بسم الله الرحمن الرحيم

CE 441
Design of Pavement

Professor Hamad I. Al-Abdul Wahhab

Phone 3828
Office: 16-111
Office hrs: SMW 8:00 – 9:00 AM
SMW 10:00 – 11:00 AM

King Fahd University of Petroleum & Minerals
CIVIL ENGINEERING DEPARTMENT

CE 441
Design of Pavement

Prof. Hamad I. Al-Abdul Wahhab
Bldg. 16-Room 111: Phone 3828

OBJECTIVE

This course is mainly designed for senior students with some background in Highway engineering, computer programming and fundamentals of *elasticity*. Students will be introduced to the basic aspects of pavement structure design for flexible asphalt pavements and rigid pavements for highways and airports.

TEXTBOOK: Principle of Pavement Design by E. Yoder and M. Witczack, McGraw-Hill Book Co., 1975.

REFERENCES

1. Thickness Design, The Asphalt Institute (MS-I), 1981.
2. AASHTO Interim Guide for Design of Pavement Structures, 1972.
3. Structural Design of Asphalt Concrete Pavement System, HRB Special Report No. 126, 1971.
4. Layered Pavement Systems, TRR No. 810, TRB, 1981.
5. Highway Design and Construction, R.J. Salter.
6. Saudi Arabian General Specifications.
7. Shell Design Manual.
8. Soils Manual, The Asphalt Institute (MS-10).
9. Full-Depth Asphalt Pavements for Air Carrier Airports, The Asphalt Institute (MS-11).

COURSE OUTLINE

Week "Approx."	Chapter	Topic
1	1	Introduction
2	1	Principles of pavement design
3,4	2	Stresses in flexible pavements
5	3	Stresses in rigid pavements
6	4	Traffic loads and its characteristics
	EXAM # 1 (in class)	
7	7	Soil classification systems
8	8	Material characterization
9,10	8	Pavement materials
11	15	Design of flexible highway pavements
12	14	Design of flexible highway pavements
	EXAM # 2 (in class)	
13	17	Design of flexible airport pavements
14	16	Design of rigid highway pavements
15	20	Design of rigid airport pavements
16		FINALS

WISH YOU VERY GOOD LUCK.

COURSE FORMAT

1. **Lectures:**

Students are required to attend unless a permissible excuse is granted. However, students are responsible to information taught in class and in reading assignments as well.

2. **Homeworks:**

Homeworks are assigned during the semester at an interval of one week. Each homework will cover one integrated part of the course. Grading of homework should measure student's understanding to the subject, organization and preparation of the homework report, and ability to discuss and deduce conclusions.

3. **Exams:**

In general, two (one-hour) exams will be given in addition to the Final. The final will carry 40% of the total grade while each one-hour exam will carry 20% and 25%, respectively.

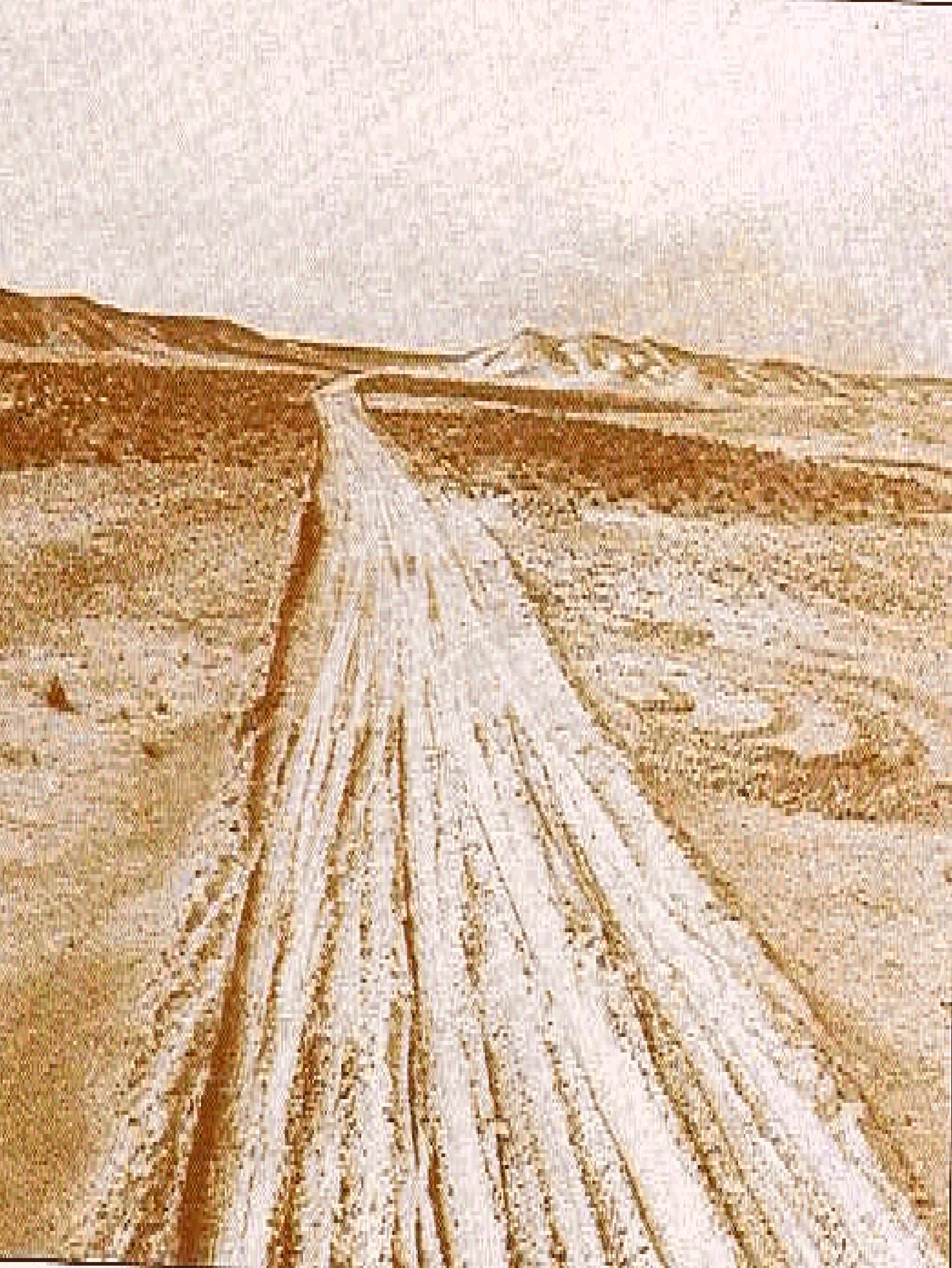
4. **Grading:**

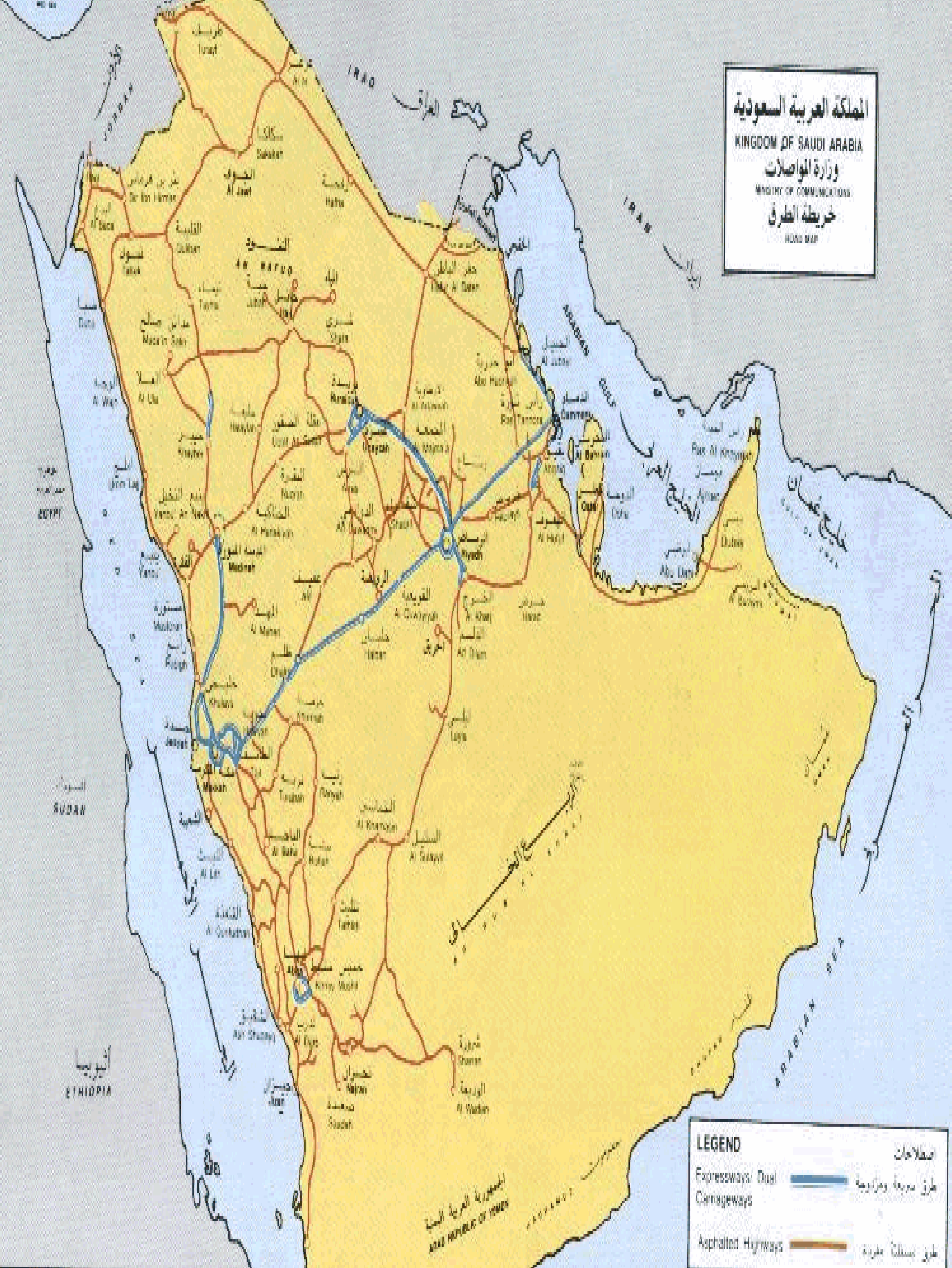
A. Attendance and participation in class………………………… **5%**
B. Homeworks…………………………………………… …… **10%**
C. 2 Midterm Exams……………………………………..…………..
- First Midterm……………………………………………….. **25%**
- Second Midterm……………………………………………….. **25%**

D. Final Exam…………………………………………………. **35%**

INTRODUCTION TO PAVEMENT STRUCTURES

Why do we need pavements? Discussion

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KINGDOM OF SAUDI ARABIA
وزارة المواصلات
MINISTRY OF COMMUNICATIONS
خريطة الطرق
ROAD MAP
LEGEND
اصطلاحات
Expressways: Dual Carriageways
Asphalted Highways
IRAQ
العراق
IRAN
JORDAN
EGYPT
SUDAN
ETHIOPIA
ARAB REPUBLIC OF YEMEN
الجمهورية العربية اليمنية
ARABIAN GULF
ARABIAN SEA
Turaif
Arar
Sakakah
Al Jawf
Hafar Al Batin
Tabuk
Tayma
Al Ula
Buraydah
Unayzah
Hail
Dammam
Al Jubayl
Ras Tanura
Al Bahrain
Qatar
Doha
Abu Dhabi
Dubai
Riyadh
Al Kharj
Al Hofuf
Madinah
Yanbu
Rabigh
Jeddah
Makkah
Taif
Al Baha
Bishah
Abha
Khamis Mushayt
Jizan
Najran
Sharurah
Al Wadiah
Al Sulayyil
Al Qunfudhah
Ahad Rufaydah


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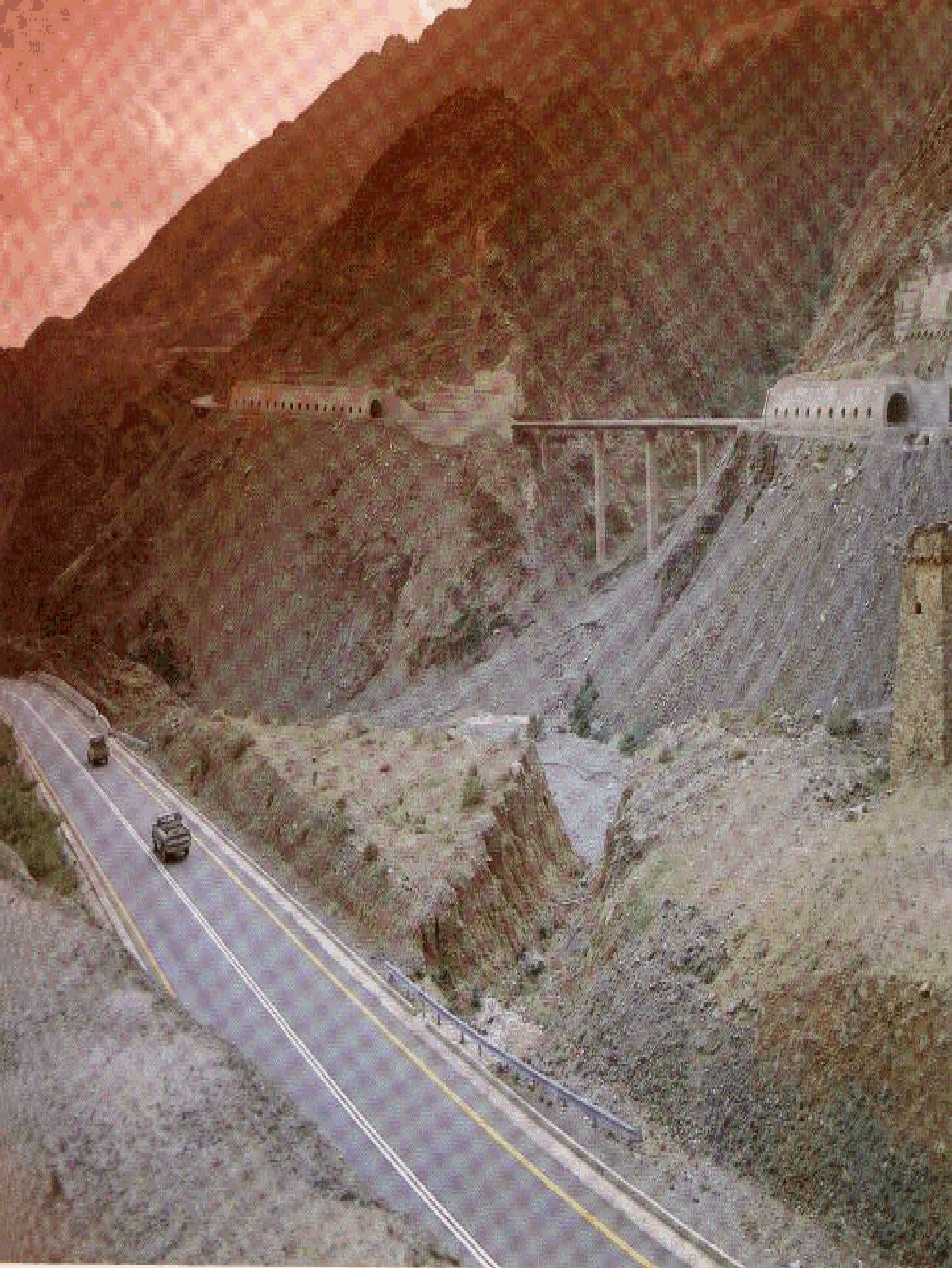

