Review of some Geotechnical Aspects on Structural Response of Rigid Pavements

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Abstract
A highway pavement consists of stacked layers of processed materials over a natural soil subgrade to distribute traffic loads. The pavement should have a suitable riding surface, skid resistance, light reflectivity, and little noise pollution. The purpose is to reduce wheel-load transmitted stresses, so they don't exceed subgrade bearing capacity. Flexible and rigid pavements are employed. This paper identifies and summarizes papers by studies on rigid pavement response and performance. It will also explain subgrade soil and its improvement, rigid pavement analysis and design by various approaches, and the appropriate plan and response reduction (stresses, strains, and deflection) to avoid early pavement failure due to traffic loads.

Keywords: -Concrete, Geotechnical Aspects, Highways, Rigid Pavements, Soil Properties, Subgrade.

1. Introduction

A rigid pavement system consists of several reasonably thick Portland cement concrete slabs with finite length and width laid over one or more foundation layers (subbase or subgrade). The structural response (stresses, strain, and deflection) occurs when traffic loads are applied to the slab.

The structural response of a rigid pavement allows for the determination of how the system reacts to various solicitations that it is subjected to during its work regime. Hence, it is the foundation of design methodologies. The fatigue failure of the concrete slab and the erosion failure of the foundation are two failure criteria considered by the design procedures in these pavements. The structural reaction in terms of tensions and displacements is obtained, and the permissible values at critical points of the slab are checked using empirical models. The models depict the system‘s behavior due to repeated loads during the design process. The rigid highway pavement is a rectangular plate supported by an elastic soil foundation with a subgrade modulus (K) that allows only downward mass displacement and no horizontal deformation. Rigid pavement types are categorized into three broad categories based on how they control cracks.

1. Jointed Plain Concrete Pavement (JPCP)
2. Jointed Reinforced Concrete Pavements (JRCP)
3. Continuously Reinforced Concrete Pavements (CRCP)

Bending theory is crucial for stress analysis in rigid pavements because it may retain a beamlike motion despite inconsistencies in the underlying materials. It is possible to determine the stresses in pavement using the beam idea supported on an elastic basis. When a load is applied from the outside, an elastic beam deforms. The subgrade soil is a portion of the pavement structure to withstand load transfer from the pavement surface layer. It is divided into two main types: fine-grain soil with a particle size less than 0.05 mm, such as (silt or clay), and coarse-grain soil with a particle size higher than 0.05 mm, such as (sand or gravel). The value (0.05mm) is the lowest measurement of soil particles observed with the naked eye, so this value was chosen.

The roles of subgrade properties such as (modulus of subgrade reaction (K), modulus of elasticity (Esub), angle of internal friction (ø), California bearing ratio (CBR)), and concrete properties such as (modulus of elasticity (Ec), Poisson‘s ratio (μ), compressive strength (f'c), modulus of rupture (Sc)) are played an important factor that is influenced on analysis and appropriate rigid pavement design as well as the determination of structural response (stresses, strains, and deflections). While inspecting the subgrade, potential failure scenarios include basal heave, slope instability, probable void formation, and subgrade compressibility (see Fig. 1).

Different concerns will apply depending on whether the foundation is a natural or built subgrade or whether it covers current trash. An adequate site study is necessary to examine voids in a non-waste subgrade to understand the possibility of soil collapse and settling. To determine the potential of voids development and the projected amount and distribution of total and differential settlements, the waste stream, method of disposal, compaction, and age of the waste must all be addressed. The stability of the subgrade is essential to prevent movement that might harm the lining system above.

For sturdiness, consideration must be given to cut, fill, and natural slopes (see Fig. 1). For the slope subgrade, stability, deformations, and void potential will be design considerations. Even after trash dumping, short-term stability does not ensure long-term leading stability for slopes in fine-grained soils. Hence, it's essential to look at time-dependent failure mechanisms. Stability assessments of rock masses should consider rock mass and jointing patterns to guarantee that the slope stays stable during and after the waste building.

