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The Effect of The Bearing Capacity of Sub-Grade Soil on The Thickness and Cost of The Superstructure of Chip Seals

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Abstract
Chip seal is an economical flexible pavement type consisting of layers of aggregate and bituminous binders. Chip seal is generally applied for preventative treatment of an existing road or to overlay low-trafficked roads. The thickness of the superstructure of a chip seal is directly related to the bearing capacity of sub-grade soil. The bearing capacity of soil is represented by Resilient Modulus (M_R) during the design of the thickness of pavement layers. This study has focused on the effect of the bearing capacity of sub-grade soil on the thickness and cost of the superstructure of chip seals. In addition, two-dimensional numerical modeling was also performed with the thicknesses of the layers found according to the M_R. It was indicated that there was a strong correlation between the bearing capacity of sub-grade soil and the thickness of the superstructure of chip seals with high R-square values. An increase in the bearing capacity of the sub-grade soil resulted in a decrease in the thickness of the superstructure of the chip seals. Additionally, Plaxis 2D modeling showed that a double-chip seal had less deformation and better bearing capacity compared to a single-chip seal. For this reason, it is economically important to choose the sub-grade soil to be used in the chip seals most properly by also considering the environmental conditions

1. Introduction

The roads are designed to meet the needs and demands depending on the socio-economic situation of the region. As road users, drivers demand smooth, comfortable, high slip resistance, fast access, low transportation costs, and low noise levels, while road authorities aim for durable, minimum maintenance, resistance to permanent deformations, high traffic safety, and long-lasting roads [1]. A road pavement consists of different elements such as sub-grade, base, and surface course [2]. These elements must be able to fulfill the conditions that will ensure that the superstructure can serve safely in all climatic conditions throughout the project life and that a large number of vehicles can pass over it [3-5]. Road pavements are generally divided into two groups as flexible and rigid pavements [6, 7]. Flexible pavements are those that are covered with bituminous or asphaltic materials, while rigid pavements consist of a surface layer of Portland cement concrete [8-11]. Chip seal is an economical flexible pavement surfacing type that consists of layers of aggregate and bituminous binder to protect and prolong the life of an existing road or to overlay low-volume roads. In other words, a chip seal is the spreading out of bitumen and aggregate one after another and is formed by compaction [12-14]. Additionally, chip seal, which can be successfully applied on both high and low-traffic volume roads, is generally used on low-traffic roads.

Chip seal is one of the most preferred flexible pavement types because it has some advantages, such as being low-cost, easy, and rapid to construct and

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improving skid resistance and smooth surface properties. This type of pavement is widely used in Turkey, South Africa, Australia, New Zealand, and England [15-22]. Chip seals could consist of one or more layers, as shown in Figure 1. Single chips are formed by spreading bituminous binder on an existing road or granular base and then laying and compacting aggregate. A single chip with double aggregate surfacing pavement type is formed by successively laying uniformly graded coarse and relatively fine aggregate over the bituminous binder. The double chip seal is formed with relatively fine aggregate and bituminous material on the top of the single-layer surface coating, which was previously formed with a coarse aggregate laid on the bituminous material. A sandwich chip seal is formed by first laying coarse aggregate on an existing road or granular base and bituminous binder on it. Then, over the bituminous binder, a relatively fine aggregate is laid and followed by compaction [12, 16, 19, 23, 24]. In Turkey, single and double chip seals are mostly preferred types. Generally, chip seal is applied on roads that have a total traffic volume of 8.2 tons equivalent standard axle load of less than 2×10^6 in one way during the service period. It should be designed as a single chip if the traffic volume is less than 500000, and for the traffic volume over that value, it should be designed as a double chip. However, it is required to apply hot mix asphalt for the roads that have traffic volume between $2\text{-}3\times10^6$ as the total equivalent standard axle load, it can be implemented double chip by thinking about economic conditions and shortening the project life [25].