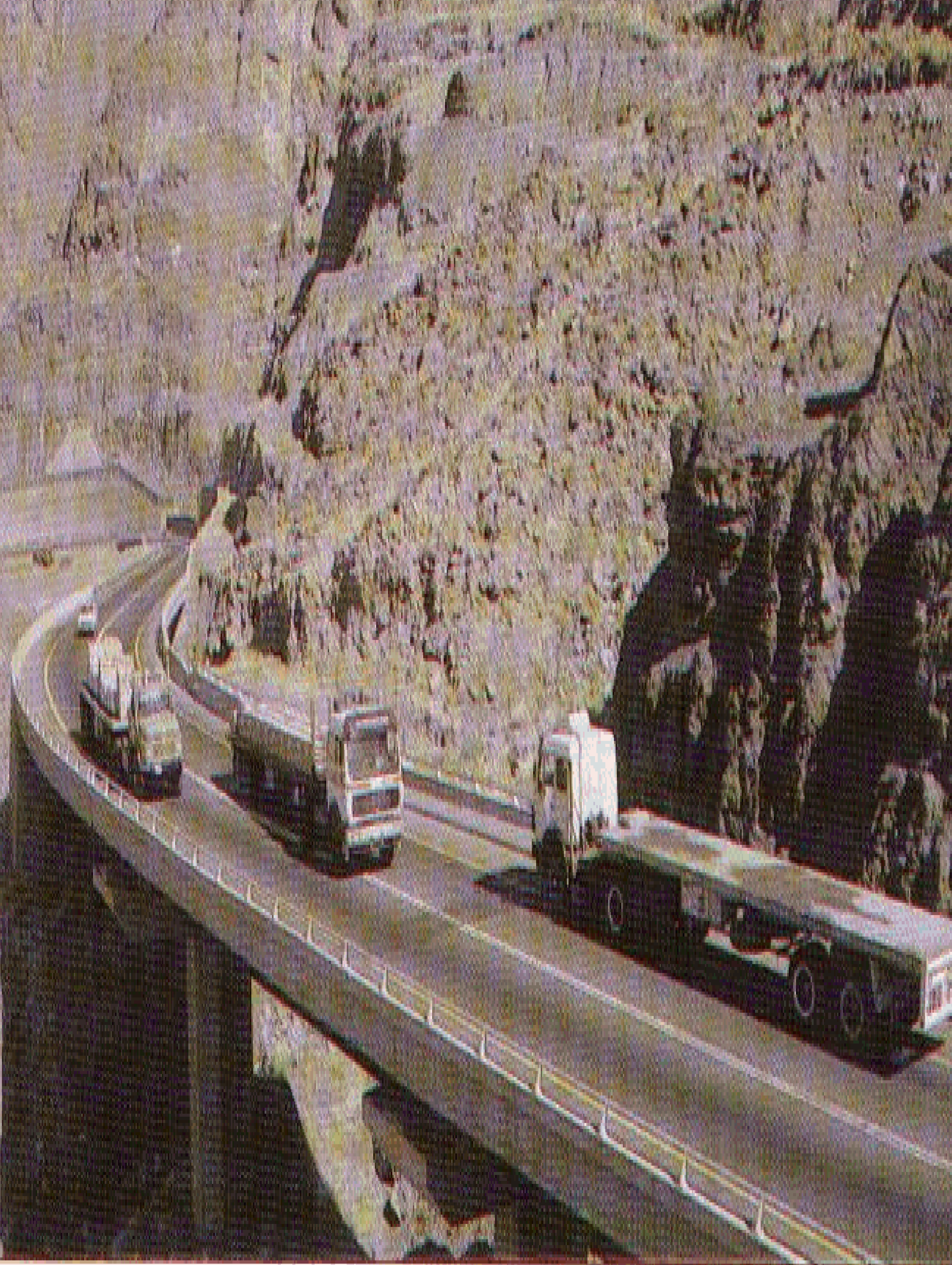

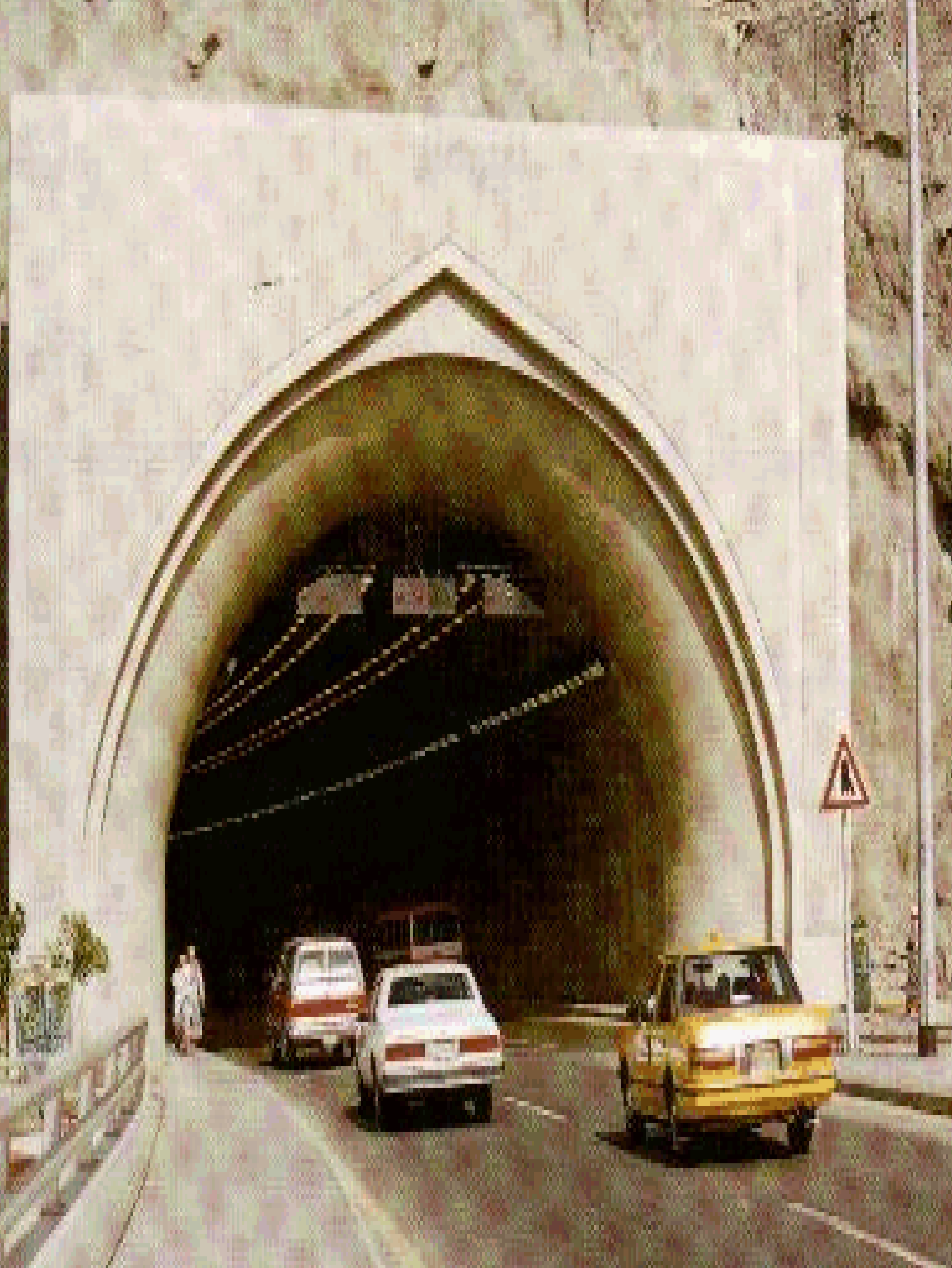

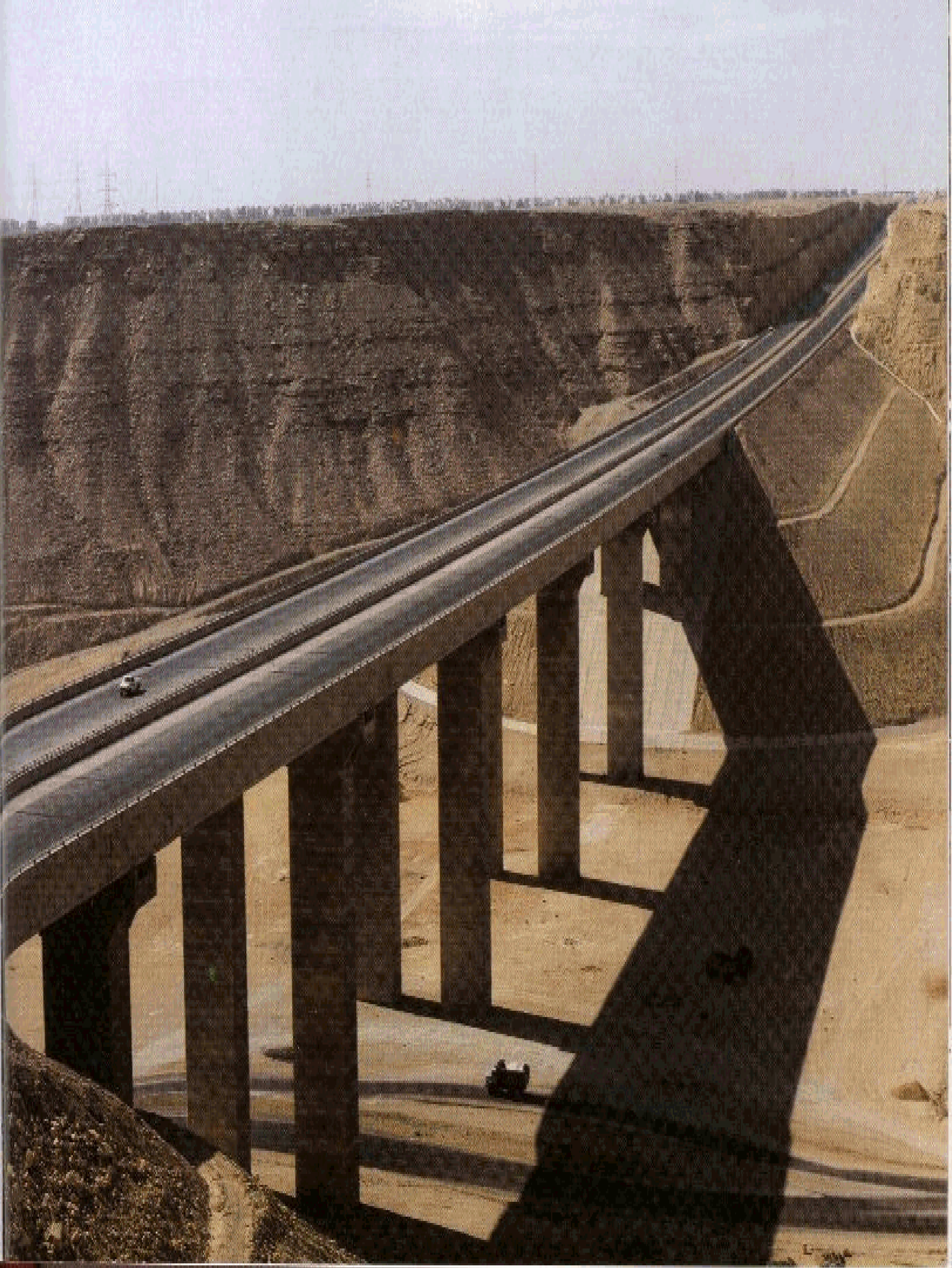


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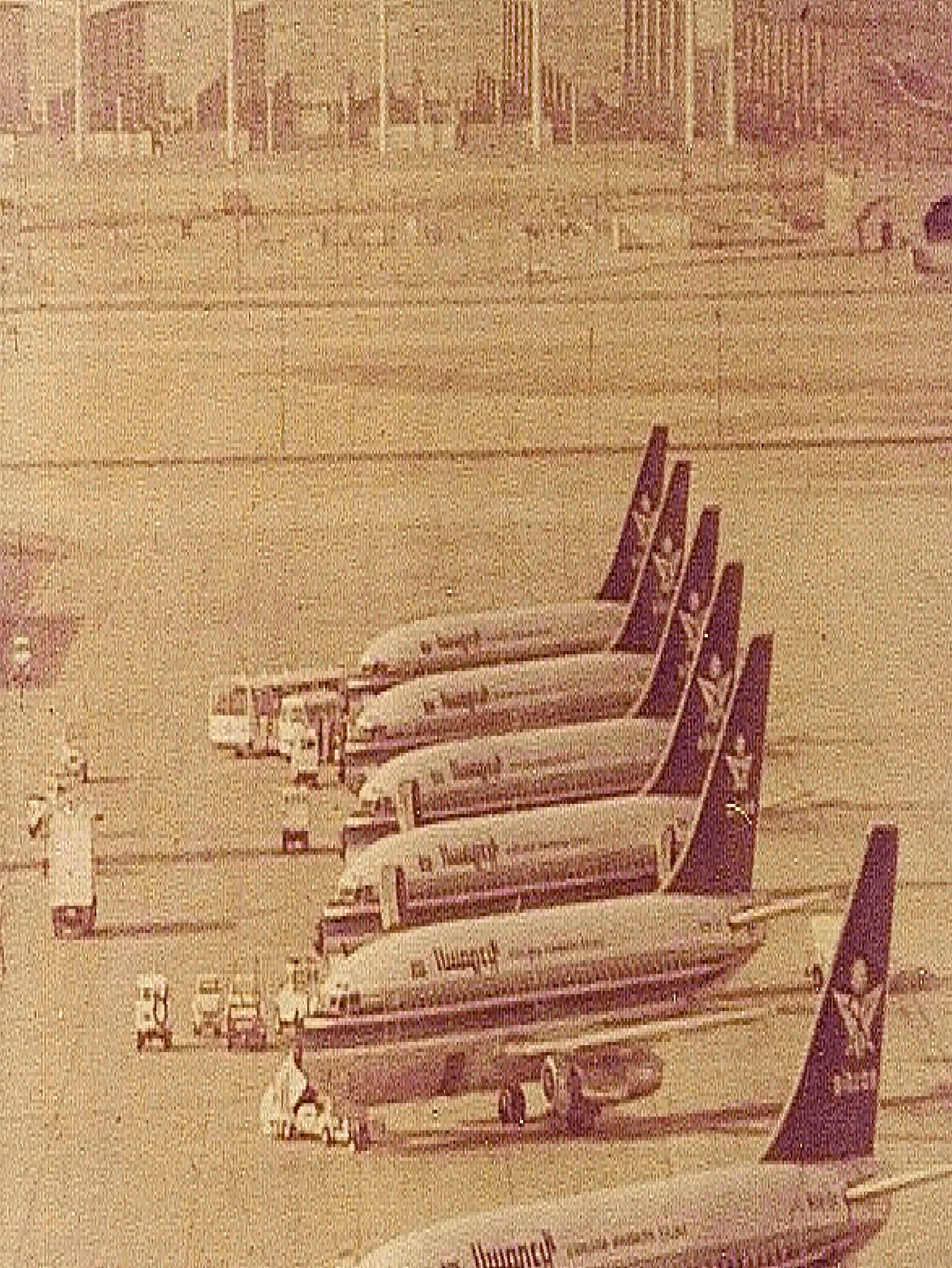
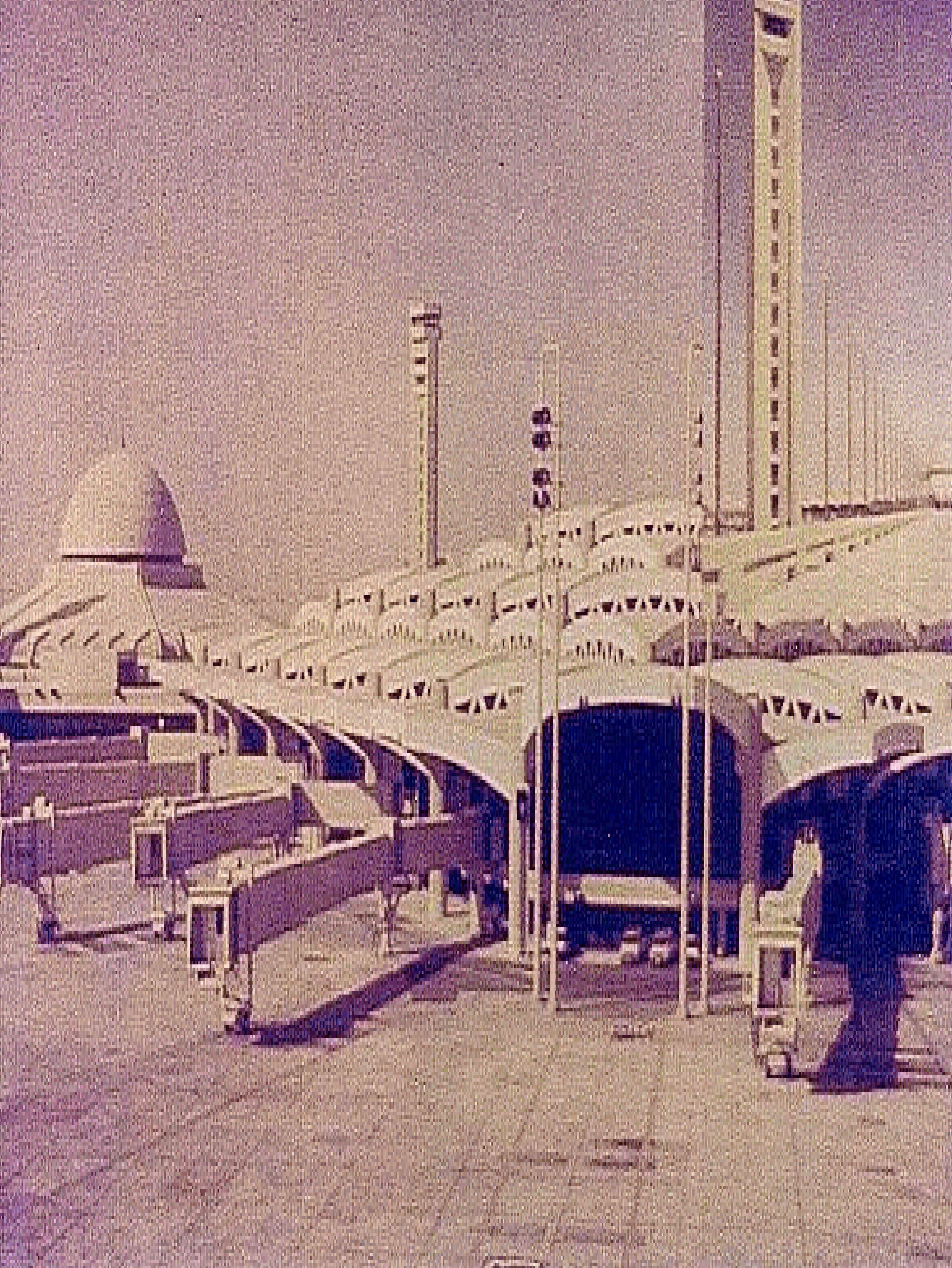




Functions of a Pavement

1. Load Bearing Capacity: Distribute load from tires to Subgrade

2. Seal Roadbed from Moisture, Prevent Dust/Loss of Soil

3. Smooth Surface for Comfortable Ride

4. Safe Ride "Friction with Tire," Skid Resistance

A pavement is a structure composed of structural elements, whose function is to protect the natural subgrade and to carry the traffic safely and economically.