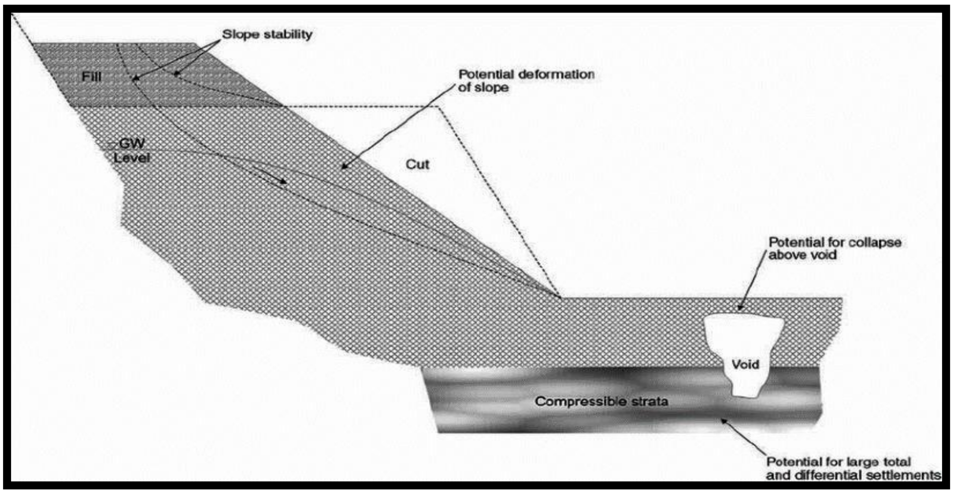


Fig. (1): Mechanisms of subgrade failure

2. Subgrade soil

Construction begins with a solid foundation in the subsoil layer. Rigid pavement design and analysis depend on subgrade quality data, which may be acquired by in-situ testing of the natural foundation soil or laboratory research to establish permissible compaction levels. It is common for the subgrade soils on a building site to be inadequate to resist the pavement structure. It may have an unsatisfactory grade, a lack of stiffness, or instability against swelling. Combining two or more types of soil and ensuring there isn‘t mechanical stability, it may be possible to remedy some of these inadequacies (compaction).

To stabilize further faults in the subgrade, such as voids and cracks in the pavement, it is possible for the bituminous binder it increases the soil‘s workability. Many admixtures may be used to improve the workability of the soil, prevent swelling, and offer a suitable platform for building, in addition to boosting the soil's strength and stiffness. The subgrade soil may be characterized as one of the following according to AASHTO and USCS classifications as shown in table (1):

Table (1): classification of subgrade soil

Subgrade Soils	
Names	**Samples**
Gravelly Soils	(A-1; A-2; GW; GP; GM; GC)
Sandy Soils:	
Loose Sands	(A-3; SW; SP)
Dense Sands	(A-3; SW; SP)
Silty Sands	(A-2-4; A-2-5; SM)
Clayey Sands	(A-2-6; A-2-7; SC)
Silty Soils	(A-4; A-5; ML; MH)
Clayey Soils:	
Low Plasticity Clays	(A-6; CL)
High Plasticity Clays	(A-7; CH)
Dry-Hard, Moist Stiff, Wet/Sat-Soft	------------

3. Subgrade Failure Mechanisms

Soil is a disorderly mix of minerals and organic and sedimentary components that may be found above bedrock and in any area that isn‘t coated with shale or rocks. When soils are classified by particle size and grade, three types of soils may be found: granular soils made up of coarse-grained or granular materials, cohesive soils composed of fine-grained materials, and silty soils, which fall somewhere in between. While water has little or no effect on mechanical forces in coarse soils, it significantly impacts electrical and chemical muscles in fine soils. Pore fluid (such as water) substantially affects the interaction between particles. Particle size and gradation are crucial in coarse-grained soils. Consistent gradation describes soils with a high degree of permeability and a uniform particle size distribution. The density and strength of a material are both improved when it is well-graded, which means it has a wide range of particle sizes. Gap grading also refers to the soil‘s absence of specific particle sizes. For this reason, roadway engineers focus more on soil shear strength as a measure of soil stability. Cohesiveness and angle of internal friction are the two factors that go into determining a soil‘s shear strength, as indicated below:

$$S = C + \sigma \tan \emptyset \text{.....................................(1)}$$

Depending on the kind of soil, either cohesiveness or the angle of internal friction gains or loses significance. When it comes to clays, cohesion is a critical factor in determining the soil's shear and strength. The angle of internal friction of saturated clays is frequently believed to be zero, resulting in shearing resistance equal to the cohesiveness C in any plane of these soils. Moisture content, drainage conditions, and density all impact the shear strength of cohesive soils. A significant source of shear strength in coarse-grained soils is the internal resistance to sliding when the particles roll over one another. As a consequence, the angle of internal friction is crucial—these facts and surface roughness- all impact the angle of internal conflict. When the density is large, the angle of internal friction tends to be as well-defined. Angular sand grains, for example, will cause a high internal friction angle in soils that include abrasive particles. Before road construction, geotechnical concerns were commonly overlooked or incorrectly evaluated. Inadequate geotechnical data has resulted in several pavement failures, detailed in this section.

a) FROST HEAVE

Because soil water expands by about 10% when it freezes, temperatures below freezing are more likely to cause it to freeze in soil pores. Two big problems will arise as a consequence of this situation. Firstly, the soil's volume also increases. The second problem is that freezing may create ice crystals and lenses several centimeters thick in the ground. The pavement might be severely damaged if one or both conditions are present. Ice lenses also melt in the spring, resulting in a large increase significant the soil's water content (spring. thaw). Due to this "spring break-up," the soil weakens, resulting in structural damage to the road surface. Three conditions must be met for considerable frost activity to occur:

1. For many days, the ambient temperature must be below freezing.
2. A shallow water table must provide capillary water to the frost line.
3. The soil must be prone to frost damage.

