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APPLICATION OF SMALL-THICKNESS CEMENT-MIXED SAND IN THE SUB-BASE COURSE AND ITS INFLUENCE ON THE VERTICAL PERMANENT DEFORMATION OF ROAD PAVEMENT

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ABSTRACT: The application of weak soils in the road pavement base leads to various settlements and instability that still need to be addressed. One common type of these settlements, which is a long-term serious concern for flexible pavements on weak soil, is permanent vertical deformation. In this research, a cyclic loading-testing model was developed to investigate the vertical permanent deformation behavior of pavements. Specifically, a typical road pavement consisting of a cement-mixed sand sub-base and a crushed stone varying base over a weak sand subgrade was investigated. The varying thicknesses of the base ranged from 0.10 m to 0.30 m, while the thickness of the cement-mixed soil subbase was 15 cm. The model pavement structure was constructed in a large testing tank measuring 1.0 x 1.0 x 0.8 m. A circular steel plate was subjected to cyclic trapezoidal load pulses to simulate traffic loading through an actuator assembly. Displacement transducers were employed at various positions and levels to monitor the pavement deformations. Three thousand cycles of cyclic load with varying loading stages ranging from 100 kPa to 550 kPa were applied. The experimental results revealed that applying a thin cement-mixed sand subbase on weak soil can reduce the pavement section's permanent vertical deformation by 2 to 6 times, as well as reduce the vertical subgrade deformation by 3.62 to 44.1 times. Furthermore, it reduced the vertical stress at midspan by up to two times and did not show any negative effect on deformation, while reducing the thickness of the base course lying on the stabilized subbase from 30 cm to 10 cm.

Keywords: Pavement, Cement mixed soil, Thin sub-base course, Cyclic loading, Permanent deformation

1. INTRODUCTION

Considering current construction activities and the rising demand for aggregate materials, especially in the road construction sector, these materials will soon become scarce. Currently, most of the materials used in highway construction are aggregates, particularly in the base and sub-base courses of the roads. Furthermore, in many regions worldwide, including desert areas, the sources of aggregate materials are located far from road construction sites, making the availability of good-quality aggregate materials a constraint in most locations. Since aggregates must be transported over long distances, this results in supply difficulties and significant increases in the initial costs of road construction. Sandy soil can be introduced as an economically viable and sustainable alternative material for road-based applications, as it is widely distributed globally [1]. However, since fine sand is a weak soil with little cohesive force, it poses challenges for compaction in road base applications. It can be stabilized with cement or other binding material. Because mixing cement with sand reduces sand's compressibility and permeability, further enhancing its strength, bearing capacity, and durability [2, 3, 4]. The application of cement-stabilized or cement-mixed soil on soft ground has been common for decades. Numerous studies have been carried out on the different properties of cement-stabilized soils. For instance, Liu et al. researched the effect of cement stabilization on the shear strength parameters of soft soil and reported that the addition of cement to soft soil could improve their resistance to shear forces [5]; Sadek et al. worked on the influence of compaction energy on cement mixed soil and concluded that the combination of cement treatment with high compaction for subgrades using weak soil could improve soil's strength parameters throughout any earthwork design phase that leads to strengthening subgrades, and reducing layer thickness [6]; Ajorloo et al. investigated the behavior of sand under triaxial testing and found that the stress-strain response is significantly influenced by effective confining pressure and cement content and added that an increase in binder content could improve the stiffness and strength of sand [7]; Ranaivomanana et al. studied the effects of cement treatment on the microstructural, hydraulic, and mechanical properties of soils [8]. Pham et al. indicated that a higher water-to-cement ratio is necessary for cement-mixed soil to achieve maximum strength based on the unconfined compressive strength of cement-mixed sand [9]. Rohmatun et al. studied on the determination of an optimum cement content for a silty sand soil as a road base [10]. A considerable percentage of aggregate used in road pavement is applied in its shallow layers, such as base and subbase courses. To lessen demand on quarry aggregate materials, utilizing cement-mixed soil in these layers should be considered. However, constructing roads on weak soil and using weak soil in shallow-layer construction can lead to various settlements, instabilities, and failures that still need to be addressed. Among the factors causing pavement failure, the most prevalent traffic-related structural distress in cement-stabilized pavements is rutting or general shape loss due to permanent deformation [11]. Rutting is a serious and long-term concern for pavement structures. To address the rutting issue, an effective design strategy for pavements with lightly cement-mixed sand materials requires characterizing cement-mixed sand in terms of permanent deformation and its effect on the pavement's overall deformation. Although many studies have analyzed the characteristics of cement-stabilized soils for subgrade and ground stabilization, there are very few studies that have comprehensively investigated the application of cement-mixed sand in the shallow layers of pavement. Therefore, this research focused on applying a thin layer of cement-mixed soil in the subbase layer of pavement over a weak subgrade. The study investigates the influence of a thin subbase layer on permanent deformation at both the subgrade and surface levels, vertical stress distribution, and the potential for flexural failure. This study was limited to 6% of normal OPC cement as the binding material and a 28-day curing period, to study the influence of a thin subgrade on the vertical permanent deformation.