Rigid Pavement

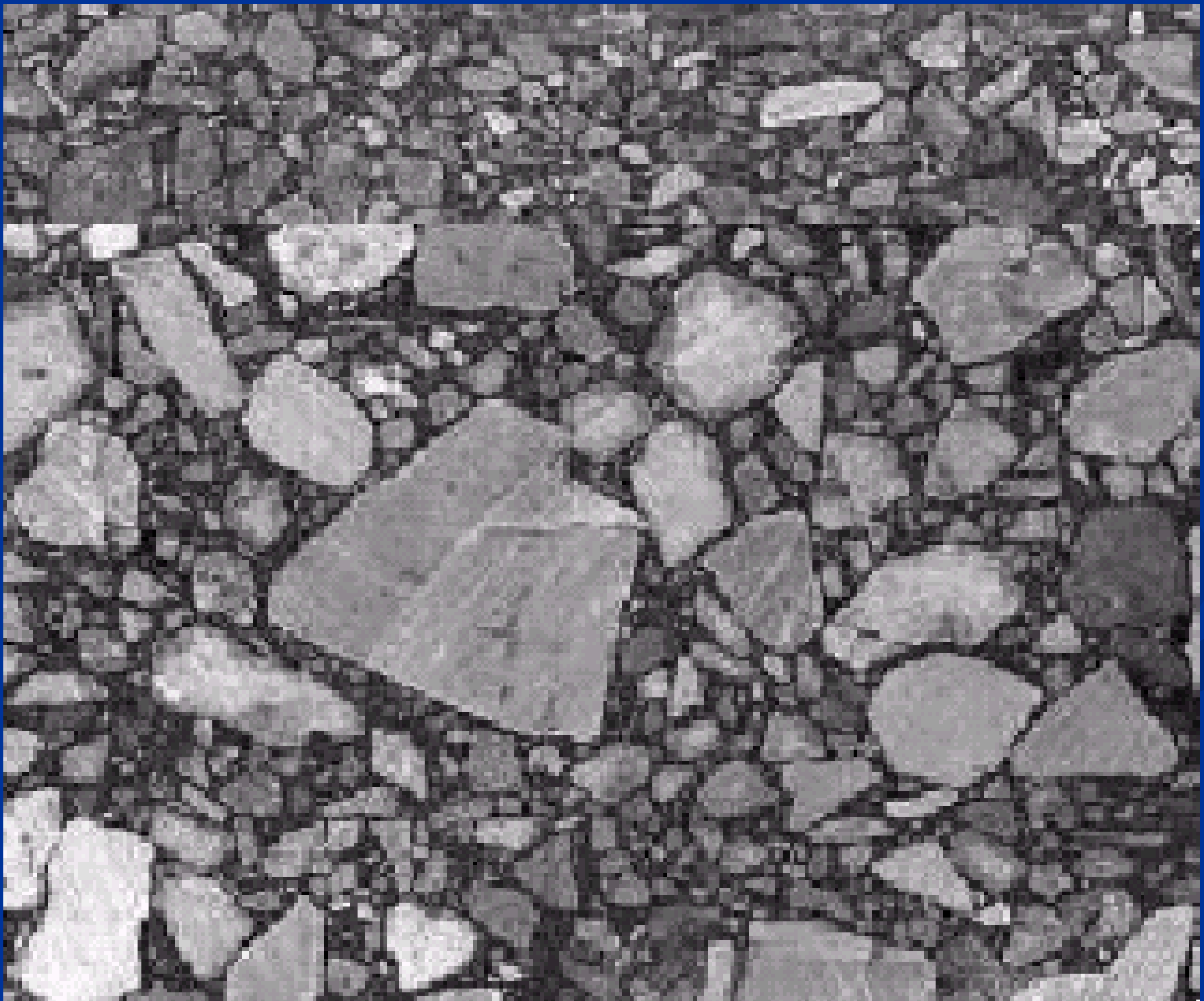
A pavement structure of which the surface course is made of Portland cement concrete

Rigid pavement tend (work as slab) to distribute the load over a relatively wide area of soil. Why?

(High modulus of elasticity)

Flexible Pavement

A pavement structure of which the surface course is made of asphaltic concrete, that maintains intimate contact with and distributes loads to the subbase or subgrade and depends upon aggregate interlock, particle friction, and cohesion for stability



Def.

Flexible pavement is one which can adjust its position to the shape of the underlying layers without sustaining significant damage.

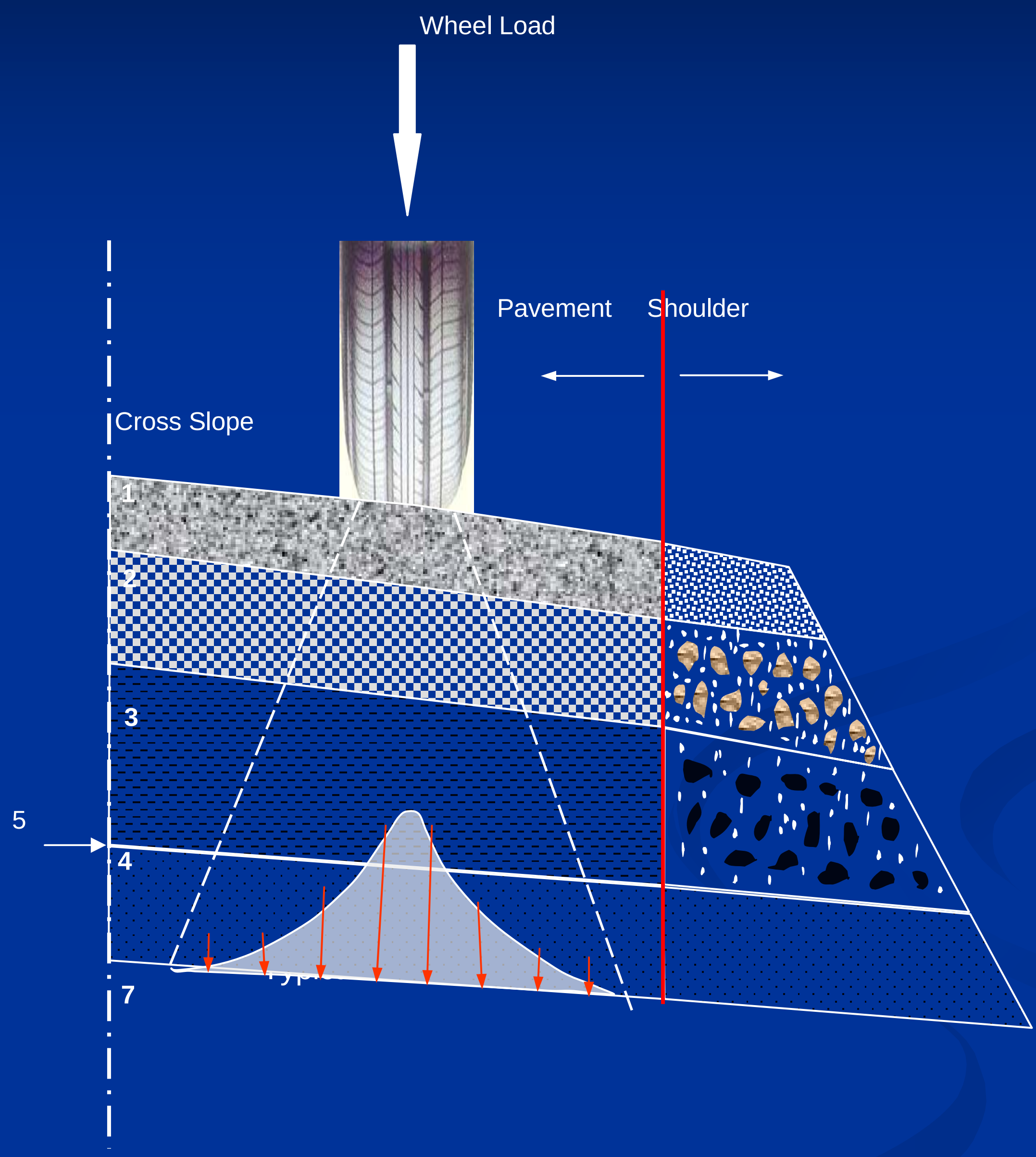
The essential difference between Flexible pavement and Rigid pavement is the manner in which they distribute the load

Pavement Section

A layered system designed to distribute concentrated traffic loads to the subgrade.

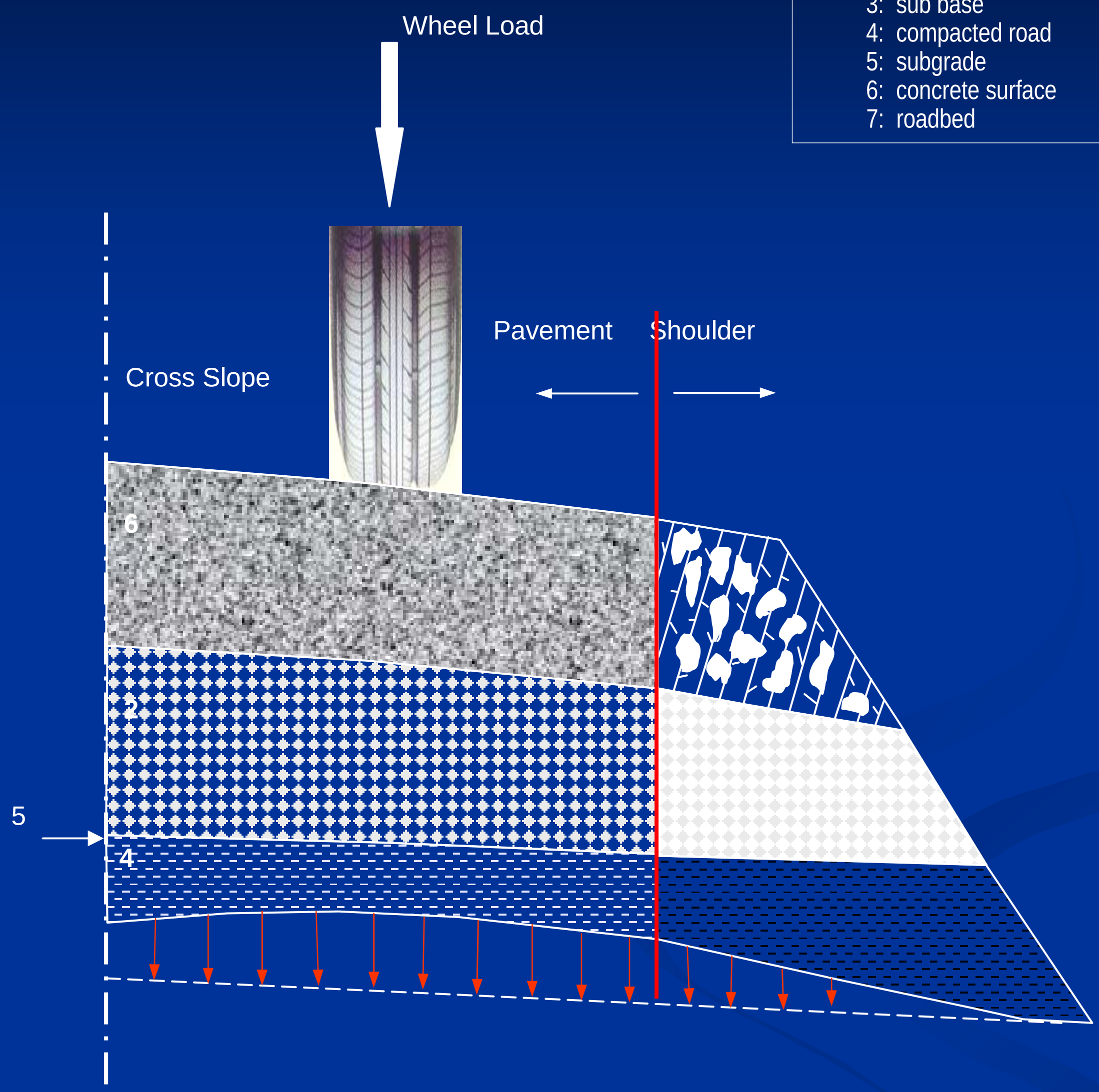
Structural Model

Key:
1: A.C. surface course
2: base
3: sub base
4: compacted road
5: subgrade
7: roadbed



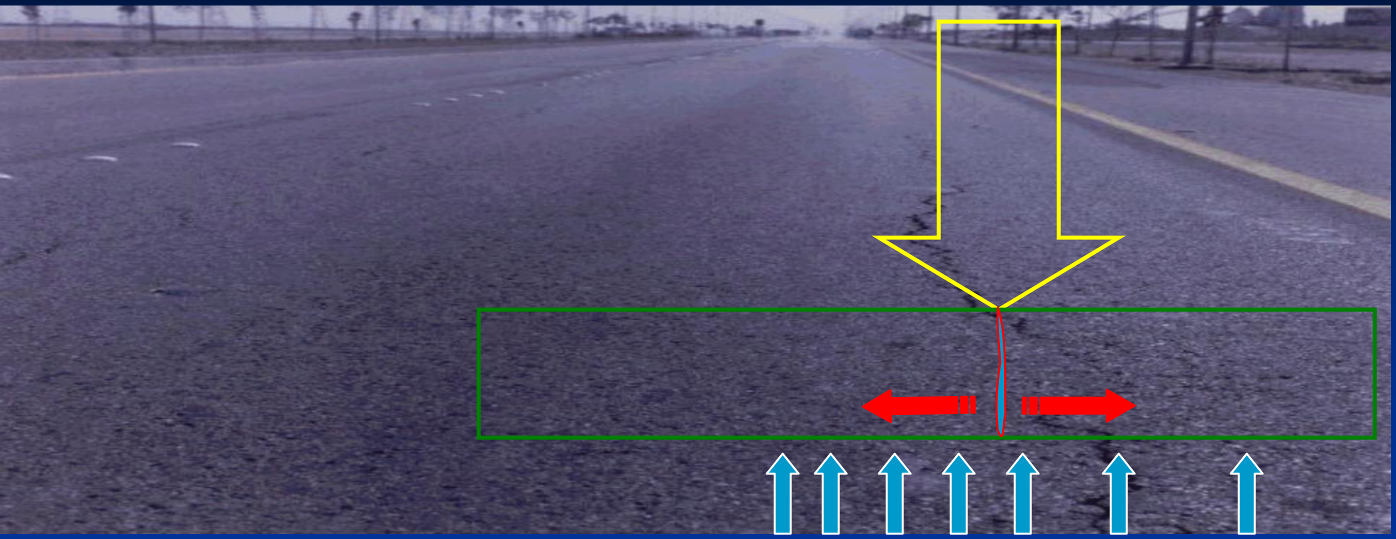
Key:

1: A.C. surface course
2: base
3: sub base
4: compacted road
5: subgrade
6: concrete surface
7: roadbed



In Flex. Pavement As a wheel passes:

- elastic deformations occur
- plastic deformations occur
- elastic deformations may lead to fatigue cracking
- plastic deformation deformations may lead to excessive rutting.



Pavement Types

*High Type	*Intermediate	*Low
- Asphalt concrete surfaced	- dense cold mix	- Un-surfaced
- Portland cement concrete	- Cold mix	- Dust oil
	- Open cold mix	- Penetration macadam
	- Lime treated base	- Surface treatment
	- Soil cement	

High Pavement Types

- Flexible (Asphalt Pavements)
  - Conventional
  - Full-depth
- Rigid (Concrete Pavements)
- Composite

- Flexible pavements: Bituminous (asphalt) and granular layers. First road in NJ in 1870.

- Rigid pavements: Portland Cement Concrete and usually drainage layers. First road in Detroit-Michigan in 1908.

Flexible Pavements

1. Conventional Asphalt Pavement

Layered systems with better materials at top and lower quality materials at bottom. High stress intensity is at the top and it decreases with depth.

1-2”	1. Surface Coarse	(wearing coarse), HMA: strong, smooth, skid resident and waterproof.
tack coat		
2-4”	2. Binder Coarse	(Asphalt base coarse), HMA: larger agg., less AC, lower Q
Prime coat		
4-12”	3. Base	granular, untreated or stabilized, open graded
4-12”	4. Subbase	lower quality, more fines, usually local agg.
6”	5. Compacted Subgrade/Stabilized	usually compacted approximately 6”, sometimes it is a borrowed material
	6. Subgrade	

Allow use of local materials and therefore less expensive layers.

2. Full Depth Asphalt Pavement

2-4”	2.1 Surface Coarse	HMA
tack coat		
2-20”	2.2 Base Coarse	HMA
Prime coat		
	2.3 Prepared Subgrade	(compacted)
	2.4 Subgrade	(natural)

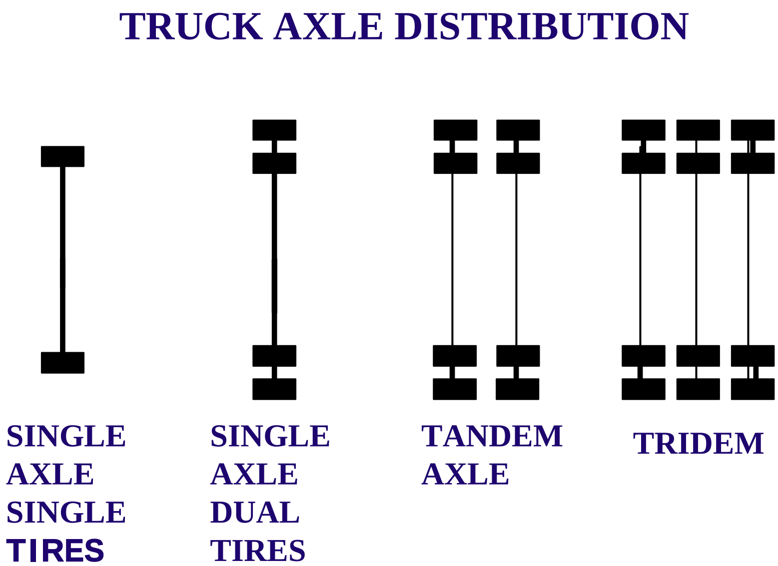
- Less construction time.
- Uniformity of pavement structure.
- More effective waterproof for subgrade.

