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ZEOLITE WONDERS: DECODING UNIAXIAL STRESS-STRAIN DYNAMICS IN ENHANCED PAVEMENT STRUCTURES

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Abstract
Semi-flexible pavements (SFP) play a crucial role in modern transportation infrastructure, and their performance is heavily influenced by the proportion of cement mortar content filling the voids in the mixture. While higher grouted mortar content enhances the performance of SFP, there exists an optimal level beyond which further improvements are not significant. Repeated traffic loads exert stress and strain on the pavement structure around the wheel axis, leading to accelerated degradation with the emergence of cracks and permanent defects. Consequently, developing stress-strain models for SFP becomes imperative.
This study focuses on the stress-strain relationship of SFP containing waste tire rubber (WTR) and natural zeolite as cement replacements in the filling mortar. A stress-strain model under uniaxial compressive load is developed to understand the behavior of such mixtures. At lower compressive loads, the stress-strain response follows Hooke's Law, exhibiting a proportional relationship between stress and strain. Moreover, stress relaxation tends to decrease with an increasing number of passes, enabling the mixture to return to its original shape without deformation upon load removal. However, under maximum load (Pmax), the stress-strain curve depicts a mixed condition with full strength and stress, gradually decreasing until the test object is crushed. Additionally, the stress-strain relationship of the SFP mixture can be represented as an elastic, perfectly plastic (bilinear) behavior. The initial phase of this bilinear curve corresponds to linear elasticity, followed by a stage where small cracks develop, leading to a linear relationship again, albeit no longer elastic. The behavior of this mixed bilinear stress-strain relationship is illustrated in Figure 1.
Understanding the stress-strain behavior of SFP mixtures, especially those incorporating WTR and natural zeolite, is essential for designing durable and sustainable pavements. Such knowledge will aid in optimizing cement mortar content, ensuring maximum performance without excessive material usage. The findings from this study contribute to the advancement of semi-flexible pavement design and promote eco-friendly practices by utilizing waste materials as cement replacements.

Keywords: Semi-flexible pavement, stress-strain model, cement mortar content, waste tire rubber

1. Introduction

The characteristics of semi-flexible pavement (SFP) are strongly influenced by the percentage of cement mortar content filling the voids in the mixture [2]. The more grouted mortar content in the mix, the higher the performance of the PSF mixture, but at a certain level, the increase in performance is not significant [1]. Pavement behavior due to repeated traffic loads causes the pavement structure to experience stress and strain around the wheel axis, resulting in fast degradation of road performance marked by the emergence of cracks and permanent defects [3]. Therefore, it is necessary to develop the stress-strain models of SFP. As a first study on the stress–strain relationship of SFP containing waste tire rubber (WTR) and natural zeolite as cement replacement on filling mortar, in this study, a stress-strain model under uniaxial compressive load is developed [4].

At a lower compressive load, the stress-strain of the PSF mixture follows Hooke's Law, where stress is proportional to strain. Stress anxiety tends to decrease with an increasing number of passes [5]. In this condition, if the load is removed, the mixture will return to its original shape without deformation [6]. At maximum load ($P_{max,}$.), a mixed condition with full strength and stress, the curve decreases until the test object is crushed. In addition, the stress-strain relationship of the SFP mixture can also be in the form of an elastic, perfectly plastic (bilinear) [7]. The shape of this bilinear curve illustrates that the initial condition is linear elastic while the next. At the same time, due to the mixture having experienced small cracks, the stress-strain relationship tends to be linear again, even though it is no longer elastic [8]. The behavior of the mixed bilinear stress-strain relationship is mentioned mentioning Figure 1.