Because granular soils have a relatively high coefficient of permeability, they are not prone to frost. Clay soils are also less sensitive to frost action due to their limited permeability, which means that not enough water can move during a freezing spell to allow ice lenses to develop. However, sand or silty clays and broken clay soils near the surface may be sensitive to frost. Silty soils are the most susceptible to frost. The grain size for frost sensitivity has been established to be 0.02 mm.

b) Expansive or swelling soils

It is a term used to describe the swelling of roadbed soils that expand as they absorb water. Causes pavement degradation. Traditional additions such as cement or lime may help to lessen the issues associated with extensive grounds. Furthermore, using "silica-alumina" or "silica" based materials in widespread soil stabilization is a cost-effective alternative to traditional cement and lime materials. These materials exhibit pozzolanic reactions, which result in gel polymers that improve soil strength. Industrial or byproduct resources such as blast furnace slag, fly ash, silica fume, and so on may be used to make pozzolanic materials [1],[2],[3]. When a rigid pavement is built on top of a lime-stabilized expanding soil, lime stabilization is used to raise a subgrade soil's CBR over a particular level. Lime is chosen since it is an inexpensive and commonly accessible substance. They used (3, 6, 9, and 12) % of lime to stabilize expanding soil. A CBR of 8% was attained on a 9 percent lime base. A variety of traffic data is used to determine the axle load spectrum. The pavement was constructed with an 8 percent CBR rating and a 0.31m thickness. [4]

When expansive soils are stabilized using pozzolanic materials, their geotechnical qualities improve to varying degrees (it has a considerable influence on swelling and Atterberg-limits, as well as a beneficial effect on compaction and strength parameters when utilized in the (1.5-30) percent range). Furthermore, a 15% content is the most significant ratio of stabilizers used as an optimal proportion. [5].

c) Collapsible soils

When saturated, collapsible soils feature metastable structures with substantial volume drops. The most prevalent kind of collapsible soil is silty loess deposits. Before construction, collapsible soil subgrades must be saturated in water and rolled with high-compaction machinery. Nano-clay has a more elevated specific surface than nano-silica, resulting in a significant drop in collapse potential when added to the soil. In contrast, nano-copper and nano-alumina had the opposite effect [6].

[7] Employing iron powder to treat collapsible soils had a favorable effect on lowering the projected collapse settlement. There have also been two distinct patterns in the connection between reduction ratio (Rs) and additives (Ad): the first is directly proportional to (Ad) values between 4 and 6 percent. In contrast, the second is inversely proportional to (Ad) values between 6 and 10 percent.

d) Pumping

Rigid pavements have more sophisticated pumping systems than flexible pavements. Pumping in the rigid pavement is the traffic-induced vertical and horizontal movement of soil particles from the completely saturated fine-grained subgrade soil into the granular subbase layer and onto the surface. To produce voids under a slab, the volume of the materials may be reduced or shifted. [8].

A rigid pavement with an erodible (poorly stabilized) layer just under the lowest bound layer (i.e., the subbase and base) is particularly prone to pumping. Passing traffic causes stress and pore pressure in the leave slab to grow fast, while the forces in the approach slab decline. The water also rapidly returns from the left slab to the approach slab to move and displace supporting elements (fines). A gap of varying widths may appear under the leave slab as the approach slab rises, producing faulting [9]. The main goal of pavement geotechnical design is to identify possible issues with soils. Approaches and mitigation strategies should be developed for these unique circumstances. Pumping is only possible if three conditions are met: intense cyclic traffic load repetitions, saturated subgrade, and subgrade soil containing considerable fines [10],[11]. As a result, the tension created at the subgrade-subbase contact is proportional to pore water pressure, with the highest stress right under the wheel path (and at the joint in rigid pavements). Pumping has the potential to compromise rigid pavement performance. Special remedial procedures may be necessary if highway embankments are built on collapsible soils to prevent large-scale cracking and differential settling. Historically, materials' permanent deformation resistance and stiffness have been assessed using strength indices such as the California Bearing Ratio (CBR). The use of the resilient modulus (MR) to measure stiffness has lately supplanted the use of these quality criteria. Most geomaterials have a high degree of correlation between their strength and stiffness.

4. Improvement of Subgrade soil under Rigid Pavement

When the subgrade soil is insufficient to resist the requisite loads, further work should be done to make the material suitable for construction and extend the pavement‘s life. The improvement of soil is one of these efforts, including two well-known categories. The first is a conventional improvement, and the second is a nanomaterial-based improvement.

