and correlated with more common mechanical properties determined on same mixtures in order to determine which of these mechanical properties have the greatest effect on durability of such material when installed as pavement course and subjected to traffic loads.

Materials and Methods

Cement stabilized base course (CBC) mixtures in this paper are composed of three fractions of natural river gravel (0-4, 4-8 and 8-16 mm), and natural river sand (0-2 mm). The used materials originate from local rivers, Sava and Drava, respectively. Three mixtures comprise of 3%, 5% and 7% Portland cement of grade 32.5R (CEM II B/M (P-S)). These three mixtures are assumed as reference mixtures and labeled as C3R0, C5R0, and C7R0. Additional two mixtures are composed with 2.5% and 5% of rubber threads (Figure 1a) as volume addition to the reference mixture aggregate composition. Their labels are C7R2.5 and C7R5. The size of used rubber threads is 0.8-3 mm and they originate from car and truck waste tyres. The used rubber threads can be found on Croatian market, which is regulated through the tax policy of the country (Association 2015) under which it is assumed that during the purchase of tires, customers pay a fee for their disposal, from which the country funds the collection of those tires. Economic entities registered for the tire collection gather car and truck tires and mechanically process them. Thus, only mixed car and truck tires are available on the Croatian market. Due to the use of alternative materials, the particle size distribution curve is created as type 4 curve described by standard 14227-1 (European commitee for standardization 2013), according to which the manufacturer defines the particle size distribution of the curve themselves. The granulometric distribution of the used mixtures, both reference and those using rubber threads is presented in Figure 1b.

Figure 1. *a) Rubber Threads 0.8-3 mm; b) Granulometric Composition of Tested Mixtures*



a) b)

As can be seen from the Figure 1, the granulometric curves of all mixtures are very similar which was the goal to make the mixtures comparable. Also, one can notice that the curves overlap in the very fine fraction range, while only minor differences occur at fractions of 1 mm and above, indicating that the tyre declaration (0.8-3 mm) correspond to the actual fraction size.

Proctor elements, optimal moisture content (OMC) and maximum dry density (MDD), are determined for each of 5 mixtures according to standard EN 13286-4 (European commitee for standardization 2021a). For Proctor elements determination, a vibrating hammer method was used, as it better corresponds to in-situ vibration compaction of this material than common Proctor test by hammer (Zvonarić et al. 2021). Proctor mould B (Φ=150 mm, h=120 mm) was used for this procedure. The material was compacted in lubricated mould with vibrating hammer in three equal layers, 60 s per layer, corresponding to compaction energy of modified Proctor. Specimens were prepared at 5 different moisture contents, and from the results, the OMC and MDD were calculated.

Prior to production and testing of samples under cyclic loads, an extensive testing of mechanical properties under static loads was carried out. Majority of this results was already reported in other papers (Zvonarić et al. 2021, Zvonarić et al. 2024), however as those results are used in this research for comparison and correlation to the here measured properties under cyclic loading, the sample preparation, curing and testing methodology is also explained. For this purpose, also the main results of this test will be shown and briefly explained.