A road body consists of two parts: the substructure and the superstructure. The substructure is composed of cut and fill processes. Then, the superstructure consists of layered structures, such as sub-base, base, and pavement that transfer the traffic loads to the sub-grade soil. Before the construction of a superstructure, a sub-grade should be prepared, following the specifications, in a way supports the superstructure. The superstructure is affected by traffic loads and the environment. The traffic loads create radial shrinkage and compressive stresses with the movement of vehicles. The intensity and degree of stresses are directly proportional to the repetition of axle loads. It is required from sub-grade soil to resist these loads transferred from superstructures. The bearing capacity of soil is represented by Resilient Modulus (M_R) which provides insight into the elastic properties of materials used under roads and railways [26-29].

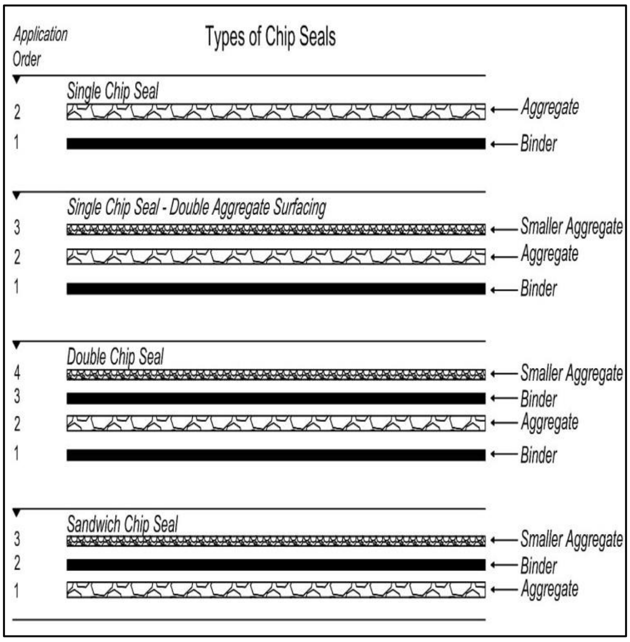

Figure 1. Types of chip seals.

This study has focused on the investigation of the effect of sub-grade soil bearing capacity on the thickness of the superstructure (sub-base and base) and the cost of chip seals. A design chart for chip seals presented in ‘‘Project Guide for Flexible Superstructure’’ was utilized to determine the thickness of the sub-base and base layers depending on the M_R of the sub-grade soil. This guide was prepared by the General Directorate of Highways in Turkey in 2008 [25]. A regression analysis was made to reveal the relationship between M_R and the thickness of the superstructure. Moreover, the displacements and stresses of the sub-base and base created by using the finite element method were shown. It has been indicated in this study that there is a strong relationship between the bearing capacity of the soil and the thickness of the sub-base layers. Thinner upper layers were obtained with the sub-grade soil with a higher M_R, and it was determined that the superstructure thicknesses increased as the bearing capacity of the sub-grade soil decreased. More realistic results were obtained by modeling the sub-base and base in Plaxis 2D. The general results indicate that it is economically important to choose the sub-grade soil to be used in the chip seals in the most appropriate way by paying attention to the environment and conditions.

2. Material and Method

In this study, the design chart of chip seals given in the ‘‘Project Guide for Flexible Superstructure’’ in Turkey was followed to determine the sub-base and base thickness in response to M_R

values. The relationship between the M_R of sub-grade soil and the thickness of the sub-base and base layers of chip seal pavement was determined. A regression analysis was performed to indicate the degree of relationship between these two parameters.

2.1. Resilient Modulus (M_R)

Pavements are designed based on the elastic theory. In this method, it is preferred to destinate M_R under repeated loads instead of the direct bearing capacity of materials. M_R is the elasticity modulus of material under cyclic loads and is the measure of the distribution of loads through pavement layers. In other words, it is the measure of the stiffness of pavement materials. The M_R is one of the main input parameters that affects the thickness of the superstructure of chip seals. The modulus of elasticity is an application of elastic theory. An approach was developed to determine the modulus of elasticity of pavement materials under repetitive traffic loads rather than static loads. Pavement materials are normally inelastic and showed some permanent deformation (plastic) after each load repetition. However, if the traffic load is small compared to the strength of the material, the material starts to show elastic behavior after a certain amount of load repetition. Figure 2 shows the deformation curve of a pavement material under the effect of repeated loads. As can be seen in the figure, in the elastic modulus test, while plastic deformations develop at a high rate under repetitive loads, as the number of repetitive loads increases, the increase in plastic deformation gradually decreases, and practically elastic behavior is observed after approximately 100-200 load repetitions [25, 30-32].