Discussion:

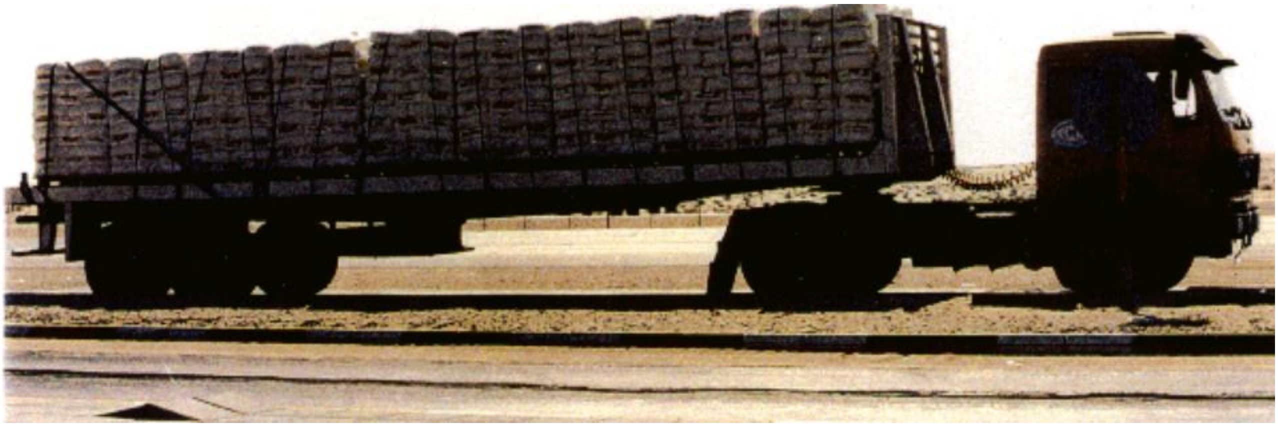
1. **Why binder course ?**
   - **a.**
   - **b.**
2. **Why subbase and base ?**
   - **a.**
   - **b.**
3. **Why in flexible pavements better materials are placed on top?**

A) Flexible pavement	B) Rigid Pavement
Flexible pavements **Asphalt Concrete (AC)** **Granular or stabilized base** **Subbase** **Subgrade** **80% + of pavements worldwide** **Full depth = AC on subgrade** **Deep strength = AC on subbase**	Rigid Pavements **Concrete slab** **Subbase** **Subgrade** **With or without steel, dowels and tie bars.**
(2) Can adjust its position to the shape of the underlying layers without damage.	One which will bridge minor undulations in underlying layers without failing.
(3) Based on layered system concept (Ch. 2).	Westergard theory or slab on elastic foundation.
(4) Asphalt cement + Mineral agg.	Portland cement + Mineral agg. (+ steel)
(5) Failure types bleeding polishing deformation fatigue	polishing scaling joint need filling fatigue pumping

Wheel load:



- Wheel can be single or dual
- Axle can be single, Tandem or Triple
- Legal axle load is (18 kip , 8 Ton) on Dual Axle. for more load add more axles
- For tandem-axles, the maximum allowable is 32 kip with spacing of 40"-48".

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INDY
THOMPSON S/S

وزارة المواصلات

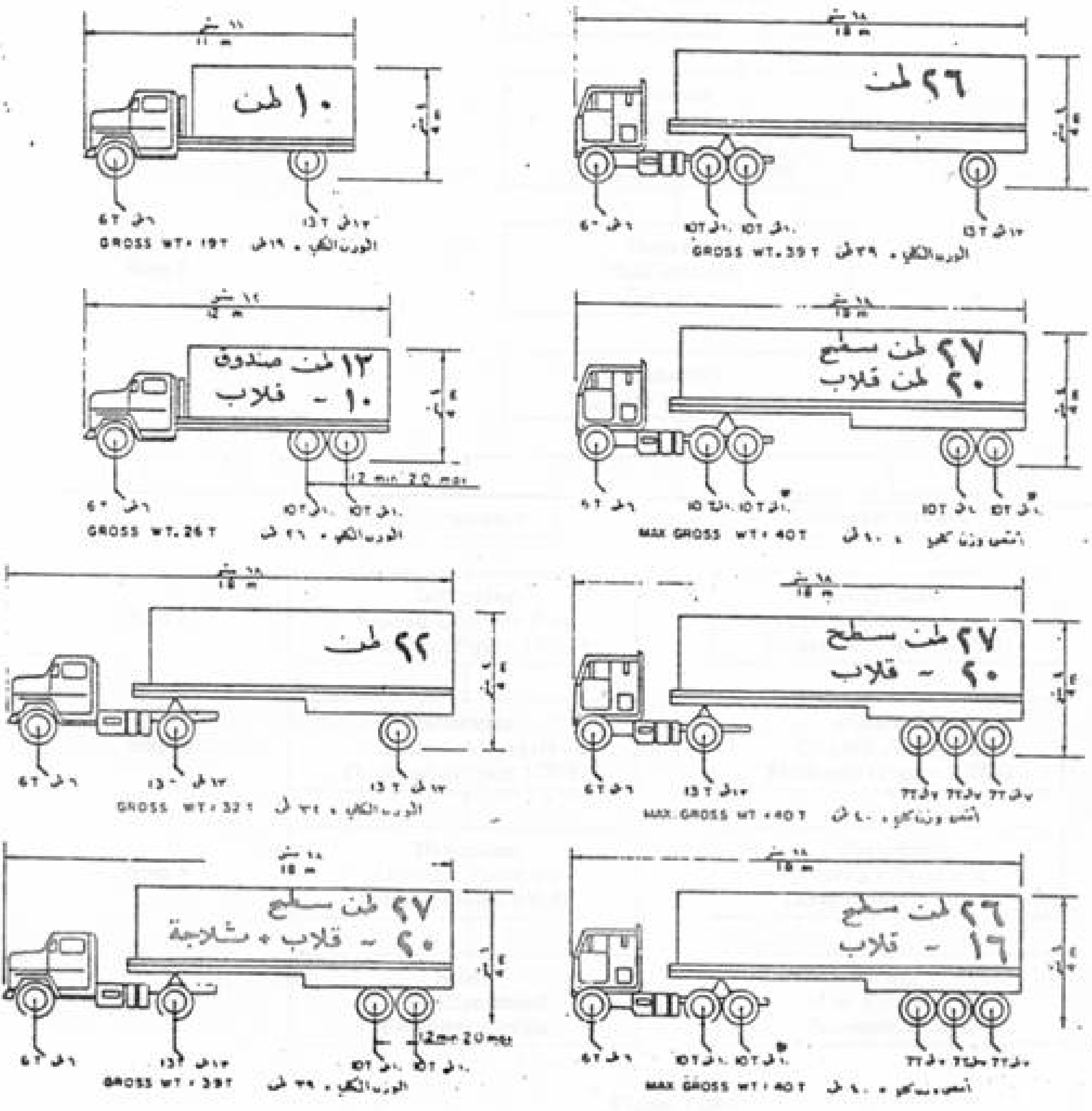
MINISTRY OF COMMUNICATIONS

الأوزان القانونية للشاحنات
LEGAL TRUCK WEIGHTS

الأرقام على صندوق الشاحنة ترمز إلى الحمولة الصافية للشاحنة .

WIDTH FOR ALL TRUCKS = 2.5 m MAX

العرض لجميع الشاحنات كحد أقصى = ٢,٥ متر



إن معلومات هذا الرسم البياني مبنية على أساس أنظمة المرور لعام ١٣٩٠ هـ

INFORMATION ON THIS CHART IS BASED ON TRAFFIC REGULATIONS (1390 H.)

* الأحمال المحورية القصوى المسموح بها على أن لا تتجاوز الوزن الإجمالي ٤٠ طن

* MAXIMUM ALLOWABLE AXLE LOADS. GROSS WEIGHT NOT TO EXCEED 40 TONS

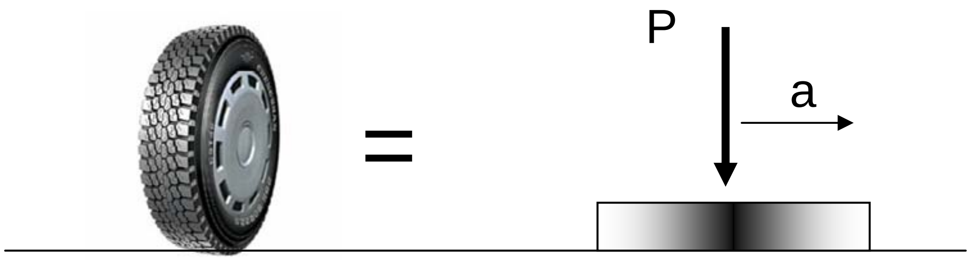
RAJAB 1404
APRIL 1984

- If tire is inflated correctly, then the contact pressure between pavement and tire is equal to the tire pressure.

- If tire has low pressure, then edge pressure is higher than center.

- If tire has high pressure, then center pressure is higher than edge pressure.

- For correct inflation, and assuming a uniform contact pressure, the tire imprint may be assumed circular. The radius of contact is

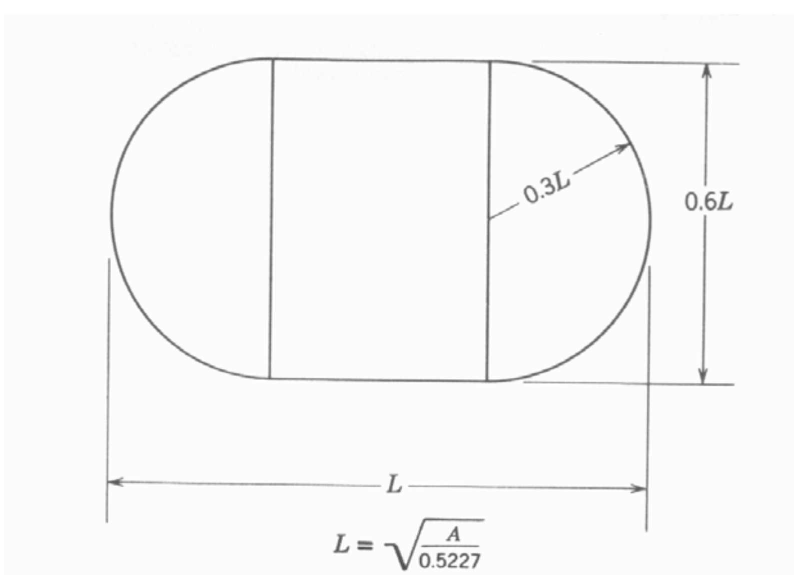


Contact Pressure = Tire pressure = p

* Circular imprint: $a = \sqrt{\dfrac{P}{p\pi}}$

$P = 4500$ lb
$p = 80$ psi , $a =$?????

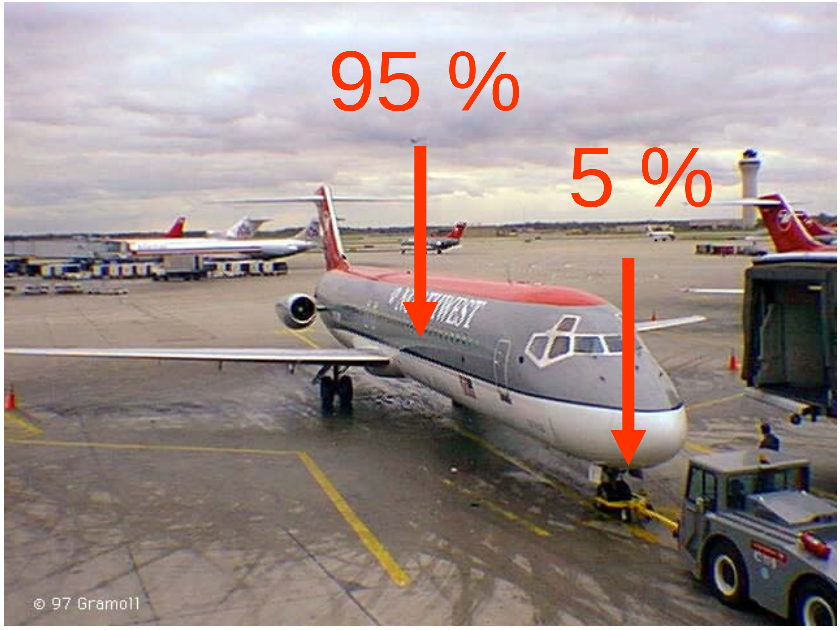
where: a = radius of contact
P = total load
p = tire pressure



* Rectangle and semi-circle

$$\ell = \sqrt{\frac{A}{0.5227}} \quad , \quad A =$$

$$A = \frac{P}{p}$$



Airport:

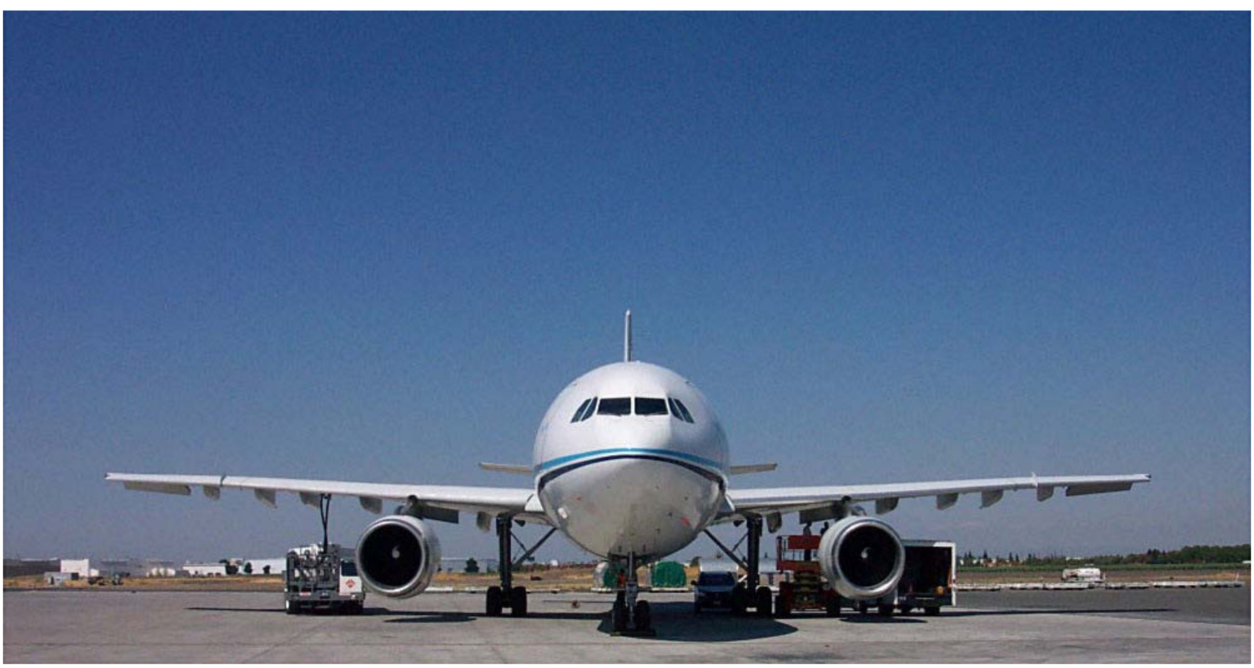
0 Single		00 dual	Nose wheels
0	0	(1) single gear	Main gear
00	00	(2) dual gear	
00 00	00 00	(3) twin-tandem gear	

00
00

00 00
00 00

(4) Double twin-tandem gear

00
00

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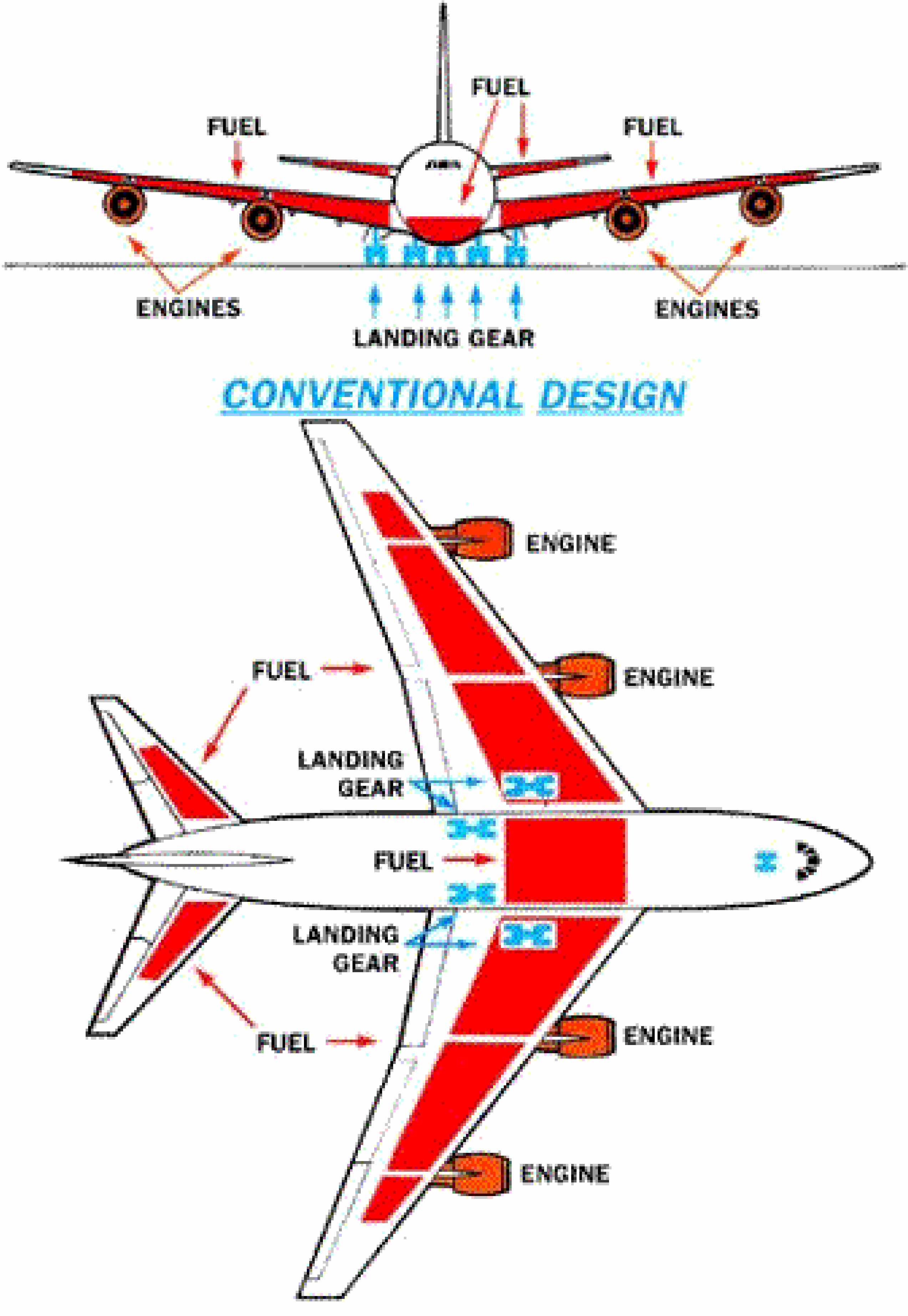
FUEL
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ENGINES
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LANDING GEAR
CONVENTIONAL DESIGN
ENGINE
ENGINE
FUEL
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LANDING
GEAR
FUEL
ENGINE
ENGINE

Importance Of Stresses in pavement?