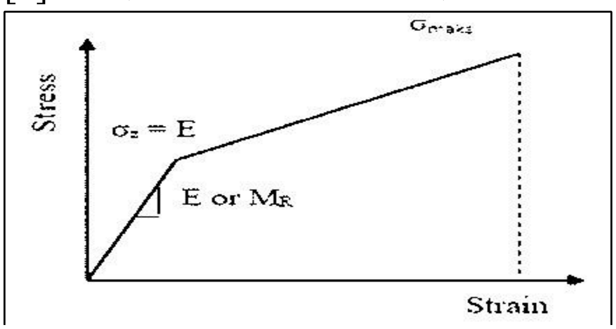

Fig 1. Typical SFP stress-strain curve

In the linear elastic area, the specimen only densifies due to loading. In that area, there has been no cracking, and the stress-strain relationship in this condition is still proportional, but in the second linear, the slope of the curve begins to decrease collapse [9].

2. Literature Review

Zeolites have been known for more than 200 years, but only recently, mid the 20th century, did they catch the attention of scientists and eng needs, which shows the importance of their technology in several fields. The history of zeolite began in 1976 when the Swedish mineralogist Cronstedt discovered the first mineral zeolite. He found zeolite as a mineral of aluminosilicate hydrated from alkaline and alkaline earth [10]. Zeolite is a crystalline aluminosilicate of group IA and IIA elements like sodium, potassium, magnesium, and calcium. In Türkiye, especially in the region**.** Middle Aegean contains many types of zeolites. In several sectors and industries, zeolite began to be used in the 90s in Türkiye [11]. In Plans five years of Development in the 2001 mining report, State Planning Organization (DPT) 13 stated the importance of zeolites.

Using zeolite as a feed additive is possible because of its open structure and ability to quickly detach water molecules and bind them back. Alternatively, it can be replaced with other liquid substances such as alcohol, ammonia, and so on [12]. Besides that characteristic, cations zeolite consists of alkalis that can be replaced with other alkalis. Second nature This allows zeolite to be used as a feed additive. Add minerals and reduce the smell of ammonia from feces [13]. There are two main strategies for nitrogen administration [14]. First, nonprotein nitrogen (NPN), e.g., urea, which produces ammonia, is expected to be utilized by rumen microbes to form microbial proteins, which will later be absorbed in the intestine and used for the production of meat, milk, or other ruminant livestock products. Second, the nitrogen from the material high-priced protein feed [15]. Protein from partial meals is degraded in the rumen resulting in increased ammonia production, and some pass into the intestine. Non-degradable protein feed inside the rumen will be absorbed in the intestine as amino acids [16].

Zeolite was first discovered in Sweden in 1756 by Axel Frederick Constant. The term zeolite comes from the word "zein" (Greek) [17]. Means foam, and "lithos" means stone. This name fits the character zeolite, which will foam when heated at 1000C. Mixed natural zeolite with other minerals such as feldspar, sodalite, nephelite, and leucite [18]. Estimated Natural zeolites are formed from volcanic lava that solidifies into volcanic rock, forming sedimentary and metamorphic rocks. These rocks then undergo a weathering process due to heat and cold influence, which eventually comprise the mineral zeolite.

3. Methods

The design of the specimens in this study was based on the optimum asphalt content (OAC) with Marshall testing based on ASTM C67091a. Based on the Marshall Value, the AAPA requirements (2004) value to obtain the required AOC is 3.5%. Based on the OAC value, the SFP mixture was designed for compressive testing with a specimen size of 102 mm in diameter and 64 mm in height. Compaction was carried out using a compactor of 6.4 ± 0.15 kg/cm2. The load is equivalent to a single axle load of 8.16 tons of double wheels (Japan Road Association, 1998). For compressive testing, the porous asphalt specimen was made with an asphalt content of OAC obtained previously, which was 3.5%. Hot asphalt was added with WTR powder as much as 3%, 4%, and 5% of the weight to obtain three different mixtures. The Aggregate that has been prepared is heated at a temperature of 170 °C. After the asphalt temperature reaches 160 °C, WTR grated according to the planned content is added to the hot asphalt, stirred evenly, and heating continues for 5 minutes. The heated aggregate is added to the asphalt mixture and stirred for about 15 minutes at a continuous temperature. The hot mix is put into a mold provided and solidified at 140 °C.