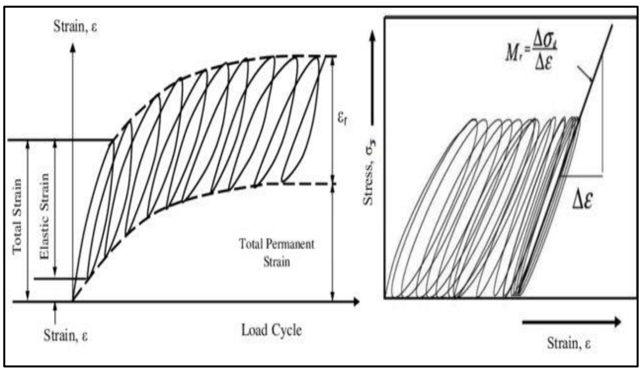

Figure 2. The behavior of the pavement materials under repetitive loads, and M_R [25].

The modulus of elasticity is the division of stress occurred by a slowly applied load divided by the recoverable strain. When the stress that occurred with rapidly applied loads is divided into recoverable strains, M_R is obtained. The M_R is measured from the cyclic load triaxial test where given a constant confining pressure and it is calculated from the relationship between the axial deviator stress and the recoverable axial strain. The schematic diagram of the triaxial test is given in Figure 3.

In the triaxial test, the ratio of deviator stress ($\sigma_d = \sigma_1 - \sigma_3$) to recoverable strain (ε_r) is called the M_R and it is calculated with the formula given below:

$$M_R = \frac{\sigma_d}{\varepsilon_r} \qquad (1)$$

The M_R for granular layers could be determined by laboratory or in-situ tests. However, these tests are very complex, sensitive, and expensive, and they require information and experience to apply. Therefore, the M_R could be determined by creating some empirical correlations with some easily found properties of the material sample. Since the M_R in granular materials depends on the soil structure, moisture content, and stress conditions, it differs in each pavement layer. The M_R tests were carried out on base, sub-base, and sub-grade samples were taken from different regions of Turkey in a way to represent all kinds of materials at the General Directorate of Highways, Superstructure Branch Directorate. The following general formula was obtained for the M_R of granular materials by analyzing the obtained test results with statistical methods.

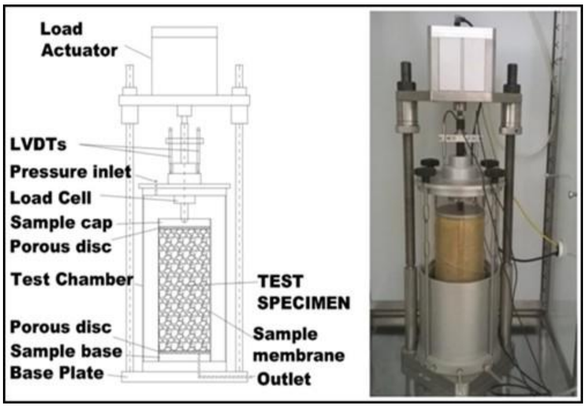

Figure 3. Testing apparatus of M_R [27].

$$M_R = 1750.(D_{BSK} + k)^{0.436}.CBR^{0.4}.\left[\frac{1}{1+\log(No_{200})}\right]^{0.35(LL.PI+1)^{0.06}}.\left[\frac{\gamma_{max}{}^2}{No_4}\right]^{0.09\log(w_{opt})} \qquad (2)$$

Here;

M_R : Resilient modulus, psi

D_{BSK} : Total thickness of bituminous hot mix, cm

CBR : California bearing ratio, %

ω_{opt} : Optimum moisture content, %

γ_{max} :Maximum dry unit weight, g/cm^3

LL :Liquid limit, %

PI :Plasticity index, %

No_{200} :Percentage passing through No_{200} sieve

No_4 :Percentage passing through No_4 sieve

k :Depth correction factor, cm

The (D_{BSK}+k) represents the variation of stress levels depending on the depth of the superstructure layer. DBSK is the total thickness of a bituminous hot mixture and is taken as 2 cm for single chips and 4 cm for double chip pavements. The depth correction factor k is selected from Figure 4 according to the layer and pavement section type.