2. RESEARCH SIGNIFICANCE

Considering the increasing demand for query aggregate and its gradually diminishing sources, cement-mixed soil can be introduced as an economically viable and sustainable alternative for road construction. However, using weak soils in the road pavement base and subbases may lead to various settlements and instability, which still need to be addressed. One common type of these settlements, which is a long-term serious concern and causes pavement failure, is permanent vertical deformation or rutting. Therefore, this study focuses on the influence of cement-mixed sand on the vertical deformation behavior of road pavements under cyclic loading.

3. MATERIALS AND METHODS

3.1 Paving Materials

The subgrade soil used in the research was Silica Sand No. 5. The soil was categorized as poorly graded sand (SP), based on the Unified Soil Classification System (USCS). This sand is commercially available in Japan [12]. The particle size distribution curve and properties of sand are presented in Fig 1.The sand was selected due to its uniform gradation and for minimizing variation in the particle size distribution of each section preparation. C40 (trade name) of crushed stone aggregate was used for the model base course, and 6% of ordinary Portland cement (OPC) was mixed with silica sand to make cement-mixed soil. C40, a crushed stone aggregate, was selected for the base course as it is currently used in pavement base course constructions in Japan. The crushed stone aggregate Fig 1 was categorized as a well-graded aggregate based on the Unified Soil Classification System (USCS).

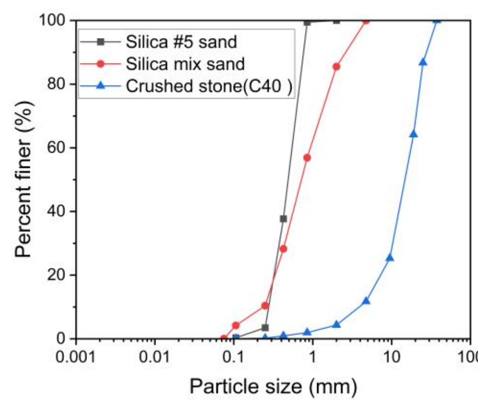

Fig 1. Particle size distribution for the paving materials

3.2 Experimental Setup

A large square container with internal dimensions of 100 cm (Length), 100 cm (width), and 80 cm (height) was used to house the testing pavement sections. Fig 2 shows a schematic view of the model pavement testing tank and the testing equipment setup for applying cyclic loading and monitoring vertical deformation. A circular steel plate with a diameter of 17.5 cm was employed to apply the cyclic loading to the pavement structure. If the width of the test tank is greater than six times the width of the footing, the boundary effect on the test results can be considered small [13]. Since the test tank width is 100cm and the load plate's diameter is 17.5cm, the ratio between the test tank and the plate is large enough (100/17.5 ≈ 6), so that the influence of the model pavement from the rigid wall boundaries can be considered minimal [14,15]. In addition, based on Boussinesq Stress Distribution Analysis, the influence of the tank boundary from the tank base would be negligible, since the total depth of the base course subgrade layer was greater than 70 cm in each test [13]. To construct the subgrade of the model pavement, the silica sand was compacted to a dry density of 1.54 g/cm³ using the sand-raining method according to the literature [12, 16]. Small pressure cells were employed to record the vertical pressure in the subgrade applied from the base course layer. The pressure cells were placed at 2 cm depth below the subgrade-base course interface, at 0, 15 cm, and 35 cm away from the center of the pavement section, see Fig 2. A plastic layer was used to avoid