After the specimens have undergone sufficient drying process, the cement mortar is poured into the cavity of the porous asphalt specimens by placing the model into a container in the form of a 5-inch diameter pipe tube, and artillery that meets the fluidity specifications is poured into the box and then vibrated for 2 minutes to maximizing the cement mortar to fill the cavity and the specimen is removed for the maintenance and drying process for 14 days. The model is declared to be able to be tested.

The stress-strain was tested using a universal testing machine with Freesia Macross type test system HJ-15A which is capable of applying a load of 1000 kN; the compressive load received by the specimen is measured by a load cell and recorded automatically using a data logger along with axial deformation using three transducers mounted on the model. The test method is the same as the compression test, but during the loading process, the increase in load uses a load cell, while the shortening is observed with the specimen using 2 CDP-100 types of transducers. The strain is then calculated based on the average recorded value of the two transducers. In contrast to the compressive strength test, a compression test machine with a capacity of 1000 kN is used. The universal testing machine with Freesia Macross test system type HJ-15A is shown in figure 2.

Fig 2. Freesia Macross system testing machine HJ-15A type

4. Results and Discussion

4.1. Stress-strain Relationship

The stress-strain relationship of the SPF at 3%, 4%, and 5% WTR obtained from experimental results is the dot plot in **Figure 3-4**, respectively. Due to the use of load control based on the lack of control for deformation in the test equipment, only the stress-strain curve in the ascending branch area was successfully recorded. After the maximum load, the specimen was immediately destroyed without any record of the values from the descending site. Moreover, the shape of the curve for all the variations was discovered to be almost the same. At the beginning of the loading, until the stress reached 14% to 20% of the maximum pressure, the relationship was linearly elastic, after which the stiffness of the SFP decreased from the initial value. This shows a micro-crack started after the SFP was loaded up to 14% and 20% of the compressive strength. After this percentage was exceeded, the relationship was linear up to maximum stress, especially for 5% WTR and 15% zeolite, which has the highest compressive and flexural strengths [20]. This means there was no cracking during the loading process at 5% WTR and 15% zeolite until the maximum load was reached. The condition of the specimens before and after damage under full load is shown in **Figures 3** and **4**.

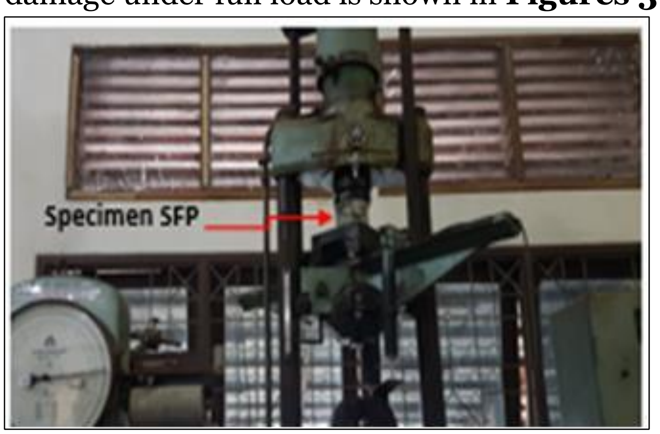

Fig 3. Specimen SFP before damage

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Fig 4. Specimen SFP after damage

The bilinear model developed in this study was based on the stress-strain relationship data obtained from the experiments. A simple bilinear model was proposed for the SFP in the ascending branch area where the initial part of the curve was linearly elastic while the next part experienced a microcrack. The proposed stress-strain relationship can be written as follows:

