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Studying the Impact of Soil Stabilization Techniques on Rigid Pavement Joints Across Various Axle Loads

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Abstract

Rigid pavement slabs are erected on a prepared subgrade or foundation layer, providing a hard and continuous surface. Transverse joints made of dowel bars connect them, and longitudinal joints made of tie bars join them longitudinally. This study is an investigation of the impact of soil strength and concrete parameters on the effectiveness of dowel bars in rigid pavements. Moreover, three parameters were examined; California Bearing Ratio (CBR), concrete compressive strength and slab thickness. The analysis was conducted using the Ever FE program and focused on several axle configurations applied to the joint. The results indicate inverse association between the pavement slab thickness and the concrete strength, under the assumption of consistent soil strength. Moreover, an assortment of reduced shear forces on the dowel bars is seen when the soil strength values increase. It indicates that soil strength has a greater impact on the shear load of dowel bars compared to the qualities of concrete. Additionally, the type of axles used and the magnitude of soil strength were shown to have a significant effect on the shear load.

Keywords: Subgrade Soil, Soil Stabilization, Soil Strength, Concrete Strength, Rigid Pavement, Dowel Bars.

دراسة تأثير تقنيات تثبيت التربة على مفاصل الطريق الصلب عبر أحمال المحاور المتنوعة

أسماء ثامر ابراهيم، حسن محمد مهدي محي الدين

الخلاصة:

تعتبر الأرصفة الصلبة من العناصر الهيكلية الأساسية في البنية التحتية للطرق والممرات حيث تكون هذه الأرصفة المثبتة فوق طبقة أرضية أو أساس مُعدَّه مسبقًا. تتألف هذه الأرصفة من سلسلة من الألواح الخرسانية المُعزَزة بقضبان فولاذية أو شبكة تسليح لغرض زيادة قوتها وقدرتها على تحمل الأحمال المُسلطة عليها. يتم توصيل هذه الألواح الخرسانية مع بعضها البعض عبر مفاصل عرضية تحتوي على قضبان وتديه (Dowel bars)، بينما تُستخدم مفاصل طولية تحتوي على قضبان ربط (Tie bars) لربط الألواح طوليًا. تمثل هذه الدراسة تحليلًا لتأثير قوة التربة وقوة الخرسانة على أداء القضبان الوتدية في الأرصفة الصلبة حيث تم احتساب هذه النتائج باستخدام برنامج Ever FE وبناءً على أنواع متعددة من المحاور المسلطة على المفاصل. وقد أظهرت النتائج أن سمك الرصيف الصلب يتناسب عكسيًا مع قوة الخرسانة، عندما تكون قوة التربة ثابتة. وأيضًا، لوحظ تناقص بقيمة قوة القص على القضبان الوتدية بنسب مُتفاوتة عند زيادة قيمة قوة التربة. استنتجت هذه الدراسة أن تأثير قوة التربة يعد عاملاً أكثر وضوحًا من تأثير قوة الخرسانة على حمل القص للقضبان الوتدية الناتجة من الاحمال العمودية المختلفة المسلطة عليها.

1. Introduction

Rigid pavements are made with concrete layers meticulously placed on a subgrade or atop a granular base. This type of pavement finds widespread usage in critical areas such as highways, airports, industrial zones, and locations with substantial traffic loads, owing to its paramount attributes of long-term performance and robustness. Concrete pavement is a good choice for areas that need to withstand heavy vehicle traffic and large loads because it is strong,

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rigid, and hard to bend. The structure of concrete pavement is frequently fortified through the incorporation of steel bars or mesh to augment tensile strength and prevent the occurrence of cracks.

The individual panels composing the pavement are connected using specialized joints to ensure a unified structure. Transverse joints employ dowel bars to facilitate connection and load transfer, while longitudinal joints employ tie bars for the panel connection only. This intricate system of joints consolidates the discrete sections into a cohesive and reliable pavement structure. On the other hand, dowel bars were used to join square or rectangular concrete pavement panels together. This joint was the pavement's weakest link, and pavement performance was inversely proportional to the load-transfer capacity of the joint [1]. For the dowel bar to be completely loose and satisfy plate shear transfer criteria, its free end must be flat and smooth. Previous studies [2, 3, 4] have been able to figure out the load of a rigid pavement on an elastic plate with a Winkler foundation, the load-transfer capacity of joints, the stiffness of joint load-transfer, and the structural characteristics.