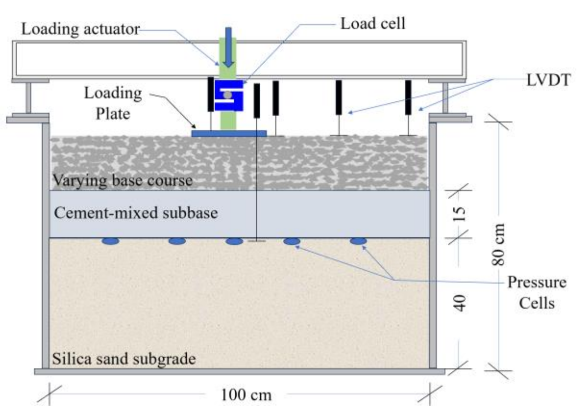

Fig 2. Schematic layout for the setup of the cyclic loading test

moisture escaping to the subgrade from the cement-mixed layer. An in-depth measurement setup was installed to monitor the vertical deformation in the subgrade layer. The in-depth measurement setup consisted of a 2 mm steel rod along with an aluminum tube covering the vertical rod. To monitor the surface deformation of the base course, four additional linear variable differential transformers (LVDTs) were installed at the base course's top surface at 0 cm, 15 cm, 35 cm, and 50 cm away from the pavement's center. A 40kN load cell was employed to measure the cyclic load. A function generator (fig), a Bellofram cylinder, and an electro-pneumatic (EP) transducer were used to apply a trapezoidal load pulse (Fig 3) with a frequency of 0.1 Hz to simulate the variable magnitudes of traffic loads [12]. Three thousand load cycles were applied with varying amplitudes ranging from 100 kPa to 550 kPa for all pavement models. Each of the five load steps was allowed until 500 cycles, except the final step, which was allowed until 1000 cycles.

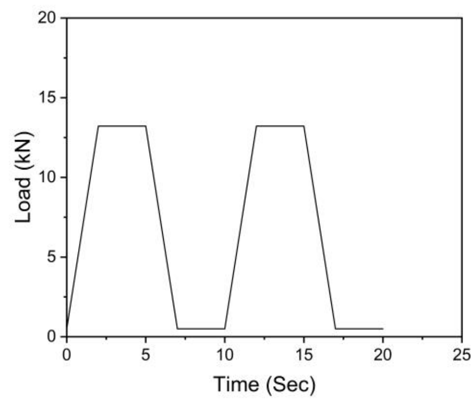

Fig 3. The loading pulse that was applied in the cyclic loading test.

3.3 Preparation of The Testing Section

A total of seven pavement sections were prepared and tested in this research, three of which had a stabilized subgrade. Varying thicknesses of the base course were used in both stabilized and non-stabilized sections, the details of which are provided in Table 1. The preparation of the test sections began with the placement of the subgrade layer at the desired thickness. The subgrade was constructed using the sand-raining method in the model test tank [12, 17]. A density of 1.54 g/cm3 was achieved for the model subgrade layer across all tests. After the pavement subgrade layer was prepared to the desired thickness, a vertical deformation monitoring system consisting of a small aluminum tube, vertical rod, small plastic plate, and small LVDT was installed to monitor the vertical deformation of the subgrade. The rod was placed inside the small vertical tube. The rod could move freely up and down inside the tube to transfer the subgrade deformation to the top-installed LVDT. Two small lubricated plastic disks were installed on the steel rod to maintain the space between the rod and the protective tube and reduce friction during the test in the event of unexpected deformations. In this system, a small thin plate was buried in the subgrade at a depth of 2 cm from the top surface of the subgrade. The vertical tube and rod were extended to the steel plate. To avoid the displacement and deformity of the aluminum tube, care was taken to keep the tube vertical with its supporting system during the construction process of the pavement base course layer. A dual plastic was placed at the interface between the subgrade and cement-mixed soil layers to prevent moisture loss from the cement-mixed layer to the subgrade. The most suitable percentage of cement for the soil of the pavement layers (6 %) was added to sand mixed thoroughly with their optimum moisture content (10.1 %) to build the subbase layer [18]. To obtain the desired maximum dry density, the cement-mixed subbase course layer was compacted in several sublayers in the test tank [11]. After constructing the cement-mixed subbase layer, the subbase was cured for 28 days using special curing sheets [19, 20]. After 28 days of curing, the base course of crushed stone aggregate was prepared in 5 cm layers to achieve the desired density of 1.6 g/cm^3. To minimize material breakage during compaction, the base course was manually compacted using a wooden plate [12]. Table 1 summarizes the test sections prepared in this research.