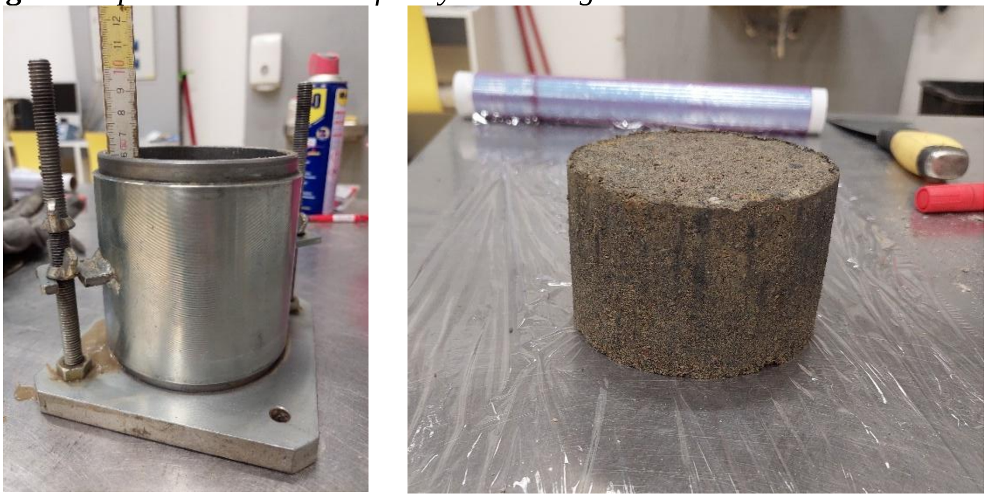
Proctor specimens in mould A (Φ=100 mm, h=120 mm) are compacted by the same procedure, extruded from the moulds, protected by cling film and put into climatic chamber at temperature of 20°C and 90% relative humidity. Six specimens of each mixture were prepared. Dynamic modulus of elasticity and compressive strength were tested on three specimens of each mixture, along with static modulus of elasticity in compression test. The remaining three specimens were utilized for indirect tensile strength testing. For dynamic modulus of elasticity determination, a ultrasonic pulse velocity method was used (CEN/ TC104 2004) which is commonly used in concrete testing, but this method is, also, relevant for testing cement-stabilized base course (Barišić et al. 2011, Marques et al. 2020). For compressive strength determination, a procedure prescribed in standard EN 13286-41 (European commitee for standardization 2021b) was used. The procedure involves applying vertical force on the upper basis of the specimen in a uniform manner in order to cause rupture between 30th and 120th second from the commencement of load. The static modulus of elasticity was determined by non-contact method using 3D digital image correlation. This test was conducted during the compressive strength test. The procedure required preparing specimens by coloring them white with contrasting black dots of appropriate size so that the charge-coupled device cameras could recognize these dots and track their displacement during the application of the load. From the obtained displacements and applied load, the static modulus of elasticity was calculated according to EN 13286-43 (Cen 2003). Also, the indirect tensile strength was tested according to procedure prescribed in standard EN 13286-42 (European commitee for standardization 2021c). The load was applied to the derivatives of the laid cylindrical specimen through wooden slats of prescribed dimensions. The rate of load application was 0.2 MPa/s. The used test procedures are presented in Figure 2.

Figure 2. *Test Procedures of: a) Compressive Strength; b) Dynamic Modulus of Elasticity; c) Static Modulus of Elasticity; d) Indirect Tensile Strength*

	
a)	b)
	
c)	d)

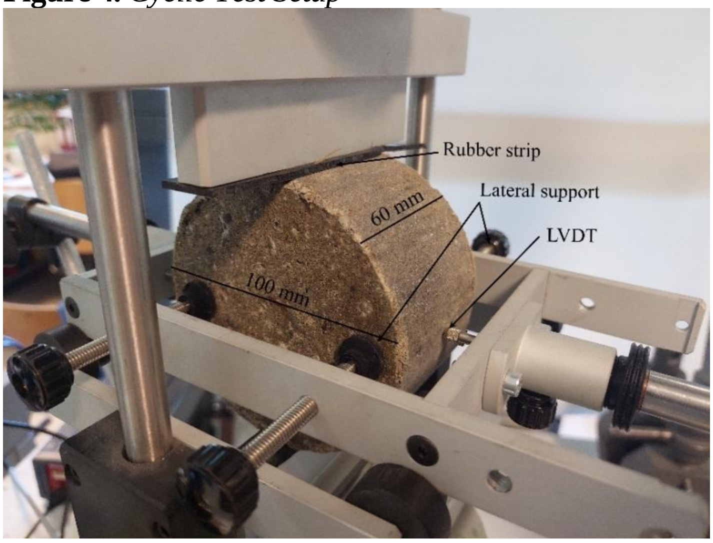
Besides standard test procedures shown, the main purpose of this research was to test impact of cyclic load to cement stabilized mixture. In the absence of methods for testing the resistance of CBC to cyclic loading, as already analyzed in the literature review, this study employed the fatigue testing method for asphalt materials EN 12697-26 (*EN 12697-26 Bituminous mixtures - Test methods - Part 26: Stiffness* 2022). However, fatigue was not determined on the tested mixtures, rather, only the methodology of this procedure was used to analyze the displacement and deformations of the tested specimens exposed to cyclic loading. This represents preliminary testing of CBC to cyclic loading. Despite differences between asphalt and cement-stabilized materials, primarily in their stiffness, both materials are subjected to the same type of loading in pavement structure. For the purposes of this study, cylindrical specimens of cement stabilization with dimensions Φ=100 mm and h=60 mm were prepared. These specimens were compacted using a vibrating hammer in a Proctor mould A, and considering the non-standard specimen dimension, their density was controlled during production. The specimens were compacted in one layer, for 60 s. Three specimens of each mixtures were prepared, wrapped into cling film in order to prevent moisture loss and put in climatic chamber in controlled environment of 20°C and 90% relative humidity for 28 days. These specimens are dimensionally aligned to Marshall specimens to fit into the standardized testing procedure. The control of specimen height and compacted specimen is presented in Figure 3.