$\sigma = E_o \varepsilon$ for $0 \le \sigma \le \sigma_{cr}$ (1) $\sigma = \sigma_{cr} + E_c(\varepsilon - \varepsilon_{cr})$ for $\sigma_{cr} \le \sigma \le f'_c$ (2) Where: = stress, = strain, E_o = initial modulus of elasticity and E_{cr} = modulus of elasticity after crack, $_{cr}$ = stress when starting to crack, $_{cr}$ = pressure related to focus at the beginning of the trial ($_{cr}$ = $_{cr}/E_o$) and f'_c = compressive strength of SFP. The magnitude of the experimental data and the stress at the beginning of the crack ($_{cr}$) are as follows: $_{cr}$ = (0,14 – 0,20) f'_c. The value of E_{cr} can be calculated as follows:

$$E_{cr} = K E_o \quad (3)$$

where K = constant. Based on experimental data, the K values of all the mixtures tested are shown in **Table 1**. The comparison of stressstrain curves calculated with this model and experimental results are shown in **Figure 5 - 7**. The figures show that the curves calculated with the proposed model approached those from the experimental results, and this means it is possible to apply the model in predicting the SFP stress-strain curve.

Table 1. Constant K

WTR (%)	Zeolite content (%)	K
3	0	0.316
	5	0.175
	15	0.310
	25	0.272
4	0	0.289
	5	0.243
	15	0.328
	25	0.269
	0	0.167

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5	5	0.222
	15	0.762
	25	0.285

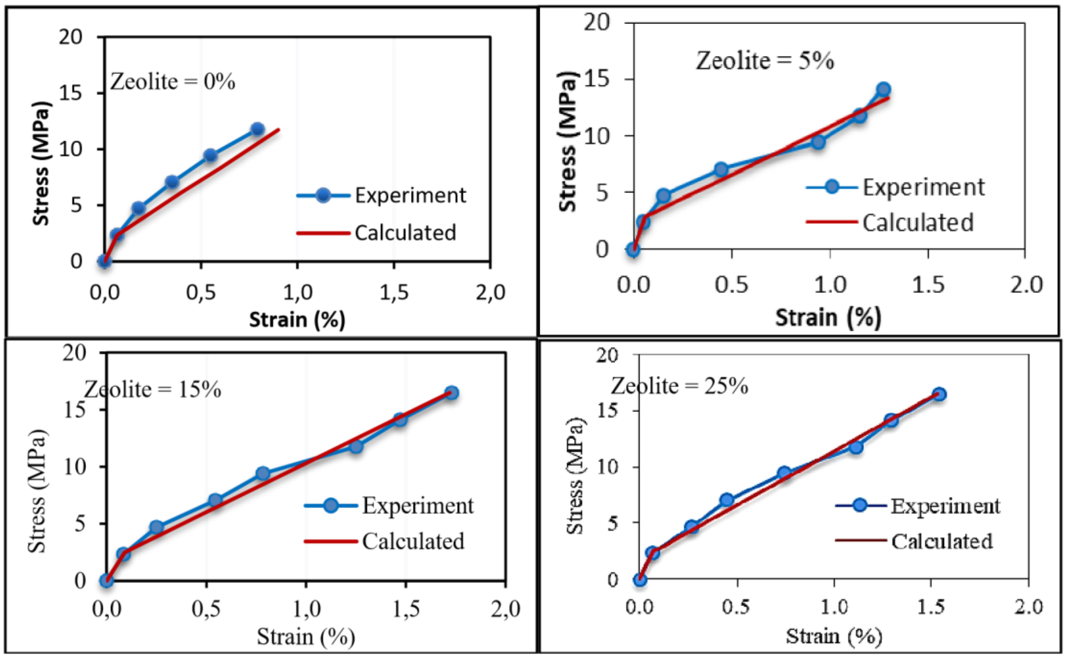

Fig 5. Comparison Of Calculated And Experimental Stress-Strain Curves For SFP With 3% WTR