4.1. Conventional Improvement

Soil stabilization is improving the soil to execute a specific task. Mechanical and admixture soil stabilization methods fall into two categories. Densification or compaction, granular material addition and compaction, and reinforcement, such as geotextile, are all options for mechanical stability. Additives like lime, Portland cement, and waste material can stabilize the mixture (including compaction as part of the process). Soil that has been lime-treated improves its strength, durability, and workability. The compressibility of the soil is also improved as a result of this treatment. A fluctuation behavior was noticed in the impact of lime on soil permeability. On the other hand, the variables impacting the permeability of the soil-lime combination should be thoroughly investigated. Despite this, carbonation, sulfate attack, and environmental degradation are only some of the downsides of lime therapy. So, magnesium oxide/hydroxide is advised as an alternative stabilizer to relieve at least some of the limitations of lime in soil stabilizing [12]. Adding 2% lime to natural soil enhanced its mechanical strength and load-carrying ability. Compaction effort and cure time generated different results in the unconfined compressive strength (UCS) and California Bearing Ratio (CBR) tests [13]. Increased density and compaction dramatically improve the strength of lime and fly ash stabilized soil after 7 and 28 days; however, the ideal lime to fly ash ratio is altered insignificantly, according to the research. Lime aggregation is caused by increasing the amount of lime added to the clay. The decrease in strength is roughly proportionate to the decreasing percentage of solids, as indicated in the results [14]. Furthermore, incorporating fly ash and cement into subgrade soil enhances its stability. While waste fly ash and cement are cost-effective and ecologically friendly alternatives to expansive soil for future pavement and foundation building [15]. When 6 and 10% Portland cement were used to strengthen the poor subgrade soil of a highway embankment, a linear relationship was discovered between the cement content, the strength of the improved soils, the stabilization depth, and the factor of safety [16]. Because of the decreased relative density of the plastic material compared to the soil particles, the results reveal that adding plastic wastes reduces the maximum dry densities of the subgrade soils. It was also discovered that adding plastic wastes to the subgrade might change the CBR and MR values. The quantity and form of the change (increase or reduction) are determined by the plastic content, shape, and type. The addition of plastic garbage enhanced the permeability of numerous subgrade soil samples, but the hydraulic conductivity of certain soils transformed with plastic remained unaltered. Plastic-coated subgrade soils showed a larger friction angle and poorer compressive strength than soils without plastic. [17]

4.2. Improvement by nanomaterials

Different types of nanomaterials additives can stabilize the subgrade soil strength and durability to make it more durable and reduce erosion. It is essential to know the physicochemical properties; mechanical properties change in subgrade soils when the nanomaterials have been added. [18] The nanomaterials additives in different subgrade soils will provide a series of physicochemical reactions among nanomaterial additives and soil particles, which improves the performances of subgrade soils such as compaction and shear strength due to filling the voids among soil particles. The effect of multi-walled carbon nanotubes and carbon nanofibers on subgrade soils' stability and physicochemical properties [19].

Scientific researchers have explained that nanomaterials can improve the mechanical properties of subgrade soils and make them an engineering subgrade. [20] observed that the stiffness of a high-expansive soil subgrade is increased due to promoting the ion exchange and hydration reaction of soil particles with nanomaterials of palm beam ash which has the same properties as volcanic ash. The stability of subgrade improved due to chemical reaction between nano-silica particles of different sizes (10 μm, 29 μm, and 100 μm) and soil particles which are produced calcium silicate hydrate (C-S-H) and calcium silico-aluminate hydrate (C–A–S–H) gels with structural chain [21]

When three nanomaterials (nano-copper, Nano-alumina, and Nano-magnesium) were added to the soft soil in small content of less than 1% by the soil dry, they provided improvement in maximum dry density and unconfined compressive strength [22]. The soil's shear strength and California bearing ratio (CBR) were increased, and the strength and stability of the subgrade soil were enhanced when a nano chemical material was added as a stabilizer to improve the subgrade [23].

[24] The combination of 30% fly ash and nano solution was added to the silty soil subgrade to treat it. They concluded that the CBR was greatly improved, and the permeability coefficient was decreased by 86%. The unconfined compressive strength rapidly increased in nano-alumina, and cement-modified disintegrated carbonaceous mudstone stabilized gradually when nano-alumina content increased. The cement-stabilized soil's unconfined compressive strength and flexibility were improved when the cement content was 13%, and the optimal nano-magnesia content was 15% [25].