Figure 3. *Specimen Production for Cyclic Testing*



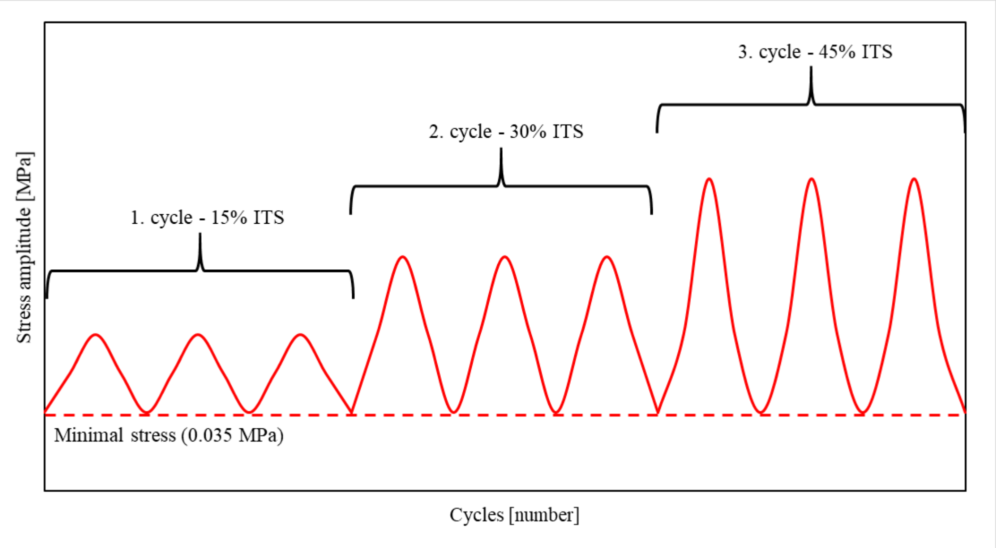
After the completion of curing regime, the specimens were subjected to sinusoidal compressive load through the diametrical vertical plane thus inducing uniform tensile stress perpendicular to the load direction. The specimens were secured within a suitable aluminum frame that held the specimens at its basis. On the bottom and upper specimen derivative, the rubber strip was placed to dampen the commencement of the load and prevent rupture due to shock. The frame with the specimen was put in dynamic compression machine. According to the standard EN 12697-26 (*EN 12697-26 Bituminous mixtures - Test methods - Part 26: Stiffness* 2022) a horizontal displacement should be measured using two linear variable differential transducers to calculate fatigue. But conducted procedure resulted with displacement of the devices which obtained unreliable results. The test setup is presented in Figure 4.

Figure 4. *Cyclic Test Setup*



In this test procedure a minimum stress level required to initiate testing and the testing amplitude are specified. The minimum stress is determined by the standard (*EN 12697-26 Bituminous mixtures - Test methods - Part 26: Stiffness* 2022) and is set at 0.0035 MPa. The loading amplitude is varied to induce the targeted stress levels in the specimens. The specimens are subjected to cyclic loading in cycles of 2500 loading and unloading repetitions. The targeted stress values were set at 15%, 30%, 45%, 60%, 75% and 90% of the indirect tensile strength of each mixture. The amplitude is the difference between the targeted stress level and the minimum stress initially applied to the specimens. The testing scheme is presented in Figure 5. The load was applied in frequency of 10 Hz which corresponds to a driving speed of a vehicle of 60-80 km/h (Dong et al. 2021, Lv et al. 2019b).

Figure 5. *Cycling Testing Scheme*



The testing resulted with values for vertical displacement at the end of each cycle. Furthermore, the critical stress at which failure occurred was analyzed, and these values were compared with other mechanical properties of the tested mixtures.

Results and Discussion

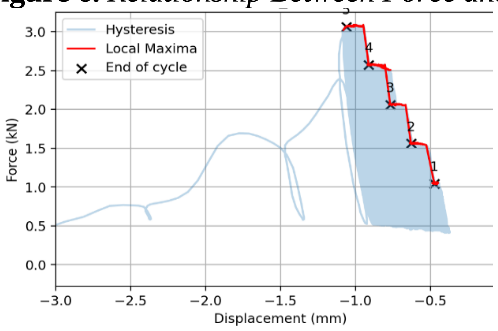
Results of compressive strength (f_c), indirect tensile strength (ITS), dynamic modulus of elasticity (E_{dyn}), and static modulus of elasticity (E_{st}) obtained by conducting standard tests are presented in Table 1. The obtained values represent average values from three tested specimens of each mixture. According to the standard EN 13285 (European commitee for standardization 2018), values that deviate more than 20% from others are neglected.