Using the Winkler foundation assumptions, ZHOU [5] determined the relationship between the joint load transfer coefficient and the stress reduction factor of a slab edge. Peng et al. [6] observed that the initial load transfer capacity reduces rapidly as the deviation angle of the dowel bar layout increases. Furthermore, they found that the load transfer capacity progressively deteriorated during the working cycles. Additionally, the researchers determined that when the dowel bar's layout deviation angle does not exceed 5°, its working performance remains unaffected and can be maintained at an intermediate level. The study concluded by providing a measurement of dowel bar looseness after subjecting it to 800,000 cycles of repeated bending tests. Additionally, technical control techniques were proposed to mitigate position deviation.

Joint discomfort is a common cause of issues with concrete pavement [7]. Either loose dowels or misaligned dowels frequently cause joint discomfort. Separate studies have been conducted on these two occurrences. In addition, repeated traffic stress, wear, or corrosion of steel dowel bars may lead to dowel looseness, which is shown as an expansion of the dowel bar socket [8].

A three-dimensional finite-element model was used to study the group action of the dowel bar system by looking at dowel-joined concrete pavements. Therefore, it was possible to determine-the proportional load that each dowel bar carried using useful connections, and it is possible to use the concluded relationships in the design and assessment of dowel-joined concrete pavements [9].

Al-Humeidawi and Mandal [10] found that 38-mm GFRP dowels have the same flexural rigidity (EI) as 25-mm steel dowels, can handle cyclic traffic stress, keep joints from locking up and dowels from coming loose, and have a good stress transfer efficiency (LTE). Furthermore, it was noted that the impact of misalignment on dowel looseness is much greater compared to the influence of the number of cycles for traffic load. The distance between the slab and the base as well as the orientation of misaligned dowels have a significant impact on the stress required to initiate joint opening.

Mackiewicz [11] examines the impact of different diameters and spacings of dowel bars on slab interaction in transverse concrete slabs. The 3D finite element method was used for calculations of concrete pavement, and the results were compared with falling weight deflectometer studies. The stress concentration around dowel bars was calculated, revealing a relationship between load transfer efficiency (LTE) and vertical compressive stresses in the concrete slab. Small-diameter dowels can cause damage due to the concentration of vertical compressive stresses under the dowel bar.

The subgrade soil beneath rigid pavement is a critical factor in determining the pavement's overall performance and longevity. The structural system should possess the capability to sustain concrete slabs, thereby mitigating the likelihood of crack formation, subsidence, and other forms of impairment. For the pavement to be adequately supported, it is imperative that the soil possess a uniform and stable subgrade [12].

The process of soil stabilization enhances the engineering characteristics of soil, rendering it more suitable for construction and various other applications. This methodology employs a range of techniques with the aim of bolstering soil strength, enhancing stability, and augmenting overall durability. Gypseous soils are considered problematic soils because they form cavities when water enters, leading to gypsum dissolving. In this research, three kinds of gypseous soils—soil1, soil2, and soil3—with gypsum contents of 28.71%, 43.6%, and 54.88% are mixed with petroleum products (engine oil, fuel oil, and kerosene) at 3%, 6%, 9%, and 12%. The increase in product percentage results in a decrease in Optimum Moisture Content (OMC), Specific Gravity, Liquid Limit, and Maximum Dry Density. Engine oil and fuel oil increase the angle of internal friction and soil cohesiveness for soils 1, 2, and 3 when tested in direct shear in dry and saturated conditions. While kerosene decreases internal friction and soil cohesiveness. In soil 1, the collapse potential (CP) fell by 47% when 6% engine oil was used, 48.8% when 9% fuel oil was used, and 55% when 9% kerosene was used; soils 2 and 3 have quite comparable collapse potentials. In the unconfined compressive test on soil 1 at maximum density, 6% engine oil and 10% fuel oil improved soil strength by 26% and 10%, respectively. In contrast, 9% kerosene lowered it by 29% [13].