Table 1. Summary of Tested Sections

Test ID	Base course thickness (cm)	Stabilized sub-base thickness (cm)	Subgrade thickness (cm)	Maximum cyclic pressure (kPa)
PS1	10	---	40	550
PS2	15	---	40	550
PS3	20	---	40	550
PS4	30	---	40	550
PS5	10	15	40	550
PS6	15	15	40	550
PS7	20	15	40	550

4. RESULTS AND DISCUSSIONS

4.1 Permanent Deformation of The Subgrade

The Permanent deformation of the subgrade layer was determined using the in-depth measurement setup employed for pavement model tests. Fig 4 illustrates the development of subgrade permanent deformation with increasing number of load cycles across all tests. As anticipated, the results show that the permanent deformation of the subgrade increased significantly with the number of load cycles (11). All cement-mixed sections exhibited much lower permanent deformations and rates of increase in subgrade permanent deformations compared to their corresponding non-cement-mixed sections. As shown in Fig 4, the largest permanent deformation of the subgrade was observed in the non-stabilized pavement with a 10 cm base (Section PS1). This deformation was evident from the initial loading phase and became significantly more pronounced at a pressure of 200 kPa. When the applied pressure reached 550 kPa, the pavement section failed suddenly, just a few load cycles later. In contrast to the non-stabilized pavement with a 10 cm base course, the subgrade deformation of the stabilized pavement was nearly imperceptible until five hundred cycles of 200 kPa pressure were applied. The deformation became noticeable when the pressure reached 550 kPa and increased gradually to an overall

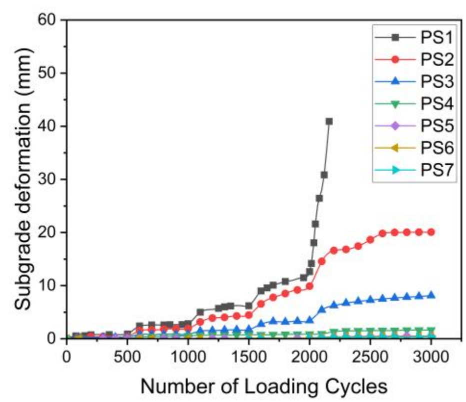

Fig 4. Development of subgrade's Permanent deformation of stabilized and non-stabilized pavement sections

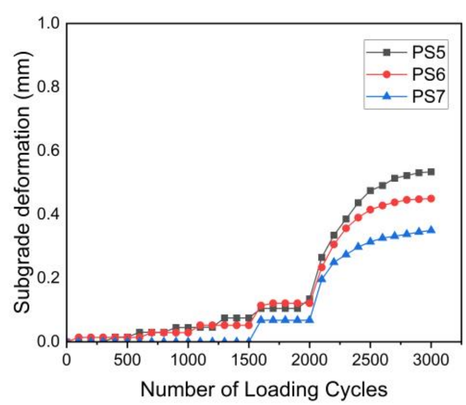

Fig 5. Development of subgrade's Permanent deformation of stabilized sections.