Table 1. *Mechanical Properties of Tested Mixtures*

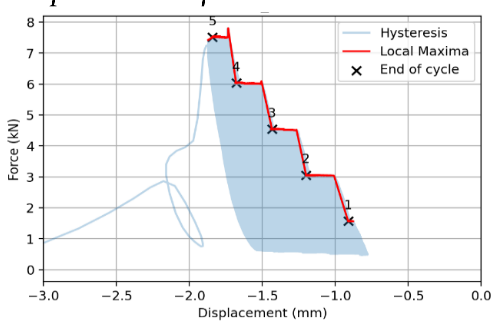
Mixture	f_c [MPa]	ITS [MPa]	E_{dyn} [GPa]	E_{st} [GPa]
C3R0	2.6878	0.3573	15.6401	3.463
C5R0	6.4537	1.0477	27.0463	10.028
C7R0	8.8892	1.7687	31.3303	11.960
C7R2.5	5.3142	1.5205	17.8167	5.369
C7R5	2.7614	0.7416	6.9877	2.254

From Table 1 a positive effect of increase in cement content on all tested properties can be seen. Also, by incorporation of rubber threads into mixture with 7% cement, an obvious decrease in all properties occurs. These results meet the expectations, and are not to be analyzed in detail in this paper. Given that the tests of the standard mechanical properties of cement-stabilized materials were conducted to establish the relationship between the results of cyclic testing and the mechanical properties of the materials, the results of the cyclic tests will be analyzed in more detail. Finally, the determination of the relationships between these variables will follow. At the end of each loading cycle, vertical deformation was analyzed through vertical displacement of the testing machine jaw. For processing such a lot of data, Phyton software was used. The relationship between applied force and obtained displacement is shown in Figure 6 for each of tested mixtures. Figure 6 presents the most representative of three specimens for each mixture. As the end of each cycle, a jump in force input was considered and marked with a cross and a number of cycle in graph. Upon occurrence of the rupture, the specimen underwent crushing, which is evident from the sudden increase in displacement.

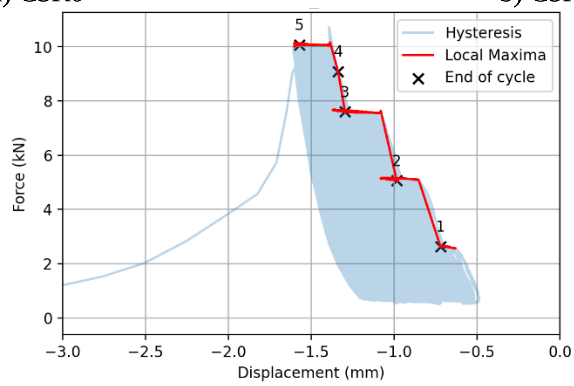
Figure 6. *Relationship Between Force and Displacement of Tested Mixtures*