According to Batra [14] and Andavan and Kumar [15], it has been determined that the application of bitumen emulsion has a positive impact on the physical and mechanical characteristics of soil. Shah and Ahmad [16] demonstrated that judicious application of MS bitumen emulsion can significantly ameliorate the CBR of subgrades. Notably, the most optimal potency of the soil emulsion is attained approximately 5.5 hours post-mixing.

The research results demonstrate a 50% enhancement in the California Bearing Ratio (CBR) value as compared to soil that has not been amended. The thickness of pavement is subject to variation, ranging from 175 mm to 400 mm, and is contingent upon factors such as traffic volume, environmental circumstances, base composition (whether rigid, semi-rigid, or flexible), slab dimensions, and the properties of the- concrete mixture. Furthermore, it is common practice to utilize combinations of C30 or C37 strength categories in the construction of pavements [17] and [18].

Additionally, the effectiveness of the concrete has a significant impact on the thickness of the concrete slab, whereas the integrity of the soil beneath the concrete slab is somewhat less significant. Although there are limitations to improving the concrete slab, it is important to acknowledge that efforts are being made to improve the condition of the underlying soil [19].

According to the findings of Vaitkus et al. [20], increasing the compressive strength of the concrete from C30/37 to either C40/50, C45/55, or C50/60 makes it feasible to reduce the thickness of the concrete pavement by anywhere from 6 to 39%. Hence, the increase in soil strength has a more significant impact on reducing the- thickness requirement for the concrete road than alterations in the compressive strength of the concrete [21].

This study seeks to address the research gap surrounding the transverse joint area in pavement construction, which is of great importance due to its critical significance and the substantial loads it experiences. Specifically, the investigation aims to examine the effects of different factors, such as variations in soil strength, pavement thickness, and load application, on the transverse joint area.

2. Experimental Work

2.1. Methodology

This article provides an overview of the characteristics, such as the CBR value, of subgrade soil prior to and following the stabilization process. In addition, it finds the properties of concrete, like the modulus of rupture and the modulus of elasticity, which have different compressive strengths. After that, the rigid pavement thickness is designed according to the above variables by using the AASHTO design method. Finally, the double slabs of the concrete are analyzed to find the load on the dowel bar using finite element theory during different axel load applications, as shown in Figure 1.

2.2. Laboratory work

The article describes a structural setup comprising two interconnected rigid pavement slabs that are connected in place using dowel bars. These slabs are situated on top of a subgrade, which can be either natural or treated. The subgrade soil specimen used in this study was obtained from the western vicinity of Al-Najaf city, extracted from a depth of 1 meter beneath the undisturbed ground surface. This specific soil sample exhibits characteristics typical of poorly graded sand, with a brown coloration and a gypsum concentration of 27%.

An asphalt emulsion called (Polycoat RBE) is introduced to enhance the stability of the subgrade soil. Different proportions of this emulsion (2%, 4%, and 6%) are used as a percentage weight of the soil sample in the study. This innovative approach serves as a robust strategy to mitigate the impact of moisture on gypsum, preventing structural degradation and potential collapse.