0.53 mm over the next one thousand cycles. However, no failure was observed. When the thickness of the base course increased to 15 cm, subgrade deformation in the non-stabilized pavement section became evident from the first cycle. It gradually intensified until a pressure of 400 kPa was applied. The subgrade deformation dramatically increased during the initial cycles of 550 kPa of pressure. However, after a few cycles, the rate of increase slowed down. After around 500 load cycles under a pressure of 550 kPa, a second sharp increase was observed before reaching a total deformation of 20 mm, as shown in the Fig 4. The subgrade deformation in the stabilized section with a 15 cm base course measured 0.45 mm, significantly smaller than that of the non-stabilized section with the same base course. An increase in the base course thickness of the sections with a stabilized subbase had a negligible effect on the permanent subgrade deformation, shown in Fig 5. This indicates that the application of a small cement-mixed layer can enable us to design a thinner base course that avoids both permanent pavement deformation and the use of an uneconomic base course.

4.2 Permanent Surface Deformation

The pavement's permanent surface deformation at the pavement's center was calculated by averaging the readings from two LVDTs installed on the top surface of the circular loading plate, whereas the permanent surface deformations at other specific points away from the center of the loading plate were taken the same as those recorded by the LVDTs installed at each point of the top surface see Fig 2 [20]. Fig 6 clearly illustrates that the permanent deformation accumulates as the number of loading cycles increases. As shown in Fig 6, the largest permanent surface deformation was observed in pavement section PS 1(Section with 10 cm base and no stabilized subgrade). The deformation appeared from the initial loading and gradually increased with loading cycles. The pavement section showed significantly larger deformations when the pressure reached 550 kPa. This abrupt and large deformation can be attributed to the bearing capacity failure of the subgrade layer. However, no significant deformation or failure was observed in pavement section PS 5 (Section with a stabilized subgrade and 10 cm base) under pressure of 550 kPa and three thousand load cycles. The deformation in this section also appeared from the initial cycles. However, it increased very slowly with load cycles and pressure increase. Moreover, the section deformation was comparatively much smaller than that of section PS 1. As shown in Fig 6, the curve levels off towards the end of three thousand cycles, which can be attributed to much

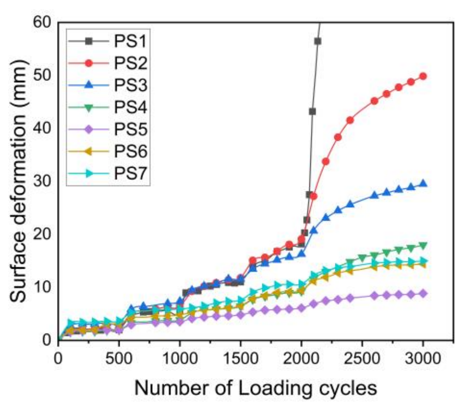

Fig 6. Development of surface permanent deformation with the number of load cycles.

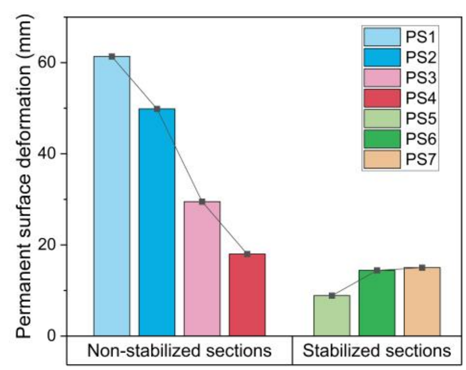

Fig 7. Surface permanent deformation of the cement-stabilized and non-stabilized sections

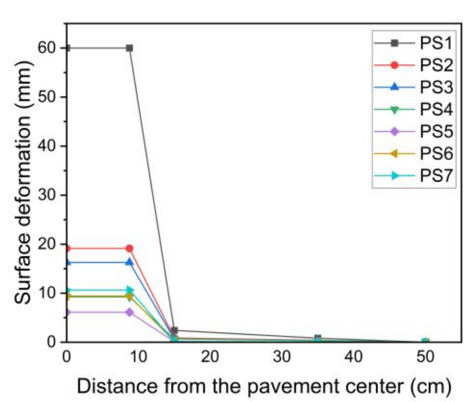

Fig 8. Profile of Permanent surface deformation after two thousand cycles.