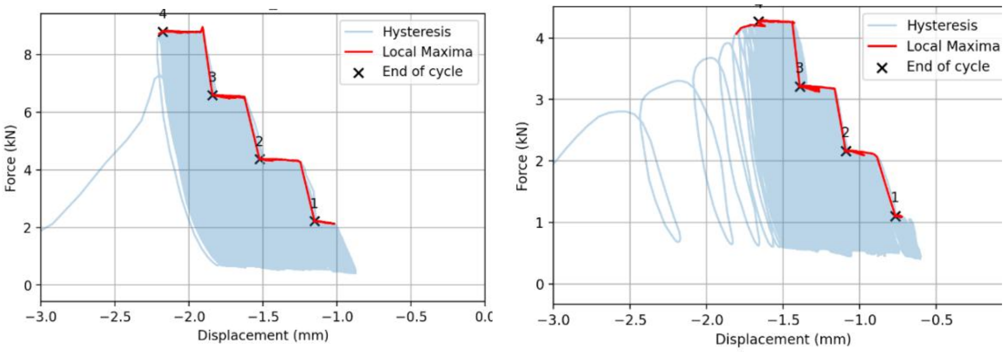
a) C3R0



b) C5R0



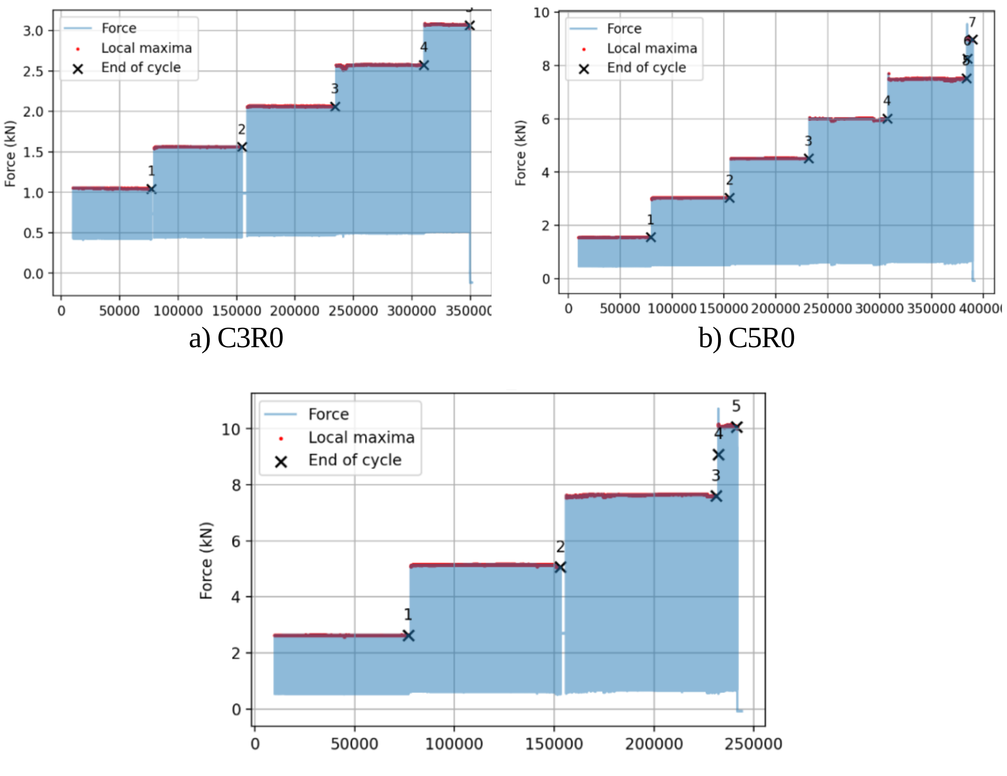
c) C7R0



d) C7R2.5 e) C7R5

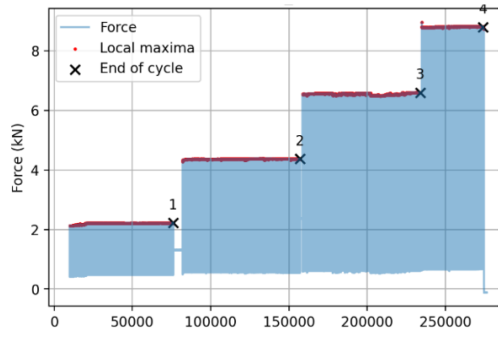
As can be seen from Figure 6, the obtained displacements are up to 2 mm, which makes up to 2% relative deformation of the specimen. It can also be observed that during the entire cycle, the deformation values remained approximately the same, and only with the increase in force input did the deformation increase, which is evident from the slope of the graph at the point of force increase.