[26] The addition of nano-iron oxide to natural soil at 0.5, 1, 2, 3, 4, and 5%. The soils were compared before and after stabilization using scanning electron microscopy (SEM) and direct shear, unconfined compressive strength, and consolidation tests. The author observed that adding up to 2% nano-iron oxide may raise the strength parameters of textural feat (including cohesiveness and internal friction angle) and decrease the compressibility and swelling coefficients of the examined soil. When Nano-clay and Nano-silica were introduced to gypsum soils from Al-Najaf in Iraq, the cohesiveness value and friction angle increased [27].

The UCS and shear strength of clay treated with 1.0% nano-SiO2 were increased by 16% and 21% compared with natural clay after nine cycles of freezing and thawing. Nano-SiO2 produces whiskers under thermal stresses when scanning electron microscopy (SEM) images were used. The formation of filamentary networks as a result of the whisker phenomenon enhances the clay's mechanical characteristics significantly [28].

5. Rigid pavement Design and Analysis

AASHTO's rigid pavement design technique entails solving an empirical equation. The only result received after the iteration is the thickness of the concrete slab. The empirical equation is written as follows:

$$log_{10}(W_{18}) = Z_R \cdot S_o + 7.35 log_{10}(D+1) - 0.06 + (4.2 - 0.32 p_t) log_{10}\left[\frac{S_c \cdot C_d \cdot (D^{0.75} - 1.132)}{215.63 \cdot J \cdot \left(D^{0.75} - \frac{18.42}{\left(\frac{E_c}{k}\right)^{0.25}}\right)}\right]$$

Fig. (2): rigid pavement design equation

Where the variables are as follows:

W18: predicted number of 18-kip traffic load applications (ESAL), S_0: the combined standard error of traffic prediction, ΔPSI: serviceability change during the design period, pt: final serviceability of pavement, Sc: modulus of rupture of PCC, Cd: drainage coefficient, J: load transfer coefficient, Ec: elastic modulus of PCC, K: modulus of subgrade reaction, D: slab thickness

A nomograph for solving the above equation is shown in Figure (3). The nomograph does not include pt since it was expected that pt = (4.5-ΔPSI).