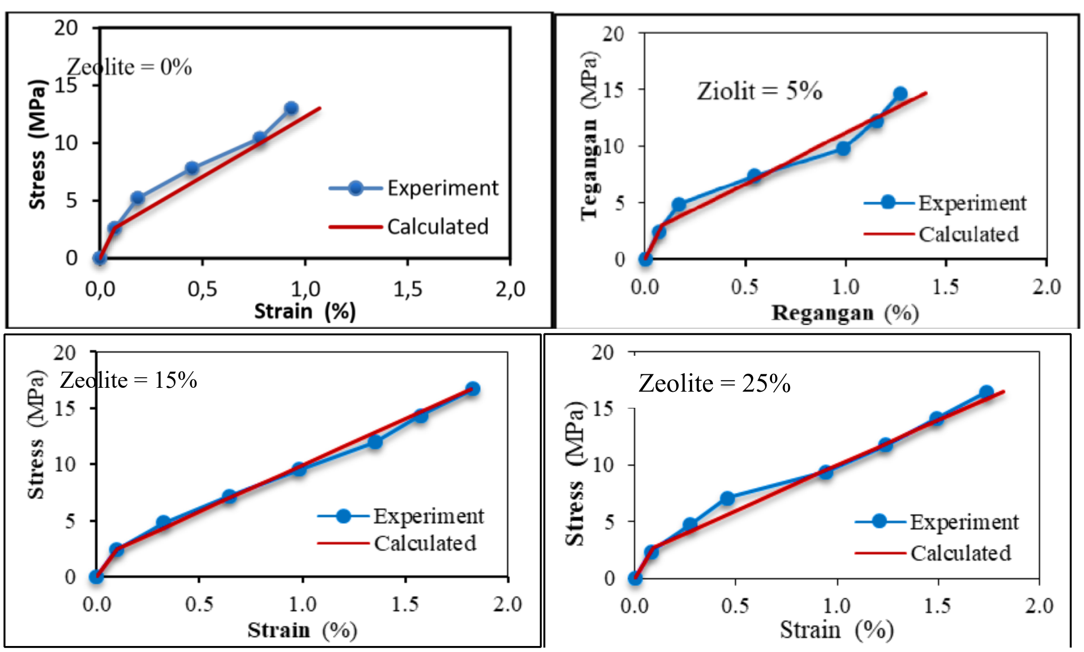

Fig 6. Comparison Of Calculated And Experimental Stress-Strain Curves For SFP With 4% WTR

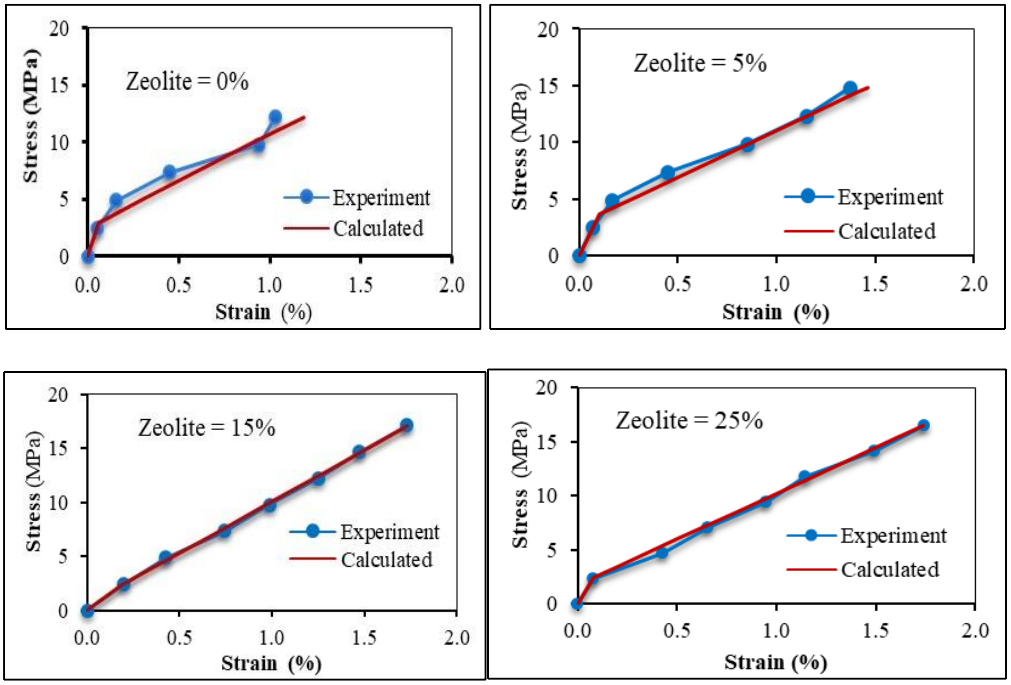

Fig 7. Comparison Of Calculated And Experimental Stress-Strain Curves For SFP With 5% WTR