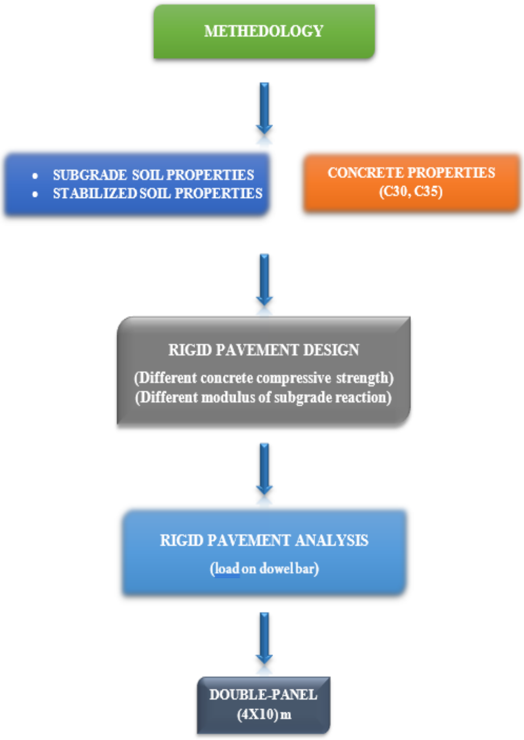

Figure (1): Methodology of Work.

Furthermore, in this research, the concrete constituents (comprising cement, fine aggregate, coarse aggregate, and water) are locally manufactured and subjected to testing in compliance with Iraqi standards. The blend proportions adhere to the guidelines specified in ACI 211 (2009), with the addition of an admixture called Sika 905. The resultant concrete demonstrates a compressive strength within the range of 30 to 35 MPa [22–32]. After that, the rigid pavement slab is designed according to the design factors of the AASHTO 1993 design method [33].

As a final step in the study, the article discusses the testing results of the subgrade before and after stabilization, as well as the concrete tests. These results are utilized for the design of rigid pavements, utilizing the AASHTO design chart, and for joint analysis, employing Ever FE software.

This study features crucial figures: Figure (2) shows concrete constituents and admixture; Figure (3) displays compressive strength; Figure (4) represents elastic modulus; and Figure (5) highlights flexural strength, all of which provide a comprehensive view of concrete properties and performance.

Figure (2): Concrete Constituents and Admixture

Figure (3): Compressive Strength of Concrete.

Figure (4): Elastic Modulus of Concrete.

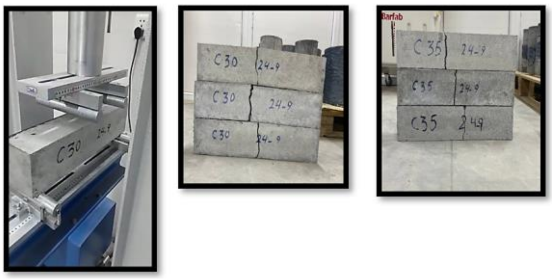

Figure (5): Flexural Strength of Concrete.

3. Results and Discussion

Laboratory investigations encompassing soil tests, conducted both prior to and subsequent to asphalt emulsion stabilization, yielded conclusive outcomes. The optimal proportion of asphalt emulsion was identified as 4%. This selection yielded noteworthy enhancements in soil attributes and a remarkable surge in the California Bearing Ratio (CBR) from 27% to 52%.

In the thickness design process, the design-results comparison was seen when the design parameters were carefully fit to the design chart shown in figure (6) and the result was compared to the AASHTO modified equation (eq. 1) for rigid pavement design. Table 1 demonstrates the correlation between soil carrying capacity (%CBR) and concrete compressive strength (f'c) in relation to the necessary slab thickness under the specified conditions. In general, slabs with higher values of %CBR and compressive strengths tend to exhibit a reduction in thickness, while slabs with lower %CBR values and compressive strengths need increased thickness in order to resist the load applied.

$$\log_{10} W_{18} = Z_R\, S_o + 7.35\ \log_{10}(D+1) - 0.06 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.5-1.5}\right]}{1+\left[\frac{(1.624\times10^{7})}{(D+1)^{8.46}}\right]} + (4.22 - 0.32\, P_t)\log_{10}\left\{\frac{S_c'\, C_d}{215.63\, J}\left(\frac{D^{0.75}-1.132}{D^{0.75}-[18.42/(E_c/k)^{0.25}]}\right)\right\} \ldots\ (1)$$

Where:

ZR: Standard normal variation for a set reliability level
So: Overall standard deviation
W18: Estimated Count of 18-kip ESAL Loadings
D: Concrete pavement thickness
ΔPSI: Design serviceability loss
Pi: Initial serviceability index
Pt: Terminal serviceability index
Ec: Elastic modulus of the concrete to be used in construction (lb/in^2)
Sc: Modulus of rupture of the concrete to be used in construction (lb/in^2)
J: Load transfer coefficient
Cd: Drainage coefficient:

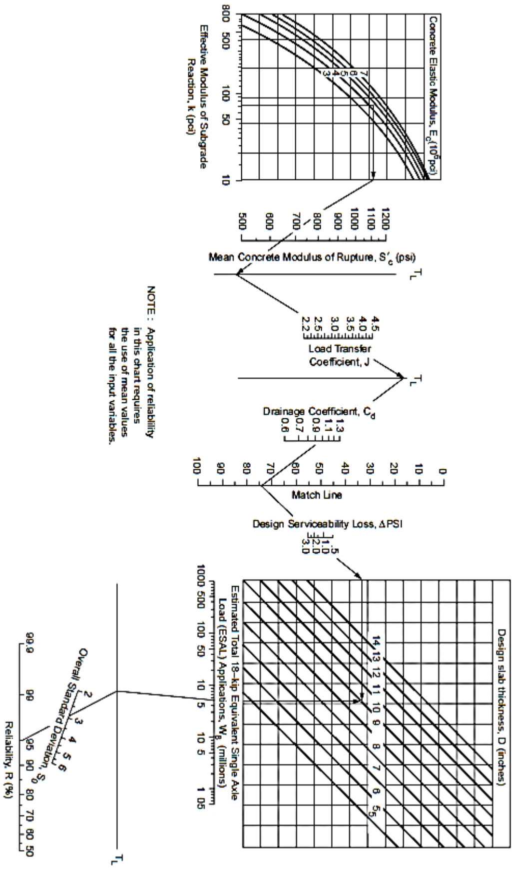

Figure (6): Rigid Pavement Design Nomograph (AASHTO, 1993).

Table (1): Thickness of Rigid Pavement

i	*%CBR*	*Compressive Strength (MPa)*	*Slab Thickness (mm)*
1	*27*	*30*	*335*
		35	*320*
2	*52*	*30*	*310*
		35	*295*

Ever FE is a finite-element analysis software designed to simulate the behavior of jointed plain concrete pavement systems in response to axle loads and environmental influences. It was used for the analysis of transverse joints and to compute the maximum load on dowel bars by using finite element theory with different axle loads applied, as shown in Figure 7, according to several factors shown below:

- Dowel diameter =32 mm
- Dowel length = 500 mm
- Dowel spacing = 308 mm
- Dowel slab support= 3500 MPa
- Tandem axle spacing= 1350 mm
- Tridem axle spacing= 1350 mm

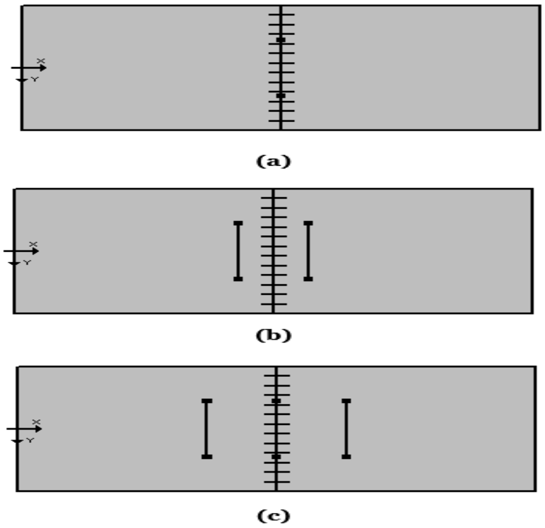

Figure (7): Method of Applied Load on the Joint Single axle load (80KN), b. Tandem axle load (160KN) and c. Tridem axle load (240KN)