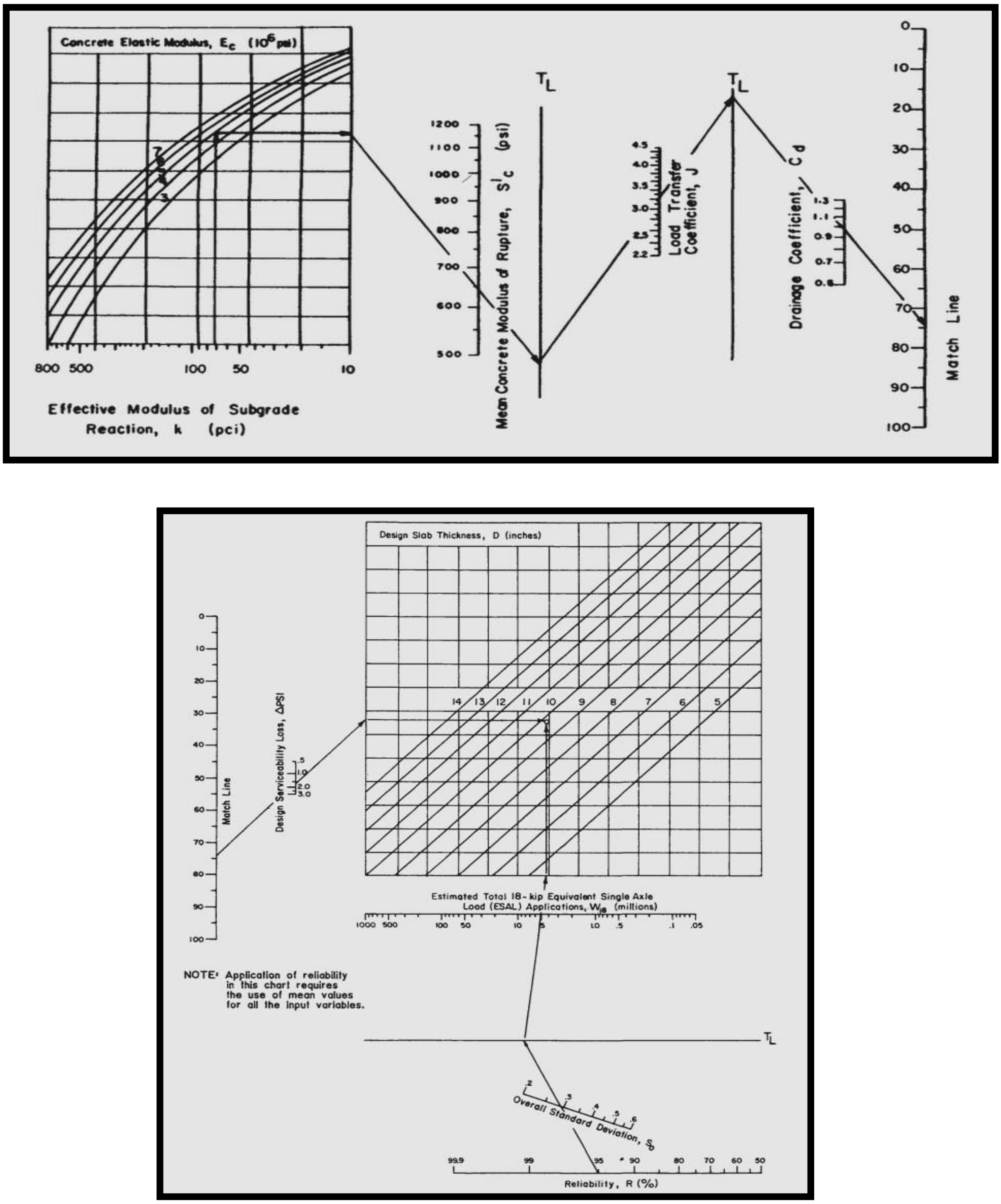


Fig (3): Design chart for rigid pavement

Final Serviceability Index (pt)

This is the ultimate serviceability index when the pavement is judged to have reached the end of its service life. Depending on how the road is used, typical values vary from 1.5 to 3.

Modulus of Rupture of PCC (Sc)

Concrete's modulus of rupture is a measurement of the material's flexural strength obtained by breaking concrete beam specimens. Flexural test data are used to calculate the Modulus of Rupture.

Drainage Coefficient (Cd)

The sub-base layers under the concrete slab have a drainage coefficient, which indicates how well they drain. Pumping is unlikely because supply water cannot sufficiently saturate the underlying layers with drainage. Drainage coefficients of 1.2 are assigned to quickly draining layers that are seldom wet, whereas drainage coefficients of 0.8 are set to slowly draining layers that are regularly saturated. Table AASHTO, 1993, lists the allowable drainage coefficient values (2). For this reason, rainfall and drainage conditions directly influence how long a pavement structure is exposed to moisture each year. The drainage coefficient is widely used as an input parameter in rigid pavement design. Because of this, the designer may choose a reasonable amount from the table (2).

Load Transfer Coefficient (J)

Load transfer coefficients explain how reinforcing steel, tie shoulders, and tied curbs alleviate stress during pavement construction. Tied shoulders and load transfer devices increase load transfer and minimize the coefficient of force transmission. This value decreases with a more significant load transfer. The allowable load transfer coefficients are listed in Table (3) for different pavement materials and design conditions.

Elastic Modulus of PCC

The modulus of elasticity measures how well a material returns to its original shape and size after being stretched or compressed. When stress and strain are given to a system, the result is known as a "load." Furthermore, the slope of a stress-strain curve may be defined as the rate at which the material's elastic range expands or contracts under continuous loading. High-stiffness materials like PCC, according to AASHTO, should have their elastic modulus measured using ASTM C 469's procedure (AASHTO, 1993). The elastic modulus of PCC may also be estimated using a correlation provided by the state's transportation agency or a reputable company. The American Concrete Institute suggests the following correlation for standard-weight Portland cement concrete. [29]

$$E = 57{,}000\, f'c^{0.5} \qquad (2)$$

Where: Ec: PCC elastic modulus (in psi), f _c: PCC compressive strength (in psi)

Table (2). Recommended Values of Drainage Coefficients Cd for Rigid Pavements

Quality of drainage		Percentage of time pavement structure is exposed to moisture levels approaching saturation			
Rating	Water removed within	Less than 1 %	1-5 %	5-25 %	Greater than 25 %
Excellent	2 hours	1.25-1.20	1.20-1.15	1.15-1.10	1.10
Good	1 day	1.20-1.15	1.15-1.10	1.10-1.00	1.00
Fair	1 week	1.15-1.10	1.10-1.00	1.00-0.90	0.90
Poor	1 month	1.10-1.00	1.00-0.90	0.90-0.80	0.80
Very poor	Never drain	1.00-0.90	0.90-0.80	0.80-0.70	0.70

Table (3) Recommended load transfer coefficients for various pavement types and design conditions.

Type of Shoulder	Asphalt		Tied PCC	
Load transfer devices	Yes	No	Yes	No
JPCP and JRCP	3.2	3.8-4.4	2.5-3.1	3.6-4.2
CRCP	2.9-3.2	N/A	2.3-2.9	N/A

Effective modulus of Sub-grade Reaction

The AASHTO guidance helps the rigid pavement designer account for all the layers that will be put beneath the concrete slab. It also allows designers to assess the impact of underlying materials losing support owing to erosion or degradation. This is accomplished by calculating the effective modulus of a sub-grade reaction (Keff.). AASHTO (1993) considers several criteria in addition to the resilient modulus of the roadbed soil. The sub-base type, the sub-bases thickness, the loss of support, and the depth of the rigid pavement are all factors to consider. The computer following theoretical relationship describes the composite modulus of subgrade response characterized by the following theoretical relationship:

$$Keff = MR/19.4 \qquad (3)$$

Where MR: is the roadbed soil elastic modulus and Keff: is the subgrade reaction effective modulus.