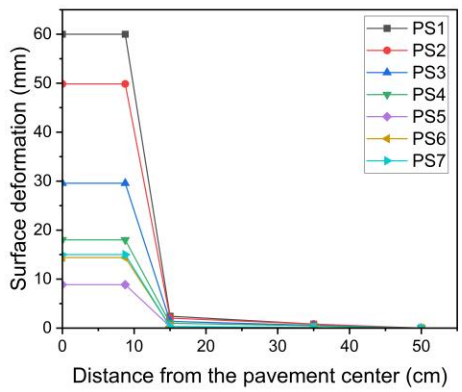

Fig 9. Profile of Permanent surface deformation after three thousand cycles.

smaller deformation at later cycles. For sections PS2 and PS3, although the permanent surface deformations were large, the bearing capacity failure of the subgrade was not observed. The surface permanent deformation of these pavement sections was also much larger than that of sections with the cement-mixed sand. The stabilized cement-mixed subbase decreased the thickness of the base course from 30 cm to 10 cm. This suggests that using a thinner cement-mixed subbase may allow for a significant reduction in the thickness of the pavement base course, resulting in more economically viable pavements, see Fig 7. Fig 8 & Fig 9 shows the permanent surface deformation profiles of all tested sections after two thousand and three thousand load cycles, respectively. It was assumed that the profiles of surface deformation were symmetrical along the vertical axis. The figures clearly illustrate that the sections with cement-mixed subbase exhibited considerably smaller deformation at the center of the pavement compared to sections without a cement-mixed sand layer.

4.3 Vertical Stress Distribution

The vertical stress at the subgrade surface was measured using pressure cells installed 2 cm below the subgrade surface at distances of 0, 15, and 35 cm from the center of the pavement. Fig 10 & Fig 11 illustrate the maximum vertical stress of the stabilized and non-stabilized sections measured along the subgrade surface versus the horizontal distance from the center of the pavement section. The result showed that stabilized sections successfully distributed the vertical stresses to a wider area in the subgrade compared to the non-stabilized sections. The non-stabilized sections exhibited a large decrease in the vertical stresses at distances of 0.10-0.25 m from the pavement center. For example, the non-stabilized section with a 10 cm base experienced a vertical stress of 154 kPa at mid-span, while the stabilized sections with 10 cm and 15 cm bases showed stresses of 93.93 kPa and 82.27 kPa, respectively, at pavement mid-span. This indicates that the non-stabilized section experienced up to twice the stress at mid-span. The large stresses may have resulted from the punching failure of the pavement subgrade. In non-stabilized sections, the vertical stresses from the center of the pavement to the edges showed a very sharp decrease. For example, the vertical stress of the PS1 dropped from 154.2 kPa at the center to 62.37 kPa and 0.31 kPa at 015 cm and 0.35 cm distances from the center of the pavement, respectively. In contrast, the stabilized sections showed a comparably gradual decrease in vertical stresses at these distances from the pavement's center. The non-stabilized section showed 2- 6 times greater surface vertical permanent deformation compared to the stabilized sections, see Fig 7. The much higher

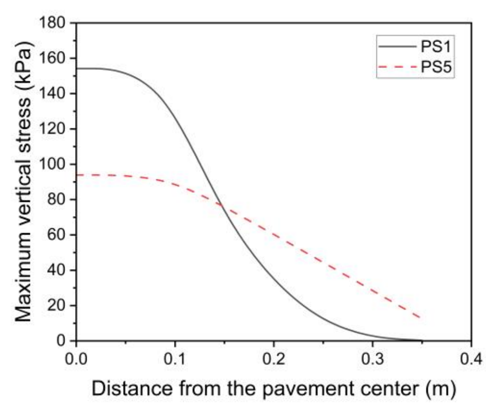

Fig 10. Maximum vertical stress distribution at the subgrade surface for Pavement sections PS1 and PS5.

vertical stress at the center of the non-stabilized pavement sections (PS1 and PS2) indicates the punching failure of the subgrade [22, 23]. The lower vertical stresses at the pavement center are attributed to the benefit of the stabilization of the subbase layer, which facilitates the redistribution of the vertical stress from the center to the edges. This result shows that the stabilized layer behaved similarly to a slab, effectively distributing the vertical stresses to the edges of the pavements. To compare the pavement stabilized sections with a varying base course layer (Fig 12), though sections with a relatively thicker base course layer showed comparably small vertical stress at the subgrade center than sections with a thinner base course layer, the difference was not considerably large. This aspect can indicate that a decrease in the base course thickness of the sections with the stabilized subbase does not considerably affect the stress distribution on the subgrade. As a result, relatively thin base courses can be considered which resulting in more economically viable pavements.