Figure 7. *Relationship Between Force and Cycle Number*

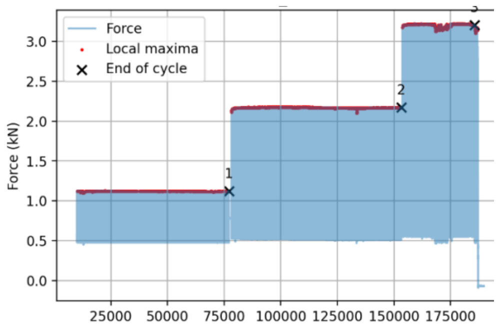


a) C3R0 b) C5R0

c) C7R0



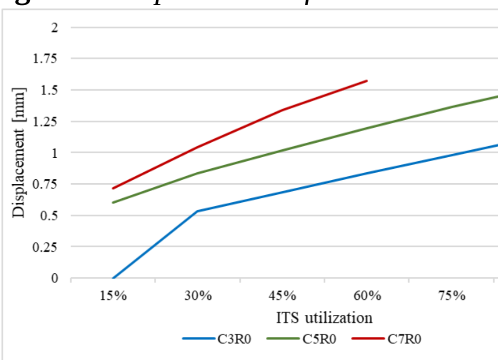
d) C7R2.5



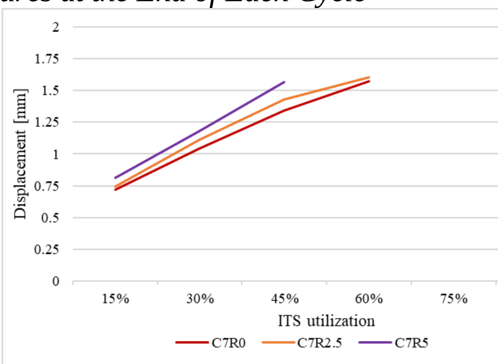
e) C7R2.5

Graphs show the movement of the force during the test. From these displays, it can be concluded that during the entire cycle, the load input is uniform, while the beginning of a new cycle is visible. At the end of each cycle, the last force before the force jump is considered, and it corresponds to the position of the deformation jump shown in Figure 6 So, it can be said that the use method succeeded in simulating uniform loading and unloading cycles. The obtained deformations at the end of each cycle is graphically presented and the results are compared in Figure 8a for reference mixtures and b for mixtures with rubber threads.