After these adjustments have been performed, the K_{eff} value is used in the primary design equation to predict the required slab thickness. Finally, to account for the likelihood of support loss due to sub-base erosion, the K_{eff} value should be raised.

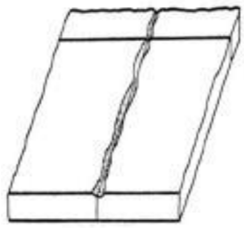
The KENSLABS computer software uses the finite-element method (Huang, 1985), which divides the slab into finite rectangular elements with many nodes. The slab is subjected to wheel loads and subgrade reactions as concentrated vertical forces at the nodes. Liquid, solid, and layer foundations are the three types of foundations. Westergaard's theory and most of today's finite- element computer systems are built on a liquid foundation. The simultaneous equations are solved using liquid foundations, resulting in a banded matrix that can be solved in a short amount of time on a computer. However, if personal computers have substantially faster speeds and more excellent storage, more realistic solid and layer foundations should be used if necessary [30].

Various methods are used to determine the rigid pavement response, including (ABAQUS, ANSYS, STAAD-PRO, ADINA, and Ever FE). Several studies used these systems to compare outcomes to established standards. After a static load revealed an inverse relationship between thickness and deflection for concrete containing 30% recycled concrete aggregate when a varying thickness of recycled concrete aggregate is used from (150-300) mm with an elastic soil foundation (K) that allows for only downward mass displacement, as well as a computer analysis program STAAD-PRO and manually Westergaard's analysis theory is used [31]. [32] Compared KENSLABS and Ever FE software findings based on modeling and solution methodologies such as element type, meshing, traffic load, temperature curling, boundary conditions, and contact conditions. The two software packages were conducted to demonstrate their significant functions based on one specific case situation. Some exciting relationships between slab thickness, stresses, and deflections were discovered as the structural packages were subjected to four types of loaded axles with the maximum legal loads per axle established in Colombia: steering axles, with a load of 6 tons; single axles with double wheels, with a pack of 11 tons; tandem axles, with a group of 22 tons when used the Ever FE finite element program [33] The optimal rigid pavement thickness was found to survive temperaturevariations, high humidity, and a variety of load combinations. Furthermore, for a better understanding of the essential stress and the places in the design where the pavement requires attention, a quick notion of pavement thickness selection according to the Finite Element Method (FEM) based on Software KENPAVE and ANSYS 12.1. This program considers these many aspects, and the results are shown in graphs, figures, and deflected forms. They found the appropriate pavement thickness using parametric change (such as varying the thickness of the QPC and DLC layers and the Modulus of Elasticity), modification in poisons ratio, and temperature. [34].

6. Rigid Pavement Failure Criteria

There are several kinds of rigid pavement failure, which will be detailed in the table (4) below:

Table (4): Kinds of rigid pavement failure.

Failure Type	Description	Figures
Joint Spalling	Joint degeneration, commonly known as spalling, is caused byexcessive compressive stress. This might be due to joint infiltration or reactive aggregates causing pavement expansion. Poor concrete or building procedures may also cause joint spalling. Little edges to massive spalls may be noticed in the rear of the slab and down to the joints. The primary causes of joint spalling in rigid pavements are as follows: Due to increased traffic or penetration of any incompressible materials, joints are exposed to extreme stress 1. The joints are made of weak concrete. 2. Water has accumulated in a joint, causing rapid freezing and thawing. Spalls in the joints can be avoided by employing proper construction procedures or sealing the joints. [35] [36]	
Joint Seal Cracking	Damaged joint seals allow incompressible materials or water to penetrate from the surface. Common joint seal deteriorationincludes extrusion, hardening, adhesive failure (bonded), cohesive failure (splitting), total sealant loss, and weed growthin the junction. This discomfort is assessed by counting sealed longitudinal joints and their length. It's irrelevant. [35] [36]	