Table 2 presents information about the performance of different types of soil, categorized as natural soil and stabilized soil, in terms of their ability to support different axle loads on a transverse joint. The data is given for two levels of concrete compressive strength (f'c) and two levels of soil density (K), along with values for different axle configurations (single, tandem and tridem) that affect the value of dowel bar shear loads. In the case of natural soil, the shear load generally follows a consistent pattern across both concrete strengths, with tridem axles having the highest value and tandem axles having the lowest value because the axle load is symmetrical on the joint. In contrast, stabilized soil exhibits a substantial reduction in shear force with more complex axle configurations, which may be due to the unique characteristics of this soil type as shown in figures 8 and 9. Importantly, the results could have practical implications for road and pavement design, as they provide insight into how different soil types and concrete strengths respond to varying axle loads. The trend of decreasing shear load with increasingly complex axle configurations on stabilized soil suggests that road designers may need to consider these findings when planning for heavy traffic. The results include some combinatorial aspects in the analytical solutions of the concrete pavement as described in reference [34] and are considered to be a supplement to the claims made by the researchers in references [9], [12], and [21].

Table (2): Load on Dowel Bars for Different Cases

NATURAL SOIL (K=40MN/m³) (CBR= 10%)				
f'c (MPa)	*D (mm)*	*SINGLE AXLE (80 KN)*	*TANDEM AXLE (160 KN)*	*TRIDEM AXLE (240 KN)*
		P(N)	*P(N)*	*P(N)*
C30	*335*	*288.1*	*226.25*	*291.4*
C35	*320*	*296.61*	*228.93*	*294.32*
STABILIZED SOIL (K= 141 MN/m³) (CBR= 52%)				
f'c (MPa)	*D (mm)*	*SINGLE AXLE (80KN)*	*TANDEM AXLE (160 KN)*	*TRIDEM AXLE (240 KN)*
		P(N)	*P(N)*	*P(N)*
C30	*310*	*167*	*67.8*	*142.54*
C30	*295*	*170.7*	*66.61*	*139.4*

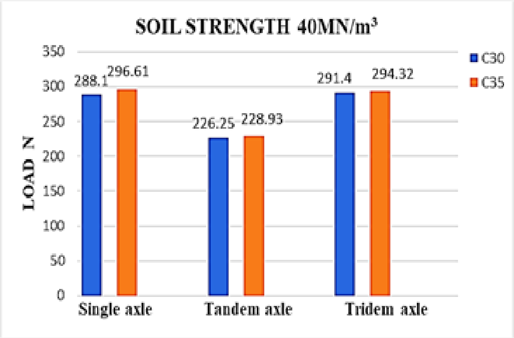

Figure (8): Shear Load on Dowel Bar when Soil Strength 40 MN/m³

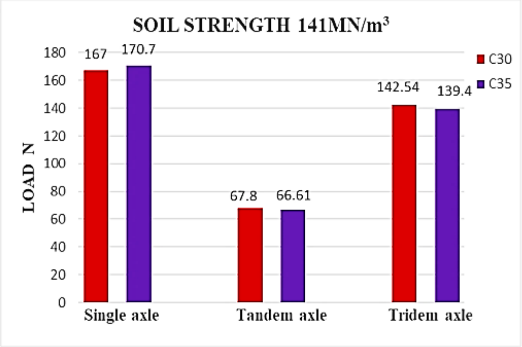

Figure (9): Shear Load on Dowel Bar when Soil Strength 141 MN/m³

4. Conclusions

As the soil strength value increases from 40 to 138 MN/m3, the load on dowel bars decreases by 42%, 70%, and 51% for single axle, tandem axle, and tridem axle configurations, respectively, across all compressive strengths. In cases where the soil strength remains at 40 MN/m3 and the concrete strength varies from 30 to 35 MPa, the load on dowel bars shows slight increases of 2.95%, 1.07%, and 1% for single axle, tandem axle, and tridem axle setups, respectively. Conversely, when the soil strength is 138 MN/m^3 and the concrete strength ranges from 30 to 35 MPa, the load on the dowel bar increases by 2.22% for a single axle. However, for tandem and tridem axle configurations, this load remains relatively stable due to the high soil strength and symmetrical load distribution at the joint. Therefore, it concludes that the change in soil strength has a more obvious effect than the change in compressive strength.

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