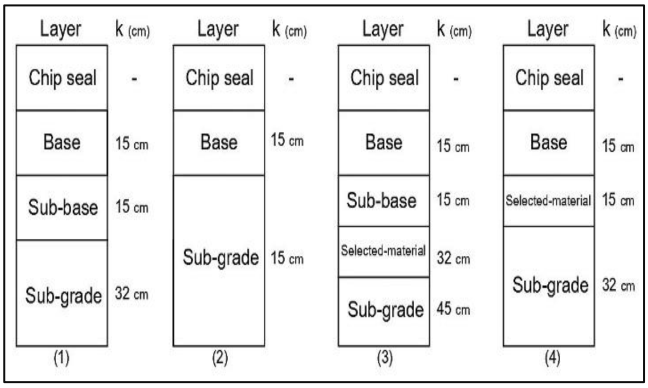

Figure 4. Depth correction coefficient (k) according to the superstructure section type [25].

In addition, various other correlations are used throughout the world. The AASHTO design guide suggests that the M_R of fine-grained soils can be estimated as [33]:

$$M_R(\text{psi}) = 1{,}500.\text{CBR} \tag{3}$$

U.S. Army Corps of Engineers [34]:

$$M_R(\text{psi}) = 5{,}409.\text{CBR}^{0.71} \tag{4}$$

South African Council on Scientific and Industrial Research (CSIR):

$$M_R(\text{psi}) = 3{,}000.\text{CBR}^{0.65} \tag{5}$$

Transportation and Road Research Laboratory (TRRL):

$$M_R(\text{psi}) = 2555.\text{CBR}^{0.64} \tag{6}$$

2.2. Design of Chip seals

It is the main aim to keep or restrain the distress resulting from traffic and environmental conditions within a limit in pavement design methods. There are two basic approaches created within the scope of the design of pavements: Mechanistic-Empirical (ME) and Empirical. The ME design method analyzes the stress and deformations caused by traffic and environmental factors on the road according to mechanical theories. Empirical design is based on experimental and observational results. Empirical design methods are widely used in road design today. In this method, the performance of the road is estimated according to the damages that will occur for a certain stress and deformation value of the road, taking into account a certain traffic load, physical properties of materials, and climatic conditions. It is important in the empirical design method to benefit from field experiences and observational results [35, 36]. In Turkey, the chip seal design guide is more empirical and based on AASHTO-1993. The thickness of chip seals is determined following the design chart given in Figure 5.

The bearing capacity of sub-grade soil and the traffic are the main parameters in the design phase of chip seals. Chip seals should be designed according to the M_R of the sub-grade soil and the total number of equivalent standard axle loads that will pass during the project life. Although the project period taken into account in the design chart is 10 years, the designer may accept the project duration as less or more, taking into account the importance and characteristics of the road [25, 37, 38]. The determination of the pavement thickness of the road, for which the M_R of the sub-grade soil and the equivalent standard axle traffic loads ($T_{8.2}$) is determined, will be as follows: By finding the number $T_{8.2}$ on the horizontal axis, a vertical line will be drawn to the axis and the point where this line intersects the curved line showing the sub-grade soil M_R value will be found. The required sub-base thickness will be found from the point where the parallel line drawn from this point to the horizontal axis intersects the vertical axis. From the upper part of the chart, the foundation thickness and chip seal type corresponding to $T_{8.2}$ will be selected.