Figure 8. *Displacement of the Tested Mixtures at the End of Each Cycle*



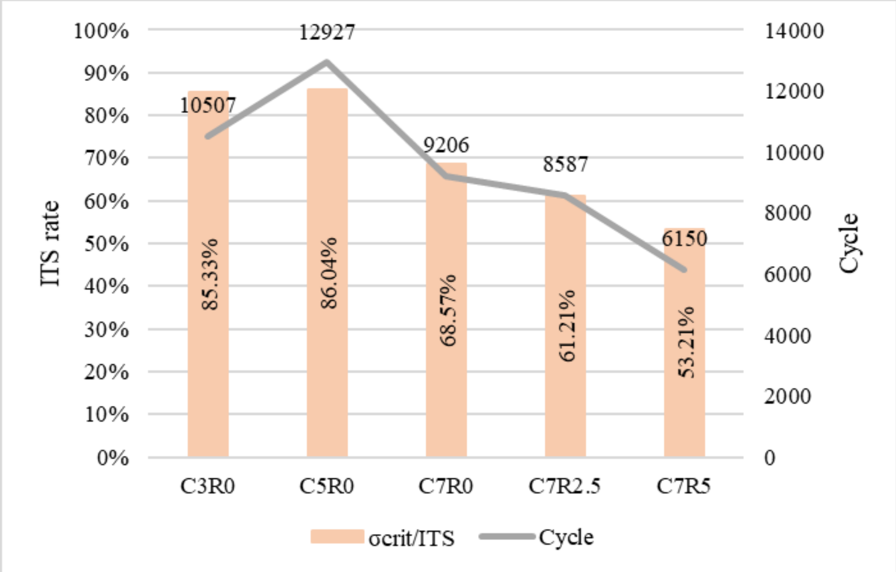
a) reference mixtures



b) mixtures with rubber threads

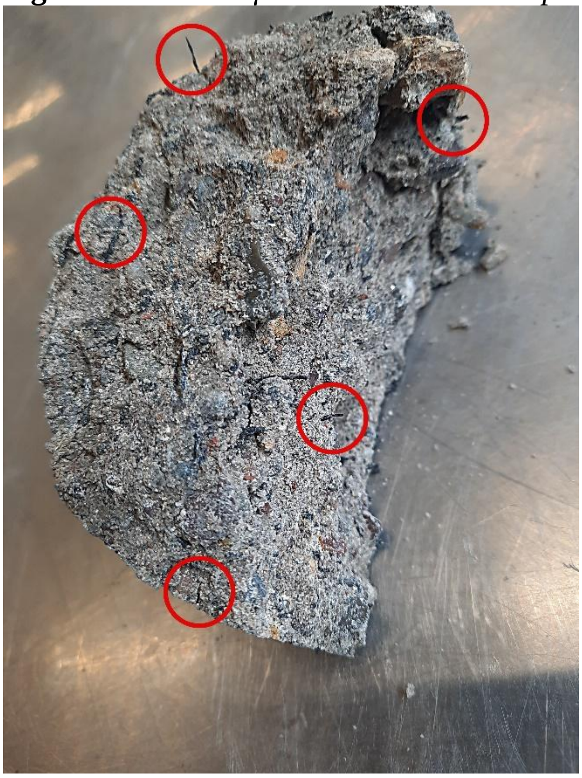
Observing displacements of reference mixtures, it can be concluded that increase in cement content brought a decrease in resistance to cyclic loading. Namely, mixtures with 3% and 5% cement failed at stress in amount of 90% of their respective tensile strengths, while mixture with 7% cement failed at stress which corresponds to 60% rate of their respective tensile strength. The obtained displacement values at failure are within 0.5 mm (0.5% relative deformation) for mixtures with different amounts of cement, which is a very small difference. This indicates that, in addition to cement, the aggregate also has a significant impact on the behavior of the material under repetitive loading. Higher cement amount resulted with stiffer mixture, and, as expected, stiffer mixture shows lower resistance to cyclic loading. Based on this presumption, rubber threads were added to the mixtures to increase resistance to cyclic loading. Considering rubber's decreasing effect on mixture's strength (Farhan et al. 2016a, Zvonarić et al. 2021), the rubber threads were added to the mixture with the highest cement amount. From Figure 7b one can see that increase in rubber threads slightly increase displacement at the end of each cycle. But these mixtures did not withstand higher rate of tensile strength than the reference mixture with 7% cement. The reference mixture and the mixture with 2.5% rubber threads failed in the 4th loading cycle at 60% tensile strength rate, while the mixture with 5% rubber threads failed earlier, at 45% tensile strength. Therefore, the addition of rubber threads did not result in a longer lifespan of the produced mixtures, nor in higher achieved displacements. The rate of ITS in the moment of specimen failure is presented in Figure 8. The rate of the ITS on the graph does not fully correspond to the target rate in the load cycle. It can be seen that the reference mixtures with 3%, 5% and 7% cement ruptured at ITS rate of 85.33%, 86.04% and 68.57%, respectively. While mixtures with 2.5% and 5% rubber ruptured at 61.21% and 53.21% ITS rate, respectively. This is the result of several factors, the first factor is the accuracy of the testing device, the second factor is the rubber band placed on the contact between the device and the sample which inevitably inhibited part of the load, while the third factor is the fact that the displayed result is the mean value of three tested specimens that differ from each other by more than 20%. The reference mixtures have highest ITS rate comparing to with rubberized mixtures. Which means that those mixtures are more resistant to cyclic loading. Cement amount of 7% brought a decrease in ITS rate. Obviously, this mixture is too stiff for such a loading. The compressive strength results from Table 1. show that the C7R0 mixture has a compressive strength of 8.89 MPa, which makes the mixture unsuitable for this application according to limitations given in Croatian guidelines for road construction (Đukan & Tomljanović 2001). Acceptable mixtures for installation develop strengths between 3 and 6 MPa. In addition, the modulus of elasticity of this mixture is very high, characterizing rigid mixture, and it is to be expected that for such mixtures are the hardest to resist cyclic loading. When observing the cycle number at the failure point, the C5R0 mixture ruptured at 12927th cycle, while C3R0 mixture ruptured at 10507th cycle. But, the rate of ITS is almost the same for those mixtures. On the other hand, C7R0 mixture ruptured at 9206th cycle, but at lower rate of ITS (68.57%) which is a result of very high tensile strength. According to the obtained results, the trend of critical stress follows the trend of cycles to failure. Furthermore, the C5R0 mixture proved to be the most durable.

Figure 8. *Rate of ITS and Cycle at Failure Point*



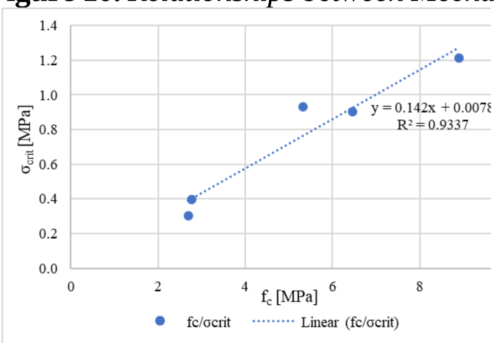
Rubber threads were added to increase resistance to cyclic loading, but the results show that this did not occur. It was expected that the elongated rubber particles would take over the load and reduce the tensile stresses in the material itself following the pattern of different fibers in other materials (Hamood Al-Masoodi et al. 2016, Lin et al. 2020). The addition of rubber greatly reduced the tensile strength, resulting in a very weak mixture. The size of these threads could be a key factor that leads to a reduction in mechanical properties of the mixtures. Namely, due to their size, the rubber threads disrupt the aggregate skelet within the mixture and represent a potential place for the development of cracks. On the other hand, the cement paste does not bond well with the rubber surface as can be seen in Figure 9. As noted by Pacheco-Torres et al. (2018) for concrete application, the addition of rubber presents a inclusion of flexible material into more rigid mixture due to differences in its elastic modulus, thus altering its performance and properties. And according to them, increase of rubber particle size leads to earlier failure of material and is a big factor in fatigue performance of concrete, due to weakening of interphase between two materials of hugely different elasticity modulus. In concrete, this is also reported by authors Srivastava et al. (2020) who represent an exception in available literature as they also used rubber threads. They recorded the reduction of both compressive and tensile strength when rubber fibers were used in modification of concrete of strength of grade M40 (40 MPa). However, according to same authors solution for this problem should be searched in different rubber pretreatment to insure better bonding with cement, as it has been shown that rubber can contribute to some improved properties of stiffer cement matrixes as higher ductility, better performance at high strain level (Azunna et al. 2024, Saloni et al. 2021, Zhao et al. 2023). But this pretreatment increase cost and it is questionable when large scale application in pavement is concerned (Pacheco-Torres et al. 2018), and therefore are problems for future research.