1- to understand the mechanism of load distribution

2- to use in improved design methods

3- to evaluate the performance of materials.

Types of analysis:

A. Flexible Pavements:

Layered elastic theory .1

Finite element analysis .2

Visco elastic analysis .3

B. Rigid Pavements:

Slab on elastic foundation (Westergard) .1

Others (finite element). .2

Multi-layer theory – Outline

2 or more layers	A) Structure
1 or more circular U.D. loads	B) Loads
E, μ for each layer.	C) Materials

Differences – Highway and Airfield Pavements

	Highway	Airfield
1- Size of loads	80,000 lb (40 ton)	750,000 lb
2- Tire pressure	100 psi	250 psi
3- Gear configuration	S, D, T	Varies S,D,T and twin T
4- Load applications	Millions	L 50,000
5- Wander	Ignored (wheel load is 3-4 ft from edge)	Not ignored (75% of loads within 7.5')
6- Geometry	Ribbon	Strip of limited length and 500' wide
7- Pavement vehicle interaction	Roughness acceptable	Not acceptable
8- Type of structure	Thin	Thick Runway end is thicker than Runway (.95 T)

(see Fig 2.12 & Fig 2.13)

* What is the effect of Tire Load ?

* What is the effect of Tire Pressure.?

Serviceability:

Present Serviceability Index (PSI) was developed during the AASHTO road test. It is based on rating scale to designate the condition of the pavement at a certain time.

very poor pavement 0 -

excellent pavement 5 -

PSI is based on satisfaction, comfort, roughness, skid resistance etc. The index can be correlated with objective with objective measurements done on the surface of the pavement such as Roughness cracking, and Rut depth in the case of flexible pavement.

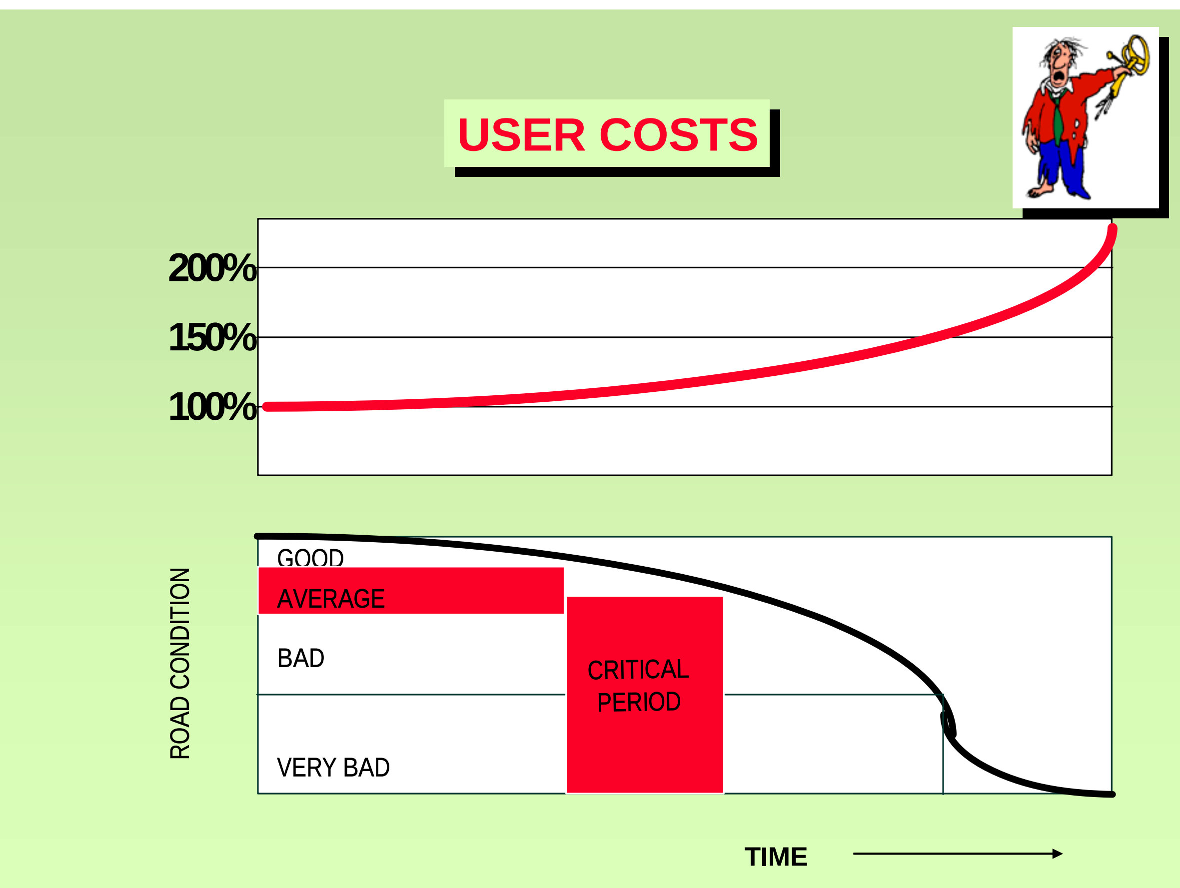
A Highway pavement is usually designed for a terminal PSI (TSI) of 2.5

flexible

$$PSI = 5.03 - 1.9 \log (1 + S_V) - 0.01 \sqrt{c + p} - 1.38 R_D$$

S_V = roughness
c = cracking   p, patching
R_D = Rut depth

for rigid pavement $R_D = 0$.



Types of distress:

Distress are caused by:

Traffic loading (overloading, tire pressure, and repetitions) (Rut, fat crack) (1)

Environmental conditions, Temp., Rainfall … (volume change due to wetting and drying) (2)

Materials. (3)

Distress types:

a) Functional: where pavement will not carry out its intended function without causing discomfort.

Ex. **Flex** **Rigid**

- bleeding
- polishing
- polishing
- joint need filling
- raveling
- scaling
- deformation

b) Structural: a breakdown of one or more of the pavement components. Pavement will be incapable of sustaining the loads.

Ex.
- fatigue
- fatigue cracks
- deformation
- pumping
- expansive soils
- overload
- drainage problems
- temp effect
- poor construction
- frost

etc.

Principles of design:

(1) Must provide for

- loading
- environment

such that the pavement will function.

(2) Some failure is acceptable if the pavement continues to function & if the cost of repair is not too high.

(3) Routine maintenance is an integral part of the highway system, and is becoming increasingly important as the need to keep the existing network in good order exceeds that for new construction.

The most extreme rehabilitation measure is the application of an overlay this may be time as follows:

Design Methods:-

Types:

- based on strength tests
- empirical approaches
- analytical (Mechanistic) Approach
- combination

Factors influencing design:

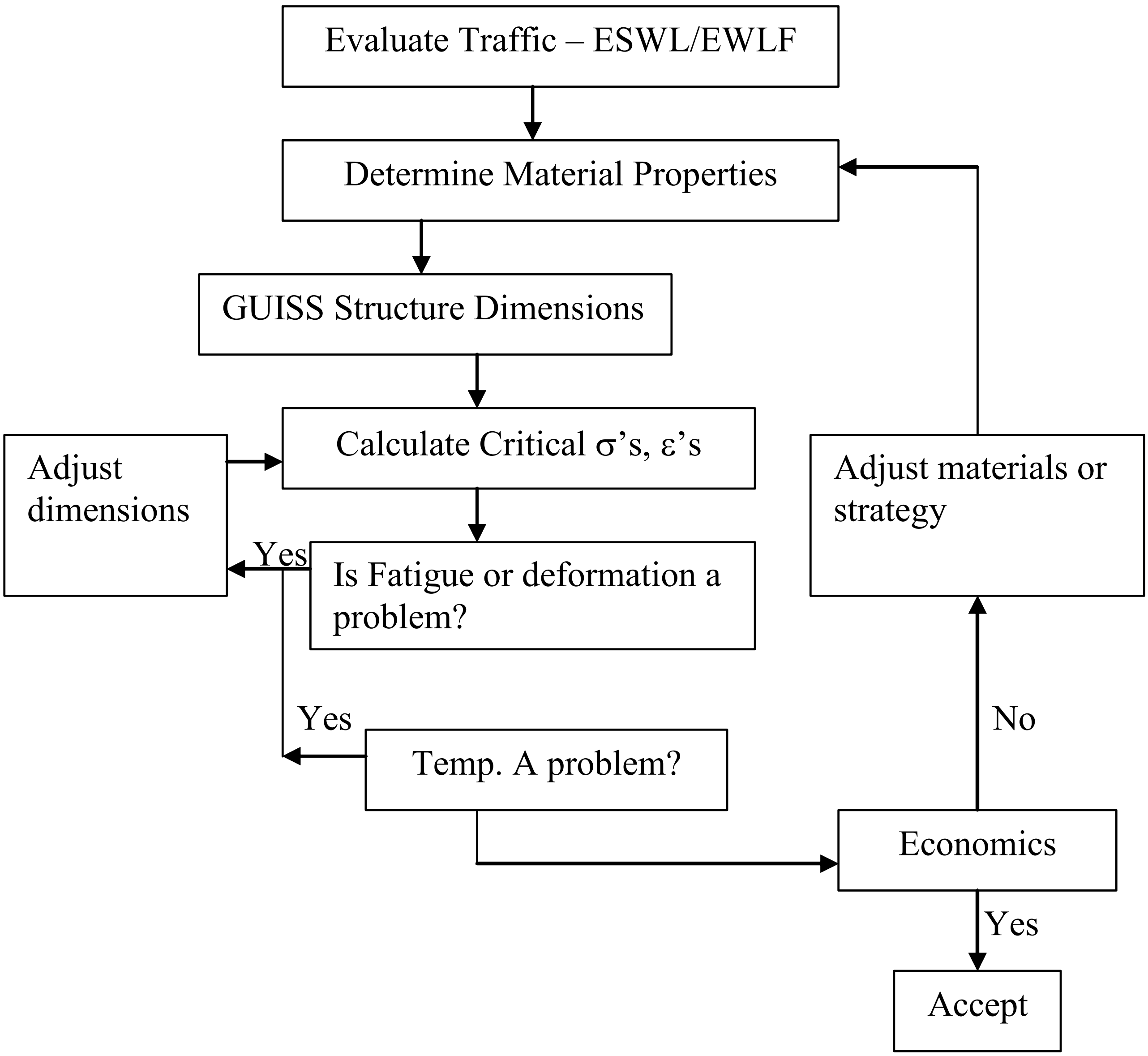
(1) Paving mixtures

(2) Structural design needs:

- traffic
- environment
- materials
- construction methods
- maintenance methods
- construction costs

Design process:

The basic elements associated with pavement design are:



Chapter 2

STRESSES IN FLEXIBLE PAVEMENT

Pavement Design History

- **What is pavement design?**

Pavement section profile (Thickness of layers), Materials used in layers, design life, drainage, shoulders, joints, reinforcement,

- **Prior to the 1920s, thickness was based purely on experience regardless of the soils encountered.**

- **It gradually evolved from art to science. However, empiricism still plays an important role.**

Pavement Design Methods

Flexible

1.Empirical – No shear test: Based on subgrade soil classification. Group Index Method. Not used widely.

2.Empirical- with shear test: Based on CBR (California Bearing Ratio) values. Very popular after the World War II.

3.Limiting Shear Failure Methods: Determine thickness required preventing shear failure of granular materials and subgrade soils. Ignores ride comfort.

4.Limiting Deflection Methods: Determine thickness to limit deflection of subgrade. Boussinesq's equation, Burmister 2-layer method, Computerized methods. Ignores stresses and strain in individual layers.

5.Regression methods: Based on analysis of road test performance. (AASHo –AASHTO road test). Design equations are useful only for conditions included in the test. New materials, new combinations cannot be reliably designed.

6.Mechanistic – Empirical Methods: Mechanics of materials are used to relate wheel load to pavement response (stress/strain/deflection). Relation between response and performance is based on correlation to field performance.

Rigid

1.Analytical: Simple closed form formulas to estimate stresses and strains in slabs. Goldbeck solution, Westergaard's liquid foundation, Pickett's old foundtaion. Assume full conatct between slab and soil.

2.Numerical solutions: Discrete elements, finite element. WESLIQID, WESLAYER, ILLI-Slab, JSLAB, RISC.

Recent Developments:

- **Computer programs: Multi-layer Elastic theory -- CHEV, DAMA, BISAR, ELSYM5, PDMAP. Finite Element – SAPIV, ILLI-PAVE, MICH-PAVE (non-linear).**
- **Serviceability and Reliability: Index for serviceability, probabilistic computer programs.**
- **Dynamic Loading: No inertia effects. Dynamics of vehicle.**
- **Fatigue of Concrete: PCA method, stress ratio of 0.45.**
- **Control of Pumping in Concrete pavements.**

CLASSICAL DESIGN APPROACH:
Relies on empirical characteristics and observations

<u>Disadvantages of empirical design models</u>
Difficult to extrapolate to other conditions than those that were used to generate the performance models

<u>Advantage of the mechanistic approach</u>
Predict future performance of new materials and new type of loading

EVOLUTION **<u>EMPIRICAL</u>** → **<u>MECHANISTIC</u>**

MECHANISTIC APPROACH

REQUIRES TO CHARACTERIZE THE FUNDAMENTAL PROPERTIES OF MATERIALS

WITH LAB OR SITE TESTS THAT SIMULATE FUTURE LOADING CONDITIONS

MATERIALS = MIXTURE OF RHEOLOGICAL BEHAVIOUR
ELASTIC, PLASTIC, VISCOUS

- **TEMPERATURE**
- **LOADING RATE**
- **LOADING LEVEL**

As a wheel passes:

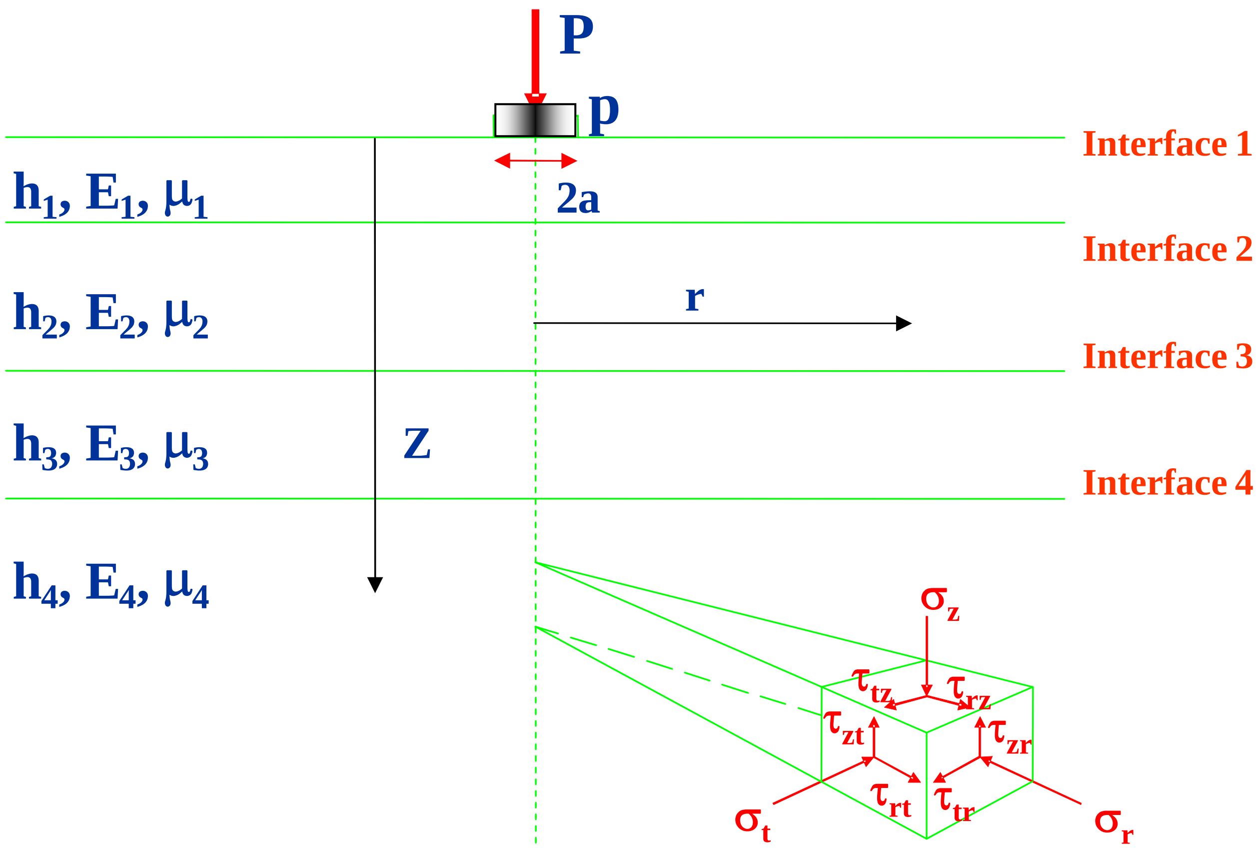
- elastic deformations occur
- plastic deformations occur
- elastic deformations may lead to fatigue
- plastic deformation deformations may lead to excessive rutting.