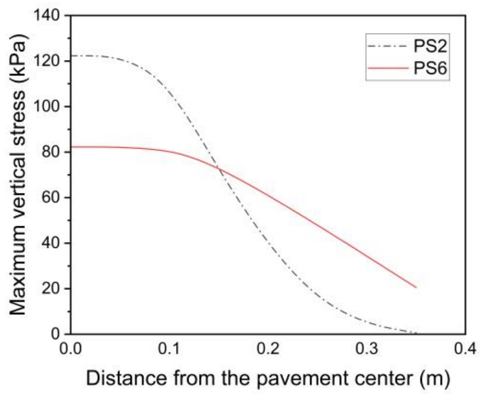

Fig 11. Maximum vertical stress distribution at the subgrade surface for Pavement sections PS2 and PS6

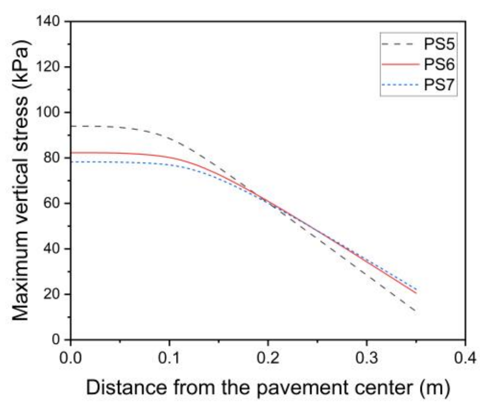

Fig 12. Maximum vertical stress distribution at the subgrade surface for stabilized pavement sections.

5. CONCLUSIONS

In this research, a cyclic loading-testing model was developed to investigate the vertical permanent deformation behavior of cement-mixed sand pavements. In particular, a typical pavement structure consisting of a cement-mixed sand subbase and a gravel varying base course over a weak sand subgrade was studied using cyclic loading model testing. Based on the experimental results, the following conclusions can be drawn:

- The stabilization of the sandy subbase layer significantly reduced the permanent surface deformation of the pavement under cyclic loading. Applying a 15 cm-thick cement-mixed subbase reduced the surface vertical permanent deformation from 61 cm, 49 cm, and 29 cm to 8.87, 14.41, and 15.01 cm for pavement sections with base course thicknesses of 0.10, 0.15, and 0.20cm, respectively. A significant portion of the surface deformation observed in the stabilized sections was contributed by the deformation of the base course layers.
- During the cyclic loading test, no deterioration, damage, or failure was observed in the stabilized subbase course layer.
- The 15 cm stabilized subgrade reduced the vertical stress by up to 200% at the midspan of the pavement sections. As a result, it can be said that the cement-mixed layer in the subbase redistributes the applied load over a broader area, which reduces stress concentration and enhances vertical stress distribution on top of the subgrade layer. This behavior leads to less permanent deformation in the subgrade.
- The permanent deformation of both the surface and subgrade of the pavement sections, which had base courses on the cement-mixed subgrade, did not increase when the thickness of the base course was reduced from 30 cm to 10 cm. This suggests that using a thinner cement-mixed subbase may allow for a significant reduction in the thickness of the pavement base course, resulting in more economically viable pavements.
- Compared to the non-stabilized pavement sections, the stabilized section exhibited 3.62 to 44.1 times less permanent subgrade deformation at midspan of the pavement. This result indicates that the cement-mixed subbase facilitates the distribution of the load over a larger area, thus preventing subgrade failure.
- The notable decrease in permanent deformation of both the surface and subgrade due to the use of cement-mixed subbase suggests that cement-mixed sand may serve as an effective method for mitigating the permanent deformation of pavements.

Practicing engineers might explore the option of implementing a thinner subgrade to control the vertical permanent deformation of the pavement, instead of opting to increase the thickness of the road pavement's base course.

6. ACKNOWLEDGMENTS

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