Based on **Figure 5** above, the stress-strain behavior of SFP using a 3% WTR additive and zeolite substitution from 0% to 25% increased the maximum stress value obtained. The maximum stress value of SFP that SFP can withstand before it disintegrates at the use of 0% zeolite, which is 12 MPa, continues to increase linearly, then on the use of 5% zeolite with a maximum stress of 14 MPa, 16.5 Mpa, and 17 MPa. The significant increase in the maximum stress value of SFP at the use of 3% WTR can be explained by the rise in zeolite composition in cement mortar; this increase in zeolite composition in cement mortar can affect cement quality. Improving the cannon quality in the mixture can slow down the development of cracks that occur in the SFP mixture. In addition, based on **Figure 4**, the elastic and plastic conditions of the SFP mixture relatively did not change.

Based on **Figure 5-7**, the calculation results with the model proposed in this paper can be compared with the experimental test stress. A comparison of calculation results and experimental results are shown in **Figure 8**. The figure shows that the plot of calculated values and experimental results is around the equivalence line, which indicates that the calculated stress is very close to the experimental results. By using linear regression, the relationship between computed pressures and practical stresses is obtained as follows:

$$\sigma_{cal} = 0.979\ \sigma_{exp} \qquad (4)$$

$R^2 = 0.985$

Where: σ_{cal} = calculated stress, σ_{exp}= experimental stress, R^2 = coefficient of determination. These results indicate that the proposed model can predict experimental results very well.

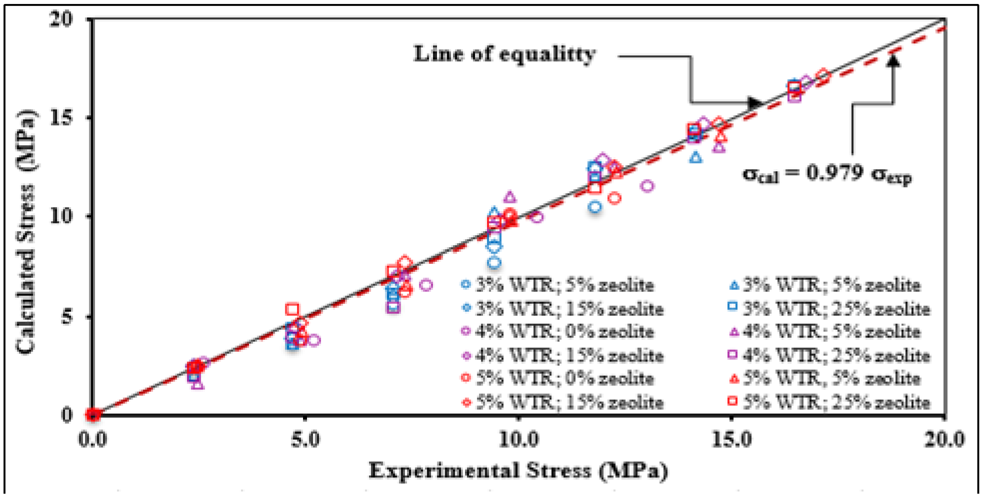

Fig 8. Comparison of calculated and experimental stress

5. Conclusion

A bi-linear stress-strain relationship model was developed with an initial stiffness equal to the initial modulus of elasticity of the mixture, and stiffness degradation occurred after the SFP mixture experienced cracks. This stiffness degradation was used in the proposal of stiffness factor K. The results obtained from applying this model were discovered to be very similar to the experiment results. Therefore, the bilinear model proposed in this study can be used to predict the stress-strain curve of semi-flexible pavement.

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