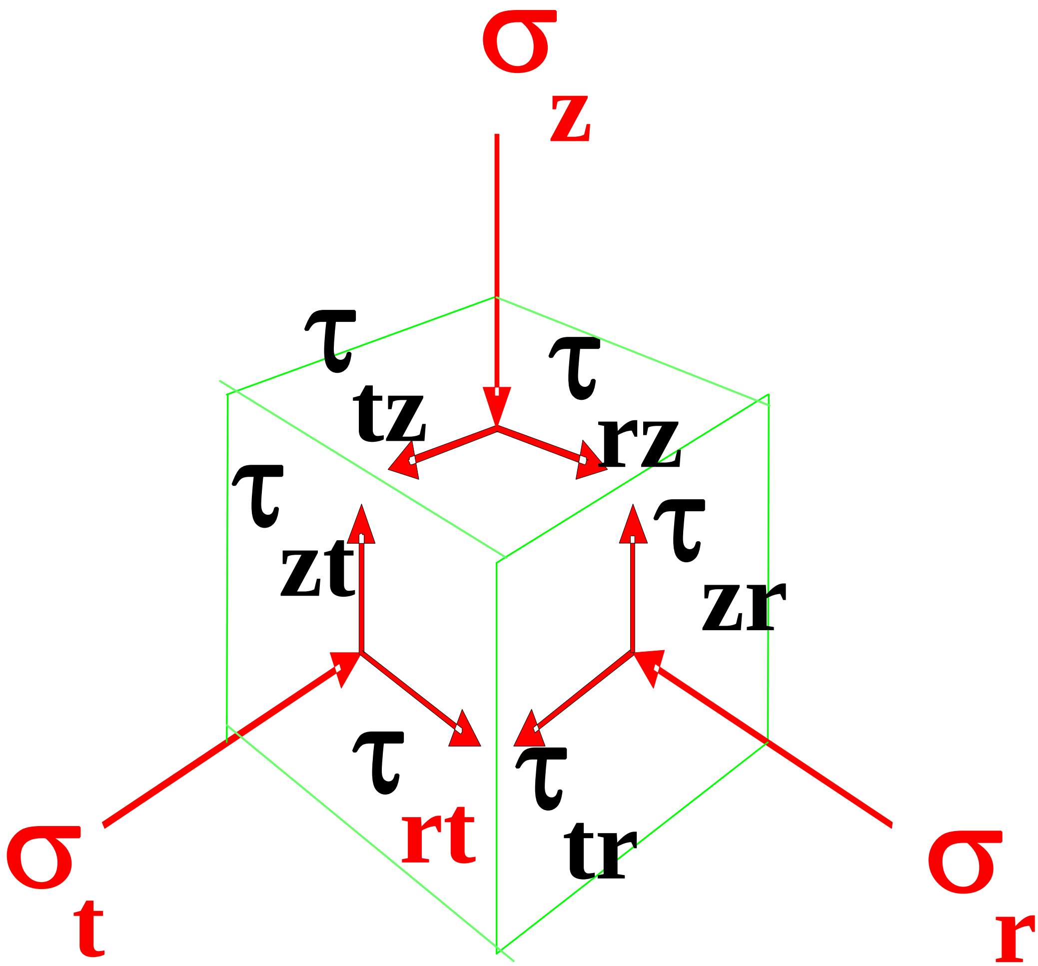
BURMISTER MODEL

BASED ON SIX (6) ASSUMPTIONS

1. Homogeneous layers
2. Isotropic layers
3. Friction between layers
4. Infinite radially
5. No surface shear
6. μ & E

GENERAL CONCEPT OF MULTI -LAYER STRUCTURAL SYSTEM




σ z
τ tz
τ rz
τ zt
τ zr
τ rt
τ tr
σ t
σ r

STRESSES ON EACH LAYER

3 NORMAL STRESSES : σ_z σ_r σ_t

6 SHEAR STRESSES : τ_{rt} τ_{tr} τ_{rz} τ_{zr} τ_{tz} τ_{zt}

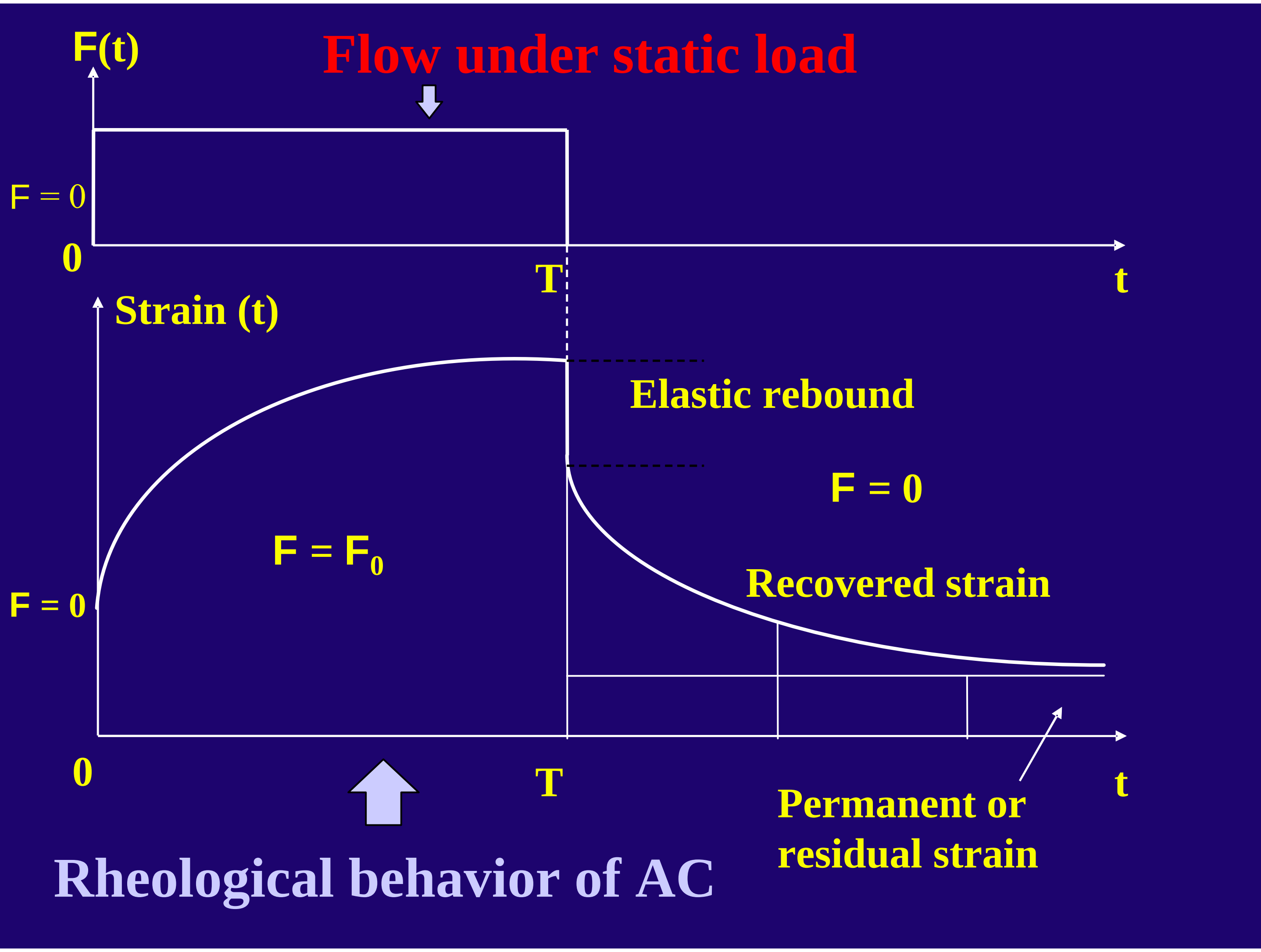
DEFORMATION EQUATIONS:

$$\varepsilon_z = \frac{1}{E}\left[\sigma_z - \mu\left(\sigma_r + \sigma_t\right)\right]$$

$$\varepsilon_r = \frac{1}{E}\left[\sigma_r - \mu\left(\sigma_t + \sigma_z\right)\right]$$

$$\varepsilon_t = \frac{1}{E}\left[\sigma_t - \mu\left(\sigma_r + \sigma_z\right)\right]$$

If $\mu = 0.5$ then $\sigma_r = \sigma_z$



Flow under static load
F(t)
F = 0
0
T
t
Strain (t)
Elastic rebound
F = 0
F = F0
Recovered strain
F = 0
0
T
t
Permanent or residual strain
Rheological behavior of AC

One layer Theory

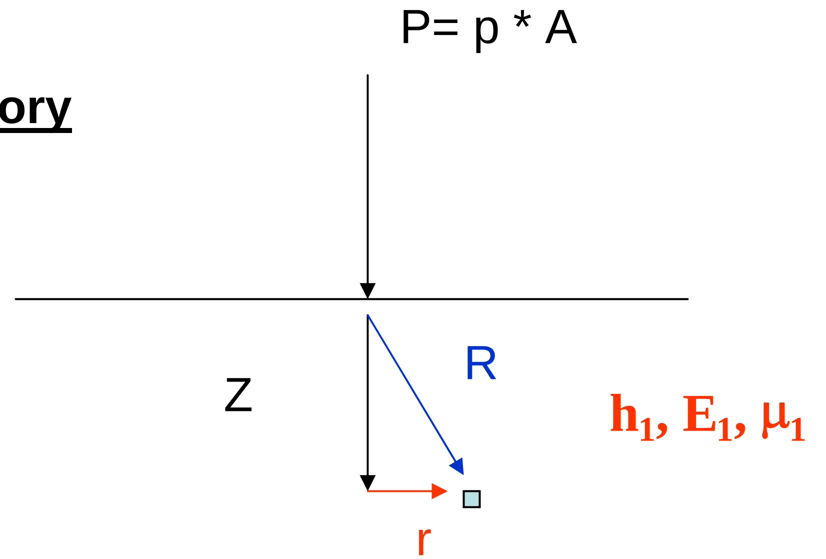


TABLE 2.1. Summary of One-Layer Elastic Equations[a] (after Ahlvin and Ulery)

Parameter	General Case	Special Case ($\mu = 0.5$)
Vertical stress	$\sigma_z = p[A + B]$	(same)
Radial horizontal stress	$\sigma_r = p[2\mu A + C + (1 - 2\mu)F]$	$\sigma_r = p[A + C]$
Tangential horizontal stress	$\sigma_t = p[2\mu A - D + (1 - 2\mu)E]$	$\sigma_t = p[A - D]$
Vertical radial shear stress	$\tau_{rz} = \tau_{zr} = pG$	(same)
Vertical strain	$\epsilon_z = \frac{p(1 + \mu)}{E_1}[(1 - 2\mu)A + B]$	$\epsilon_z \quad \frac{1.5p}{E_1} B$
Radial horizontal strain	$\epsilon_r = \frac{p(1 + \mu)}{E_1}[(1 - 2\mu)F + C]$	$\epsilon_r = \frac{1.5p}{E_1} C$
Tangential horizontal strain	$\epsilon_t = \frac{p(1 + \mu)}{E_1}[(1 - 2\mu)E - D)]$	$\epsilon_t = -\frac{1.5p}{E_1} D$
Vertical deflection	$\Delta_z = \frac{p(1 + \mu)a}{E_1}\left[\frac{z}{a}A + (1 - \mu)H\right]$	$\Delta_z = \frac{1.5pa}{E_1}\left(\frac{z}{a}A + \frac{H}{2}\right)$
Bulk stress	$\theta = \sigma_z + \sigma_r + \sigma_t$	
Bulk strain	$\epsilon_\theta = \epsilon_z + \epsilon_r + \epsilon_t$	
Vertical tangential shear stress	$\tau_{zt} = \tau_{tz} = 0 \therefore [\sigma_t(\epsilon_t)$ is principal stress (strain)$]$	
Principal stresses	$\sigma_{1,2,3} = \frac{(\sigma_z + \sigma_r) \pm \sqrt{(\sigma_z - \sigma_r)^2 + (2\tau_{rz})^2}}{2}$	
Maximum shear stress	$\tau_{max} = \frac{\sigma_1 - \sigma_3}{2}$	

[a] See Table 2.2 for values of the functions A, B, C, D, E, F, G, and H. (+) values compressive

TABLE 2.2. One-Layer Elastic Function Values (after Ahlvin and Ulery)

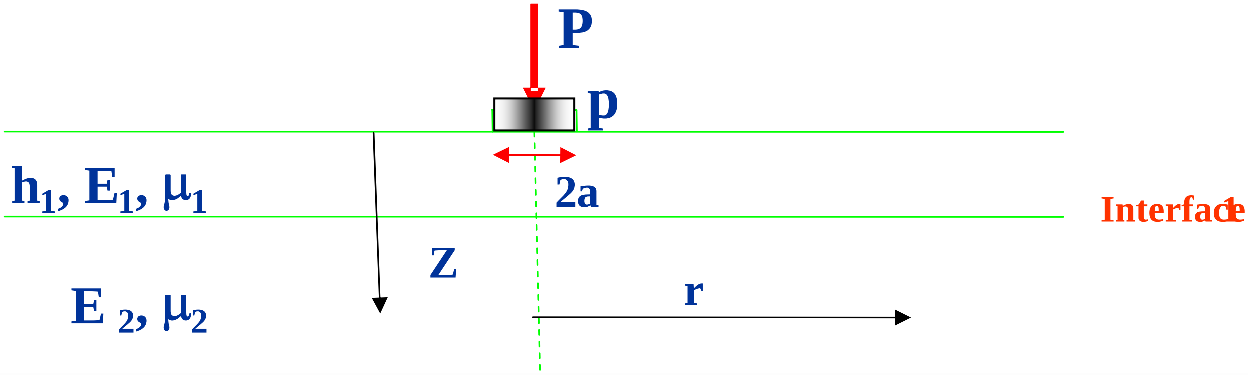
Function A

Depth (z) in Radii	Offset (r) in Radii: 0	0.2	0.4	0.6	0.8	1	1.2	1.5	2	3	4	5	6	8	10	12	14
0	1.0	1.0	1.0	1.0	1.0	.5	0	0	0	0	0	0	0	0	0	0	0
0.1	.90050	.89748	.88679	.86126	.78797	.43015	.09645	.02787	.00856	.00211	.00084	.00042					
0.2	.80388	.79824	.77884	.73483	.63014	.38269	.15433	.05251	.01680	.00419	.00167	.00083	.00048	.00020			
0.3	.71265	.70518	.68316	.62690	.52081	.34375	.17964	.07199	.02440	.00622	.00250						
0.4	.62861	.62015	.59241	.53767	.44329	.31048	.18709	.08593	.03118								
0.5	.55279	.54403	.51622	.46448	.38390	.28156	.18556	.09499	.03701	.01013	.00407	.00209	.00118	.00053	.00025	.00014	.00009
0.6	.48550	.47691	.45078	.40427	.33676	.25588	.17952	.10010									
0.7	.42654	.41874	.39491	.35428	.29833	.21727	.17124	.10228	.04558								
0.8	.37531	.36832	.34729	.31243	.26581	.21297	.16206	.10236									
0.9	.33104	.32492	.30669	.27707	.23832	.19488	.15253	.10094									
1	.29289	.28763	.27005	.24697	.21468	.17868	.14329	.09849	.05185	.01742	.00761	.00393	.00226	.00097	.00050	.00029	.00018
1.2	.23178	.22795	.21662	.19890	.17626	.15101	.12570	.09192	.05260	.01935	.00871	.00459	.00269	.00115			
1.5	.16795	.16552	.15877	.14804	.13436	.11892	.10296	.08048	.05116	.02142	.01013	.00548	.00325	.00141	.00073	.00043	.00027
2	.10557	.10453	.10140	.09647	.09011	.08269	.07471	.06275	.04496	.02221	.01160	.00659	.00399	.00180	.00094	.00056	.00036
2.5	.07152	.07098	.06947	.06698	.06373	.05974	.05555	.04880	.03787	.02143	.01221	.00732	.00463	.00214	.00115	.00068	.00043
3	.05132	.05101	.05022	.04886	.04707	.04487	.04241	.03839	.03150	.01980	.01220	.00770	.00505	.00242	.00132	.00079	.00051
4	.02986	.02976	.02907	.02832	.02802	.02749	.02651	.02490	.02193	.01592	.01109	.00768	.00536	.00282	.00160	.00099	.00065
5	.01942	.01938				.01835			.01573	.01249	.00949	.00708	.00527	.00298	.00179	.00113	.00075
6	.01361					.01307			.01168	.00983	.00795	.00628	.00492	.00299	.00188	.00124	.00084
7	.01005					.00976			.00894	.00784	.00661	.00548	.00445	.00291	.00193	.00130	.00091
8	.00772					.00755			.00703	.00635	.00554	.00472	.00398	.00276	.00189	.00134	.00094
9	.00612					.00600			.00566	.00520	.00466	.00409	.00353	.00256	.00184	.00133	.00096
10								.00477	.00465	.00438	.00397	.00352	.00326	.00241			