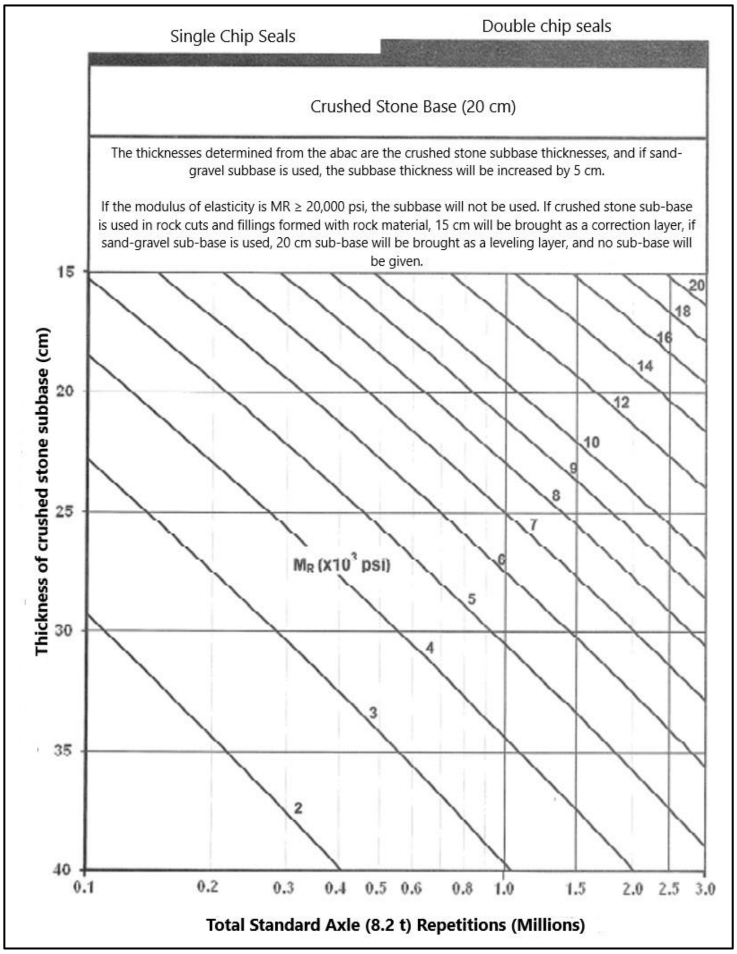

Figure 5. Design chart of Chip seals in Turkey [25].

2.3. Modeling of chip seals and substrates in Plaxis 2D

The behavior of many soil structures is analyzed using the finite element method [39]. Two- and three-dimensional analyses are made with the Plaxis finite element program, which is widely used in geotechnical engineering problems. Generally, it provides a faster and simplified solution with Plaxis 2D modeling. Therefore, the plaxis 2D finite element program was used in this study. The geometric model created in the Plaxis 2D program is shown in Figure 6. While creating the geometry of this model, it was prepared based on the technical specifications of the highways and the measurements in similar modeling studies [39-41].

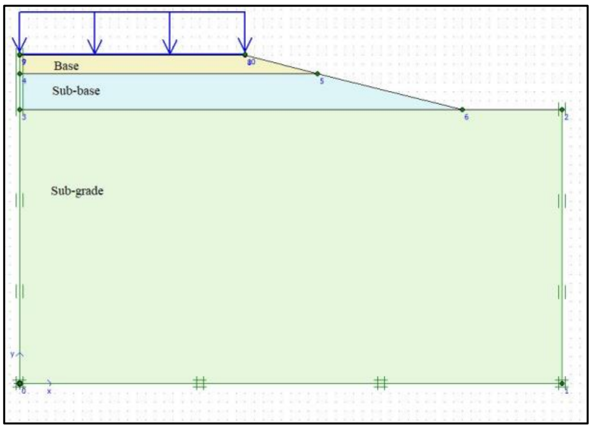

Figure 6. Layer representation used in modeling

The numerical model was created according to the plane unit deformation conditions and there is no groundwater table. In addition, a medium-density finite element mesh is used. It has been seen in the analysis that the geometric dimensions of the sub-grade are sufficient in terms of boundary conditions. In the Plaxis 2D program, they are defined as sub-grade, sub-base, base, and chip seal, respectively. The soil layer properties are given in Table 1. Layer thicknesses were solved separately for the cases indicated in Tables 2 and 3. The slope was chosen as 1 (vertical): 4 (horizontal) from the applied in highway road embankments. In addition, in the modeling, a load of 15 kPa, which corresponds to the heavy traffic load, is loaded evenly on the road surface [39]. Analyzes were made using the Mohr coulomb model in the Plaxis 2D program. The parameters specified in Table 1 are, respectively, the modulus of elasticity (E), unit weight (ɣ), Poisson's ratio (v), cohesion (c), internal friction angle (ϕ), and dilatation angle (Ψ).