Figure 9. *Position of Rubber Threads in Ruptured Specimen*

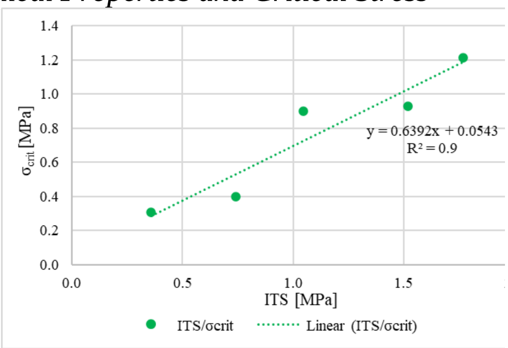


As already mentioned in the introductory part, usually the quality of CBC is evaluated by classic static tests. Therefore, in the continuation of this research, the connection between determined mechanical properties and the critical stress at failure was determined. Figure 10 presents relationship between each of compressive strength, indirect tensile strength, dynamic modulus of elasticity, and static modulus of elasticity and the corresponding critical stress for five tested mixtures.

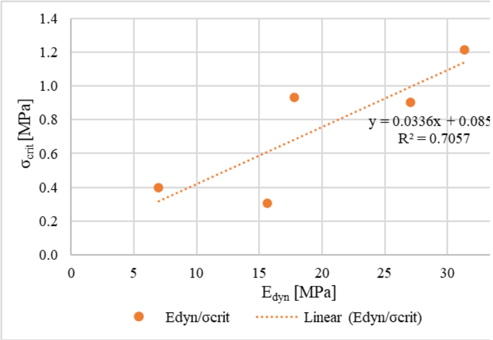
Figure 10. *Relationships between Mechanical Properties and Critical Stress*



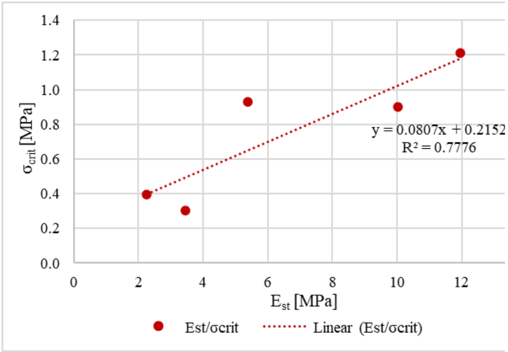
a) f_c-σ_{crit} relationship



b) ITS-σ_{crit} relationship



c) E_{dyn}-σ_{crit} relationship



d) E_{st}-σ_{crit} relationship

From the shown graphs, it can be concluded that all established relationships are strong and represent reliable results. The relationship between compressive strength and critical stress along with indirect tensile strength-critical stress relationship have a very high coefficient of determination and these two relations are equally reliable. Thus, both material strengths are equally related to resistance to the cyclic loading. On the other hand, there is weaker relationship between two types of elasticity moduli and a critical stress. The elasticity of a material is characterized by its ability to undergo deformation and return to its original shape when subjected to a load. However, the primary reason for the lower correlation of elasticity moduli and critical stress is testing method, which involves inducing tensile stresses in the specimens that correspond to the tensile strength of each mixture. In conclusion, the relationship might appear if all mixtures were subjected to the same level of stress that would be relevant for the use of material in pavement structures.

Conclusions

This research encompasses the dynamic testing of various cement-stabilized pavement base course mixtures subjected to cyclic loading. Additionally, the mechanical properties of this material were examined to identify the most influential factors on resistance to cyclic loading. The impact of rubber fibers on the behavior of mixtures under cyclic loading was also investigated. Based on the conducted research, the following conclusions can be drawn:

- The addition of rubber fibers significantly impacted the reduction of the mechanical properties of the mixtures.
- The established testing method ensured uniform stresses within the cycles.
- The addition of rubber fibers did not result with extended lifespan of tested specimens.
- The trend of critical stress follows the trend of the cycle number at which rupture occurred.
- The critical stress shows a stronger correlation with compressive and tensile strength than with elastic moduli.

For further research, it is recommended to determine stress levels over several cycles that would be relevant for each road category. All test mixtures should be subjected to the same stress levels.

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