Function B

Depth (z) in Radii	Offset (r) in Radii: 0	0.2	0.4	0.6	0.8	1	1.2	1.5	2	3	4	5	6	8	10	12	14
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.1	.09852	.10140	.11138	.13424	.18796	.05388	−.07899	−.02672	−.00845	−.00210	−.00084	−.00042					
0.2	.18857	.19306	.20772	.23524	.25983	.08513	−.07759	−.04448	−.01593	−.00412	−.00166	−.00083	−.00024	−.00010			
0.3	.28362	.26787	.28018	.29483	.27257	.10757	−.04316	−.04999	−.02166	−.00599	−.00245						
0.4	.32016	.32259	.32748	.32273	.26925	.12404	−.00766	−.04535	−.02522								
0.5	.35777	.35752	.35323	.33106	.26236	.13591	.02165	−.03455	−.02651	−.00991	−.00388	−.00199	−.00116	−.00049	−.00025	−.00014	[illegible]
0.6	.37831	.37531	.36308	.32822	.25411	.14440	.04457	−.02101									
0.7	.38487	.37962	.36072	.31929	.24638	.14986	.06209	−.00702	−.02329								
0.8	.38091	.37408	.35133	.30699	.23779	.15292	.07530	.00614									
0.9	.36962	.36275	.33734	.29299	.22891	.15404	.08507	.01795									
1	.35355	.34553	.32075	.27819	.21978	.15355	.09210	.02814	−.01005	−.01115	−.00608	−.00344	−.00210	−.00092	−.00048	−.00028	[illegible]
1.2	.31485	.30730	.28481	.24836	.20113	.14915	.10002	.04378	.00023	−.00995	−.00632	−.00378	−.00236	−.00107			
1.5	.25602	.25025	.23338	.20694	.17368	.13732	.10193	.05745	.01385	−.00669	−.00600	−.00401	−.00265	−.00126	−.00068	−.00040	[illegible]
2	.17889	.18144	.16644	.15198	.13375	.11331	.09254	.06371	.02836	.00028	−.00410	−.00371	−.00278	−.00148	−.00084	−.00050	[illegible]
2.5	.12807	.12633	.12126	.11327	.10298	.09130	.07869	.06022	.03429	.00661	−.00130	−.00271	−.00250	−.00156	−.00094	−.00059	[illegible]
3	.09487	.09394	.09099	.08635	.08033	.07325	.06551	.05354	.03511	.01112	.00157	−.00134	−.00192	−.00151	−.00099	−.00065	[illegible]
4	.05707	.05666	.05562	.05383	.05145	.04773	.04532	.03995	.03066	.01515	.00595	.00155	−.00029	−.00109	−.00094	−.00068	[illegible]
5	.03772	.03760				.03384			.02474	.01522	.00810	.00371	.00132	−.00043	−.00070	−.00068	[illegible]
6	.02666					.02468			.01968	.01380	.00867	.00496	.00254	.00028	−.00037	−.00047	[illegible]
7	.01980					.01868			.01577	.01204	.00842	.00547	.00332	.00093	−.00002	−.00029	[illegible]
8	.01526					.01459			.01279	.01034	.00779	.00554	.00372	.00141	.00035	−.00008	[illegible]
9	.01212					.01170			.01054	.00888	.00705	.00533	.00386	.00178	.00066	.00012	[illegible]
10								.00924	.00879	.00764	.00631	.00501	.00382	.00199			

Two Layer system



Flexible plate $$\Delta = 1.5 \frac{pa}{E_2} F_2 \tag{2.8}$$

Rigid plate $$\Delta = 1.18 \frac{pa}{E_2} F_2 \tag{2.9}$$

where p = unit load on circular plate
a = radius of plate
E_2 = modulus of elasticity of *lower* layer
F_2 = dimensionless factor depending on the ratio of moduli of elasticity of the subgrade and pavement as well as the depth to radius ratio

Curves of F_2 for various depth ratio and moduli of elasticity are shown in Figure 2.7.

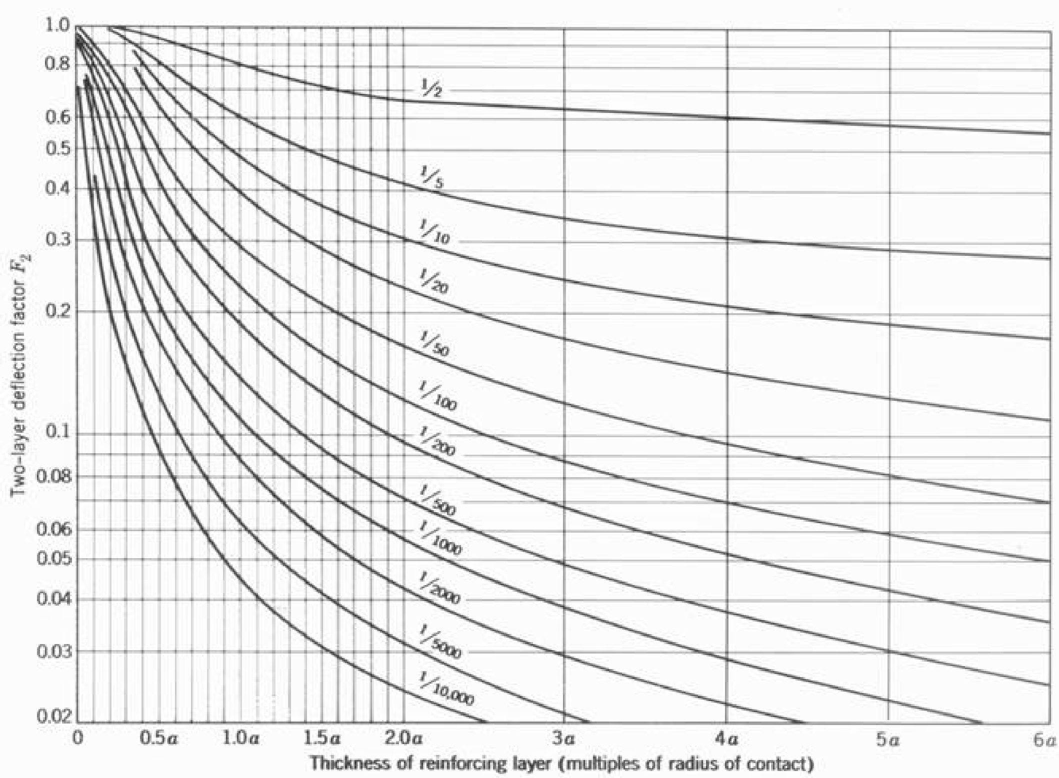
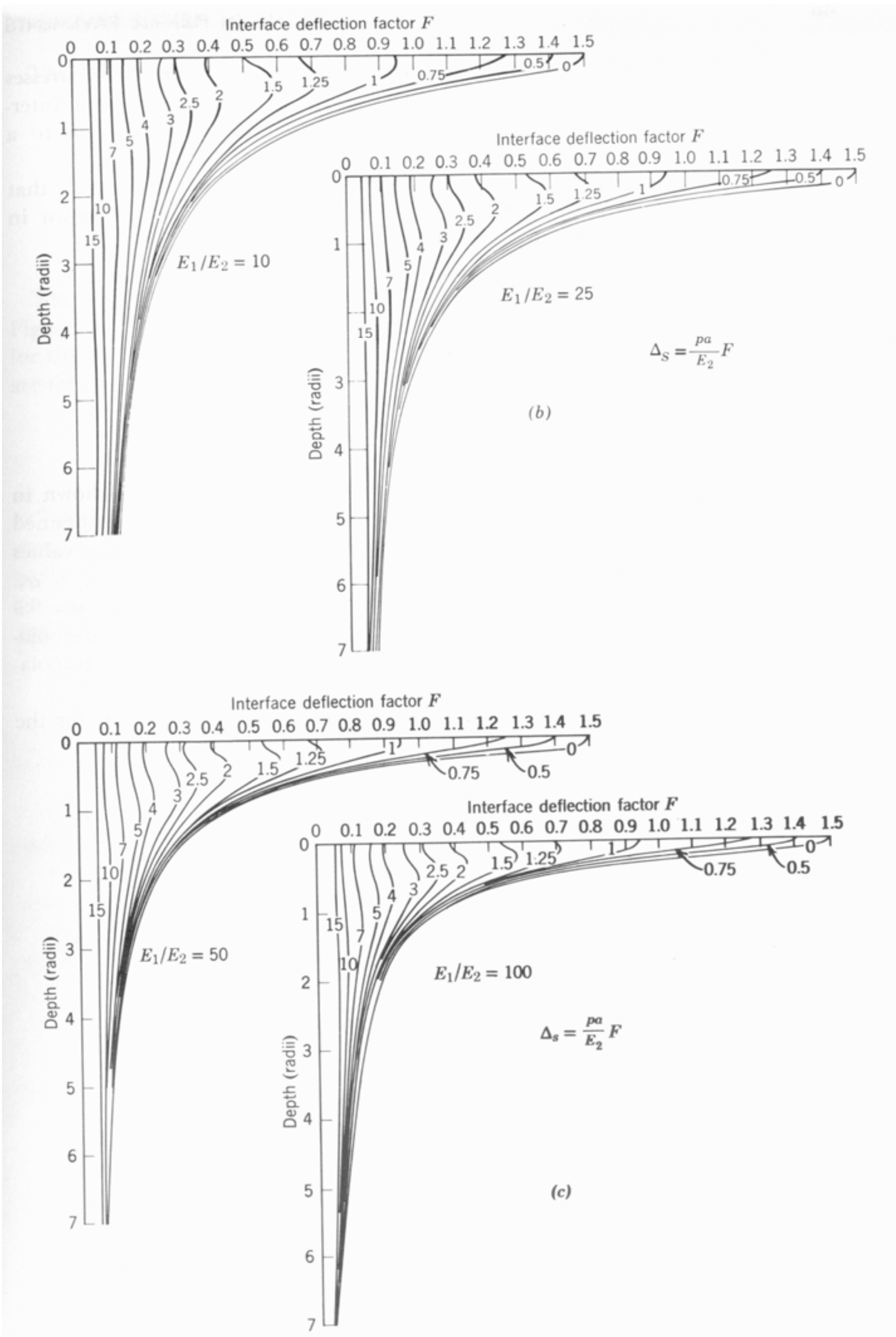


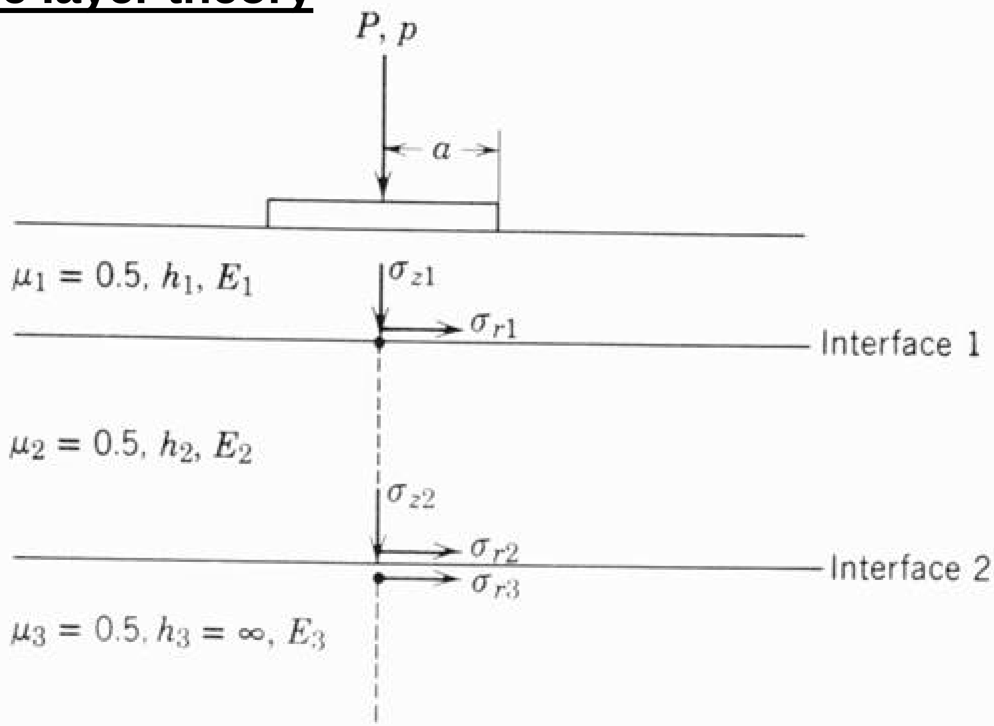
Figure 2.7. Influence values—two-layer theory. (From Burmister, *Proceedings*, Highway Research Board, 1943.)

Interface Deflection

$$\Delta_s = \frac{pa}{E_2} \cdot F$$



Three layer theory



$$\sigma_{Z1} = p(ZZ1)$$

$$\sigma_{Z2} = p(ZZ2)$$

use with Figure 2.10

Function of

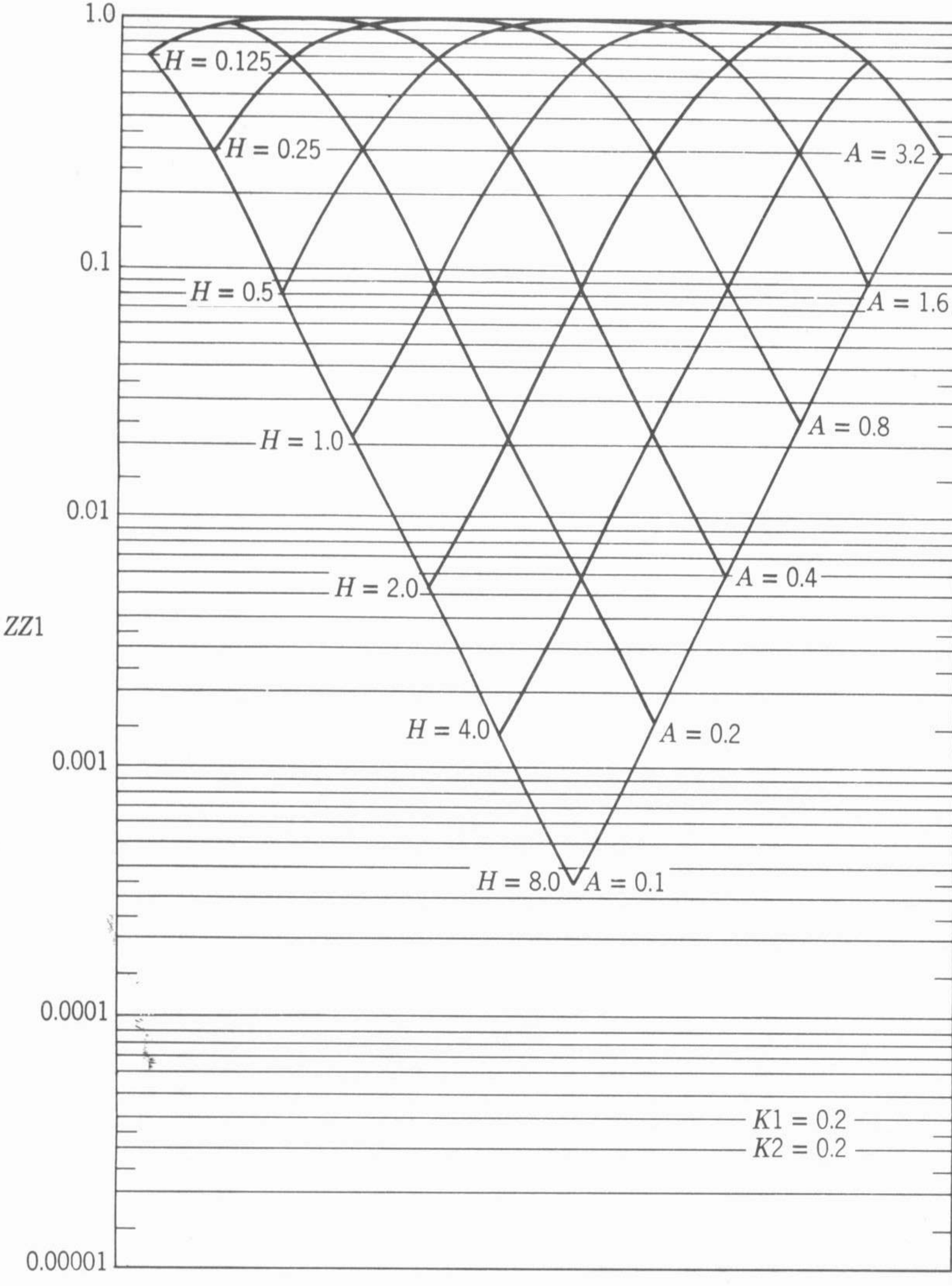
$$k_1 \text{ or } K1 = \frac{E_1}{E_2} \qquad k_2 \text{ or } K2 = \frac{E_2}{E_3}$$