Table 1. Properties of materials defined in Plaxis 2D

Parameters	Sub-grade	Sub-base	Base	Chip seal
E(kPa)	12500	50000	40000	120000
ɣ (kN/m^3)	16	16	17	27
v	0.4	0.3	0.3	0.3
c (kPa)	15	1	1	1
ϕ (°)	12	30	32	35
Ψ (°)	0	0	0	0

3. Result and Discussion

This study focused on the effect of the bearing capacity of sub-grade soil on the thickness and cost of the superstructure of chip seals. In addition, a linear regression analysis was performed to investigate the relationship between the bearing capacity of the subgrade soil and the thickness of the superstructure. Two-dimensional numerical modeling (Plaxis 2D) was also performed with the layer thicknesses found according to the M_R.

3. 1 Thickness of superstructures of chip seals

In this study, the relationship between the M_R of sub-grade soil and the thickness of the superstructure of chip seals was studied. In this manner, two traffic loads ($T_{8.2}$) were selected as 400.000 and 1.000.000. For these two values and some M_R values, the thickness of the sub-base and base layer of chip seals were determined as given in Tables 2 and 3. It is noticed that decreasing of M_R results in increasing sub-base thickness when Tables 2 and 3 are examined. The maximum and minimum values of the sub-base are 40 and 15 cm, respectively, for all conditions. And, the base thickness is 20 cm and constant for all M_R and $T_{8.2}$ values. Also, increasing $T_{8.2}$ values causes a thicker sub-base and results in changing of chip seal type from single to double.

Table 2. The thickness of the superstructure of Chip Seals for $T_{8.2}$ of 400.000

Traffic ($T_{8.2}$) (×1000)	Resilient Modulus (M_R)	Thickness of Sub-base (cm)	Thickness of Base (cm)	Chip Seal Type
	2	40		
	3	33		
	4	28		
	5	25		
400	6	22	20	Single
	7	20		
	8	18		
	9	16		
	10	15		

Table 3. The thickness of superstructure of Chip seals for $T_{8.2}$ of 1.000.000

Traffic ($T_{8.2}$) (×1000)	Resilient Modulus (M_R)	Thickness of Sub-base (cm)	Thickness of Base (cm)	Chip Seal Type
	2	40		
	3	39		
	4	34		
	5	31		
	6	28		
1.000	7	25	20	Double
	8	23		
	9	21		
	10	20		
	12	17		
	14	15		

A regression analysis was made to reveal the relationship between M_R and sub-base thickness for the value of $T_{(8.2)}$ 400.000. The analysis results are given in Figure 7. The R-square value and power function equation are also illustrated in the figure. The coefficient of determination (R^2) is 0.9304 and indicates a strong relationship and a confidence level between M_R and sub-base thickness.

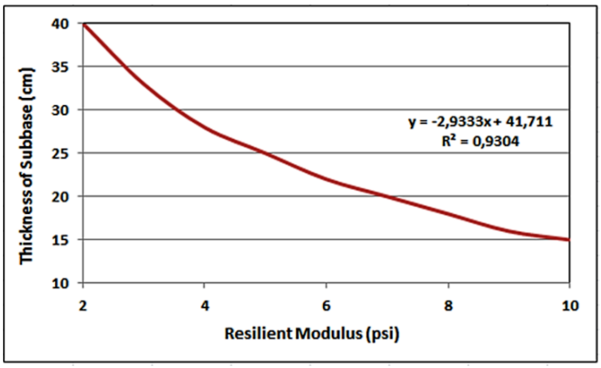

Figure 7. The relationship between Resilient Modulus (M_R) and sub-base thickness of chip seal for $T_{(8.2)}$ of 400.000.