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Faulting	Faulting is the variation in elevation between the joints. The following are the most common faulting-related failures in rigid pavements: **1.** Settlement of the pavement as a result of a spongy base. **2.** Pumping or erosion of material beneath the pavement slab, resulting in cavities beneath the slab and causing settlement. **3.** Curling of the slab edges is caused by temperature and moisture variations. [35] [36]	
Polished Aggregate	The repetitive application of traffic causes this distress. These rigid pavement failures occur when the aggregates above the cement paste in the case of PCC are tiny, the particles are not rough, the aggregates are angular in shape, and the vehicle skid resistance is insufficient. Before starting the building, the polishing degree should be selected. The results of this investigation are included in the condition survey, which is listed as a flaw. [35] [36]	
Pumping	Pumping is the removal of water from under a layer of pavement. Dynamic vehicle loads across the pavement often cause this annoyance. Consequently, the sub-delicate base's components will flow with the water and be evacuated with it—evacuation results in more significant gaps under the surface. Stains on the pavement or the shoulder detect this rigid pavement collapse. Pumping may be avoided by minimizing water collecting at the pavement's sub-base contact. This may be done by limiting deflection and providing a strong, well-built sub- base. So that the subgrade underneath it does not get saturated, the built sub-base must have enough drainage. Installing an underground drainage system in the current pavement design is the best answer for pumping difficulties. [35][36]	

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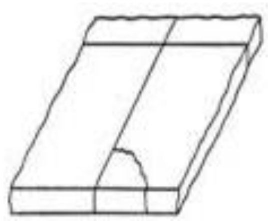
Corner break	These are rigid pavement defects caused by heavy pumping. Corner cracks happen when the underlying support is eliminated, and there is no longer any aid below to sustain the vehicle‘s weight. It is necessary to replace the whole slab or repair it to its full depth. [35] [36]	
Blowups	Concrete cracking may occur due to blowups, which are differences in slab length that produce localized upward displacement of the pavement surface at transverse joints or face fissures. The number of tantrums is a standard metric for assessing a user's level of discomfort. [35] [36]	
Punchout	Punch-out distress is a term used to describe a fractured concrete slab in a specific place. Distress can manifest itself in a variety of ways. Joints and cracks are the most prominent features. The breadth of the joints and cracks will mostly remain at 1.5 meters. Heavy repetitive loads, slab thickness insufficiency, foundation support loss, or design flaws such as honeycombing are themost common causes of punchouts. [35] [36]	
Longitudinal Cracking	The length of these stress fractures, in meters, is consistent with the pavement's centerline. A low degree of distress is indicated by cracks with a width of less than 3 mm, the absence of spalling and measurable faulting, or cracks that are effectively sealed and whose width cannot be identified. Crack widths vary from 3 to 13 mm in discomfort, spalling can reach up to 75 mm, and faulting may reach up to 13 mm for a severe severity level. It takes a crack width of 13 mm to cause high-severity pain, 75 mm to spall, and 13 mm to fault. [35] [36]	

Transverse Cracking	These stress fractures are measured in meters and are primarily perpendicular to the pavement centerline. Crack widths are 3 mm for low- severity distress, with no spalling or observable faulting, or are effectively sealed like longitudinal cracking. Crack widths between 3 and 6 mm indicate moderate-severity distress, paying up to 75 mm and faulting up to 6 mm. Crack widths >6 mm, spalling >75 mm, or faulting >6 mm are all indicators of high-severity distress. [35] [36]	
Map Cracking &Scaling	As the name suggests, map cracking is a series of connected fractures that runs the slab‘s top edge length. Often, large fractures are lined along the slab's longitudinal axis and linked by minor transverse or random fractures. Square meters and the frequency of occurrence are used to measure them. Scaling is the deterioration and flaking of the top surface of the concrete slab, and it may occur anywhere on the pavement in the range of 3–13 mm. This is determined by the number of incidents and the square meters of the affectedarea. [35] [36]	

7. Conclusions

As previously stated, the following conclusions can be drawn from the strong point of scientific reviews of subgrade soil geotechnical aspects with the general problems that occur in it and finding suitable solutions through methods of construction, stabilization, and improvement, as well as the scientific element of analyzing and designing rigid pavements:

1. Soil stabilization and improvement will make the subgrade soil stiffer and provide appropriate support for the rigid pavement slab.
2. Soil improvement solves subgrade soil failures such as (swelling or expansive, collapse, and pumping) as well as the modification of physical and mechanical properties.
3. Adequate rigid pavement thickness design will give improved durability to traffic loading.
4. Increasing the thickness of a rigid pavement slab reduces the pavement responses (stresses, strains, and deflections).

5. An excellent joint design will decrease collective failure.
6. Improper mixture design resulted in pavement failure.
7. Proper sealing prevents pumping through the joint and allows for more pavement expansion due to freezing and thawing.
8. The studies on soil properties and their improvement were conducted independently of the rigid pavement analysis and design. However, soil and concrete properties are played an essential role in this matter. In addition to this, one of the most critical of these properties are:

For concrete: Modulus of elasticity (Ec), Poisson‘s ratio (µ), Compressive strength (f'c), Modulus of rupture (Sc).

For soil: Modulus of subgrade reaction (K), Modulus of elasticity (Esub), Angle of internal friction (ø), California bearing ratio (CBR)

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