Figure 8 shows the relationship between M_R and sub-base thickness for a traffic value of 1.000.000. The R-square value and power function equation are also presented in the figure. The correlation between M_R and sub-base thickness provided a higher R^2 value of 0.9478, thereby indicating a confidence level for the correlations.

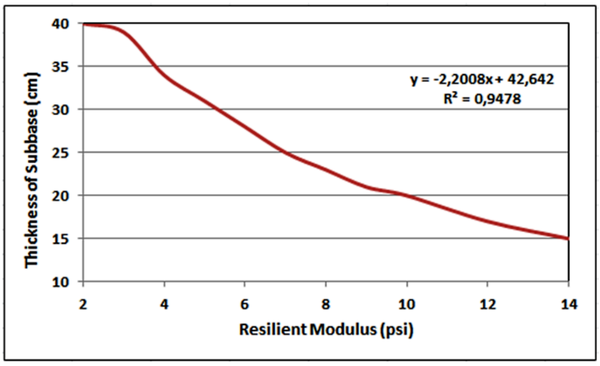

Figure 8. The relationship between Resilient Modulus (M_R) and sub-base thickness of chip seal for $T_{(8.2)}$ of 1.000.000

3.2. Modeling of Chip seals in Plaxis 2D program according to sub-base and base thickness

Single and double chip seals are modeled with the Plaxis 2D program. Soil parameters are given in Table 1, and layer thicknesses are given in Tables 2 and 3, which were used in the modeling. As a result, the total displacement, horizontal displacement, and total stresses of the single and double-chip seals in Tables 4 and 5 were found.

In Table 4, the total displacement increases as the single-chip seal thickness of the sub-base decreases, and accordingly, the stresses increase as the layer thickness decreases. In addition, as the sub-base layer thickness decreases, the horizontal displacement decreases.

In Table 5, as the double chip seal sub-base layer thickness decreases, the total displacement increases, and the total stresses increase. Moreover, horizontal displacement decreases as the layer thickness decreases in the double-chip seal.

Comparing the results of the Plaxis 2D program for single and double chip seals, the double chip seal produced 50% less total displacement and 20% less total stress on the substrates. As can be seen from the results, it is understood that the double-chip seal provides more bearing capacity and is less deformed. According to the results; since the double chip seal is less deformed, it provides a longer service life and requires less maintenance cost. In the literature, it has been observed that there are close results in experimental studies conducted in the field [40].

Table 4. Modeling results of the total displacement, horizontal displacement, and total stresses of the single-chip seal for $T_{8.2}$ of 400.000

Traffic ($T_{8.2}$) (×1000)	Resilient Modulus (M_R)	Thickness of Sub-base (cm)	Thickness of Base (cm)	Chip Seal Type	Total Displacement (mm)	Horizontal displacement (mm)	Total Stress (kN/m^2)
	2	40			0.186	0.127	65.64
	3	33			0.189	0.119	65.78
	4	28			0.191	0.114	66.05
	5	25			0.193	0.110	66.31
400	6	22	20	Single	0.194	0.108	66.59
	7	20			0.195	0.106	66.99
	8	18			0.196	0.104	67.41
	9	16			0.197	0.102	68.10
	10	15			0.197	0.101	69.11

Table 5. Modeling results of the total displacement, horizontal displacement, and total stresses of the double-chip seal for $T_{8.2}$ of 1.000.000

Traffic ($T_{8.2}$) (×1000)	Resilient Modulus (M_R)	Thickness of Sub-base (cm)	Thickness of Base (cm)	Chip Seal Type	Total Displacement (mm)	Horizontal displacement (mm)	Total Stress (kN/m²)
	2	40			0.0647	0.0837	54.15
	3	39			0.0686	0.0827	54.43
	4	34			0.0726	0.0777	54.89
	5	31			0.0739	0.0743	54.94
	6	28			0.0767	0.0713	55.33
1000	7	25	20	Double	0.0807	0.0685	55.58
	8	23			0.0847	0.0652	56.06
	9	21			0.0889	0.0630	56.49
	10	20			0.0937	0.0625	56.97
	12	17			0.1010	0.0590	57.77
	14	15			0.1020	0.0557	57.95

3.3. Cost Analysis of Chip Seals

The layers that constitute the superstructure of chip seals have top and bottom limits. The sub-base of chip seals has a bottom limit of 15 cm. The thickness of the base is generally taken as 20 cm for crushed stone and the thickness of the crushed stone base is also taken as 20 cm for this study [25]. In this study, the effect of sub-grade soil bearing capacity on the cost of chip seals for the aforementioned traffic loads of $T_{8.2}$ was investigated. In the Highways General Directorate unit price lists, the cost of the bituminous layer is given in decare (1000 m^2) units. The unit of plant-mix base and sub-base layer is given in tons and m^3 respectively. The cost and unit price of layers of chip seals according to the year 2022 are clearly given in Table 6 [42].

The total costs of a 1 decare (1000 m^2) of a single chip with M_R 10 (psi) and 5 (psi) and traffic loads of 400.000 $T_{(8.2)}$ are 84992,23 TL and 96652,23 TL, respectively.

The total costs of 1 decare (1000 m^2) of a double chip with resilient modulus 10 (psi) and 5 (psi) and traffic loads 1.000.000 $T_{(8.2)}$ are 94003,03 TL and 106829,03 TL respectively. If the bearing capacity is taken as approximately 50% less than the actual value, the total cost of both single and double chip seals increases by approximately 14% for 1000 m^2 chip seals type pavement. When Tables 2 and 3 are examined, it is seen that with the doubling of the M_R, significant reductions in layer thickness occur.

4. Conclusions

Chip Seal is an economical, flexible type of pavement consisting of layers of aggregates and bituminous binders and is applied as a preventative improvement to an existing road or for paving low-traffic roads. The main parameters for the design of chip seals are the bearing capacity of sub-grade soil and traffic values. The bearing capacity of sub-grade soil is represented by the Resilient Modulus (M_R) of pavement material. This study presented hereby focused on the investigations of the relationship between the bearing capacity of sub-grade soil and the thickness of the superstructure of chip seals. In addition, the displacement and stresses of the sub-base and base created by using the finite element method are shown. The study has revealed that there is a strong relationship between these two parameters. Increasing M_R, in other words, the bearing capacity of sub-grade soil resulted in a decrease in the thickness of the superstructure of chip seals in all observed traffic values. The higher coefficients of the R-square of relationships between the bearing capacity of soil and the superstructure thickness of chip seals indicate a high confidence level for the correlation. It is important to take exact values of M_R of sub-grade soil in calculations of the thickness of pavements because of having a great impact on bearing capacity on the thickness of pavement layers considering economic. In addition, the importance of M_R in Plaxis 2D modeling has been seen. No matter how much the thicknesses changed, it was observed that the settlements and stresses did not increase as the M_R increased. According to the conclusion reached together with the general evaluation, it is economically important to choose the sub-grade soil to be used in the chip seals in the most correct way by paying attention to the environment and conditions.

Table 6. Unit costs according to layer types

No	Definition	Unit	Unit Price
KGM/6540	A bituminous surface coating with one layer lining (Type-1) (With crushed and sifted quarry stone)	daa	3719,83
KGM/6560	A bituminous surface coating with double layer lining (Type-1+Type-3) (With crushed and sifted quarry stone	daa	6900,63
KGM/6100/3	A plant-mix base layer (with crushed and sifted quarry stone) (Note: The density of the layer is 2,4 gr/cm^3)	ton	132,88
KGM/6000	Sub-base construction (with 2" crushed and sifted quarry material)	m^3	116,60

Contributions of the authors

Muhammed TANYILDIZI: Conceptualization, Methodology and Writing- Original Draft Preparation, Visualition, Supervision, Reviewing and editing.
Muhammet ÇINAR: Data curation, Writing- Original draft preparation, Software, Validation, Reviewing and editing

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

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