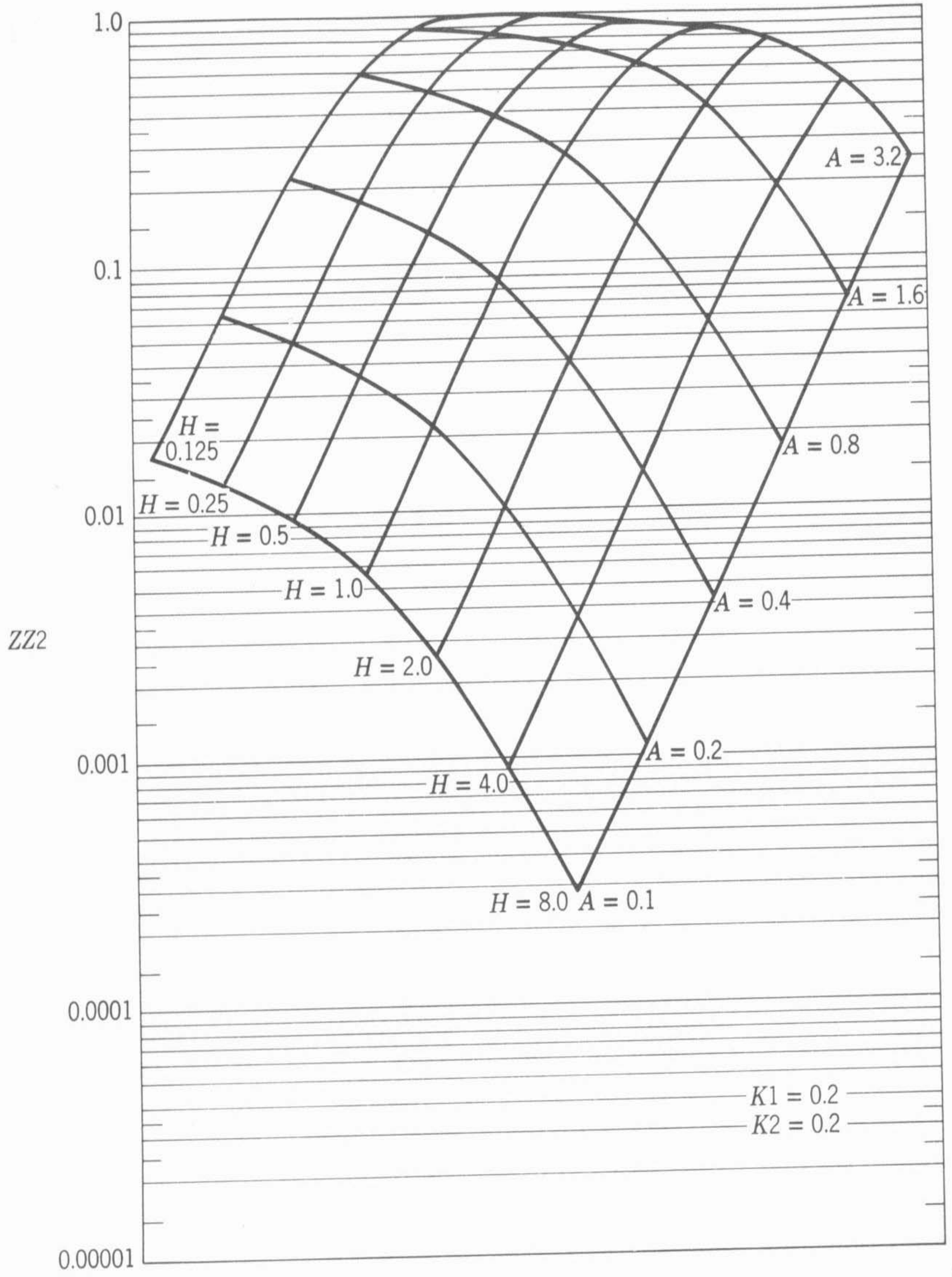
$$a_1 \text{ or } A = \frac{a}{h_2} \qquad H = \frac{h_1}{h_2}$$

$$\sigma_{z1} - \sigma_{r1} = p[ZZ1 - RR1]$$
$$\sigma_{z2} - \sigma_{r2} = p[ZZ2 - RR2]$$
$$\sigma_{z2} - \sigma_{r3} = p[ZZ2 - RR3]$$

use with Table 2.3

$$\varepsilon_z = \frac{1}{E}\left[\sigma_z - \mu\left(\sigma_r + \sigma_t\right)\right]$$
$$\varepsilon_r = \frac{1}{E}\left[\sigma_r - \mu\left(\sigma_t + \sigma_z\right)\right]$$
$$\varepsilon_t = \frac{1}{E}\left[\sigma_t - \mu\left(\sigma_r + \sigma_z\right)\right]$$


1.0
0.1
0.01
0.001
0.0001
0.00001
ZZ1
H = 0.125
H = 0.25
H = 0.5
H = 1.0
H = 2.0
H = 4.0
H = 8.0
A = 3.2
A = 1.6
A = 0.8
A = 0.4
A = 0.2
A = 0.1
K1 = 0.2
K2 = 0.2

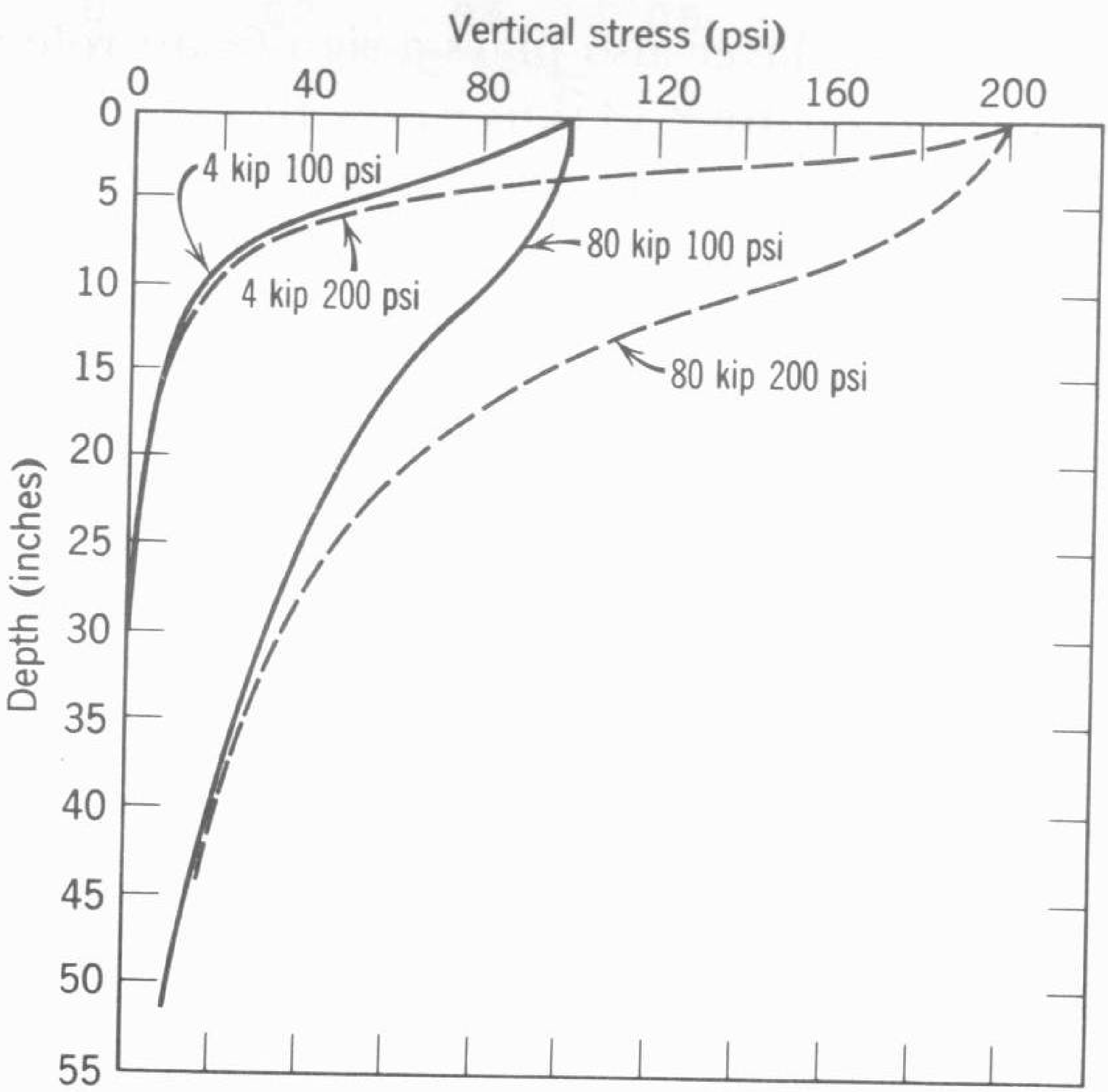


1.0
0.1
0.01
0.001
0.0001
0.00001
ZZ2
A = 3.2
A = 1.6
A = 0.8
A = 0.4
A = 0.2
A = 0.1
H = 0.125
H = 0.25
H = 0.5
H = 1.0
H = 2.0
H = 4.0
H = 8.0
K1 = 0.2
K2 = 0.2

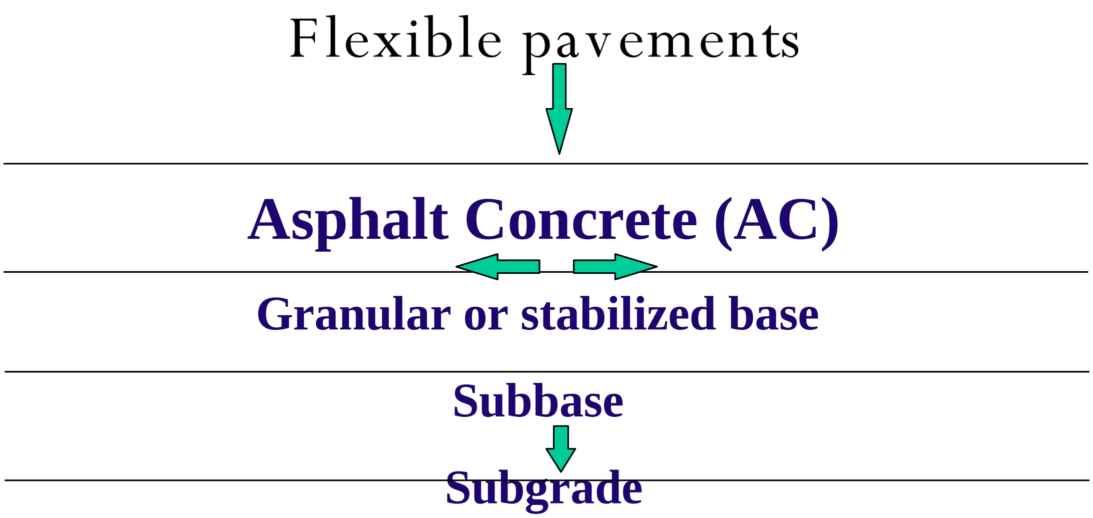
TABLE 2.3. Three-Layer Stress Factors (after Jones)

	$H = 0.125$ $k_1 = 0.2$			$H = 0.125$ $k_1 = 2.0$			$H = 0.125$ $k_1 = 20.0$			$H = 0.125$ $k_1 = 200.0$		
a_1	$(ZZ1-RR1)$	$(ZZ2-RR2)$	$(ZZ2-RR3)$	$(ZZ1-RR1)$	$(ZZ2-RR2)$	$(ZZ2-RR3)$	$(ZZ1-RR1)$	$(ZZ2-RR2)$	$(ZZ2-RR3)$	$(ZZ1-RR1)$	$(ZZ2-RR2)$	$(ZZ2-$
			$k_2 = 0.2$			$k_2 = 0.2$			$k_2 = 0.2$			$k_2 =$
0.1	0.12438	0.00332	0.01659	0.71614	0.00350	0.01750	1.80805	0.00322	0.01611	2.87564	0.00201	0.01
0.2	0.13546	0.01278	0.06391	1.01561	0.01348	0.06741	3.75440	0.01249	0.06244	7.44285	0.00788	0.03
0.4	0.10428	0.04430	0.22150	0.83924	0.04669	0.23346	5.11847	0.04421	0.22105	15.41021	0.02913	0.1
0.8	0.09011	0.10975	0.54877	0.63961	0.11484	0.57418	3.38600	0.11468	0.57342	9.70261	0.08714	0.4
1.6	0.08777	0.13755	0.68777	0.65723	0.13726	0.68630	1.81603	0.13687	0.68436	7.02380	0.13705	0.6
3.2	0.04129	0.10147	0.50736	0.38165	0.09467	0.47335	1.75101	0.07578	0.37890	2.35459	0.06594	0.3
			$k_2 = 2.0$			$k_2 = 2.0$			$k_2 = 2.0$			$k_2 =$
0.1	0.12285	0.01693	0.00846	0.70622	0.01716	0.00858	1.81178	0.01542	0.00771	3.02259	0.00969	0.00
0.2	0.12916	0.06558	0.03279	0.97956	0.06647	0.03324	3.76886	0.06003	0.03002	8.02452	0.03812	0.01
0.4	0.08115	0.23257	0.11629	0.70970	0.23531	0.11766	5.16717	0.21640	0.10820	17.64175	0.14286	0.07
0.8	0.01823	0.62863	0.31432	0.22319	0.63003	0.31501	3.43631	0.60493	0.30247	27.27701	0.45208	0.2
1.6	−0.04136	0.98754	0.49377	−0.19982	0.97707	0.48853	1.15211	0.97146	0.48573	23.38638	0.90861	0.4
3.2	−0.03804	0.82102	0.41051	−0.28916	0.84030	0.42015	−0.06894	0.88358	0.44179	11.87014	0.91469	0.4
			$k_2 = 20.0$			$k_2 = 20.0$			$k_2 = 20.0$			$k_2 =$
0.1	0.12032	0.03667	0.00183	0.69332	0.03467	0.00173	1.80664	0.02985	0.00149	3.17763	0.01980	0.00
0.2	0.11787	0.14336	0.00717	0.92086	0.13541	0.00677	3.74573	0.11697	0.00585	8.66097	0.07827	0.00
0.4	0.03474	0.52691	0.02635	0.46583	0.49523	0.02476	5.05489	0.43263	0.02163	20.12259	0.29887	0.0
0.8	−0.14872	1.61727	0.08086	−0.66535	1.49612	0.07481	2.92533	1.33736	0.06687	36.29943	1.01694	0.0
1.6	−0.50533	3.58944	0.17947	−2.82859	3.28512	0.16426	−1.27093	2.99215	0.14961	49.40857	2.64313	0.1
3.2	−0.80990	5.15409	0.25770	−5.27906	5.05952	0.25298	−7.35384	5.06489	0.25324	57.84369	4.89895	0.2
			$k_2 = 200.0$			$k_2 = 200.0$			$k_2 = 200.0$			$k_2 =$
0.1	0.11720	0.05413	0.00027	0.67488	0.04848	0.00024	1.78941	0.04010	0.00020	3.26987	0.02809	0.0
0.2	0.10495	0.21314	0.00170	0.85397	0.19043	0.00095	3.68097	0.15781	0.00079	9.02669	0.11136	0.0
0.4	−0.01709	0.80400	0.00402	0.21165	0.71221	0.00356	4.80711	0.59391	0.00297	21.56482	0.43035	0.0
0.8	−0.34427	2.67934	0.01340	−1.65954	2.32652	0.01163	1.90825	1.95709	0.00979	41.89873	1.53070	0.0
1.6	−1.21139	7.35978	0.03680	−6.47707	6.26638	0.03133	−5.28803	5.25110	0.02626	69.63157	4.56707	0.0
3.2	−2.89282	16.22830	0.08114	−16.67376	14.25621	0.07128	−21.52546	12.45058	0.06225	120.95931	11.42045	0.0

Effect of Tire Load and Pressure



Typical Structure:



<u>80% + of pavements worldwide</u>
<u>Full depth = AC on subgrade</u>
<u>Deep strength = AC on subbase</u>

..

For most rational design procedures ε_t, ε_c are required. Their levels are limited to keep fatigue and rutting from occurring too soon.

Development of layered elastic theory:

1) 1848 Kelvin – elastic half space
2) 1885 Boussinesq – elastic half space
3) 1926 Westergard – 2 layers
4) 1943 Burmister - > 2 layers
5) 1948 Fox – solution for two layers
6) 1961 Jones & Peattie – 3 layers
7) 1963 Commercial programs - $\geq$ 5 layers

Layer theory general rule:

1. Increase in flexural stiffness of any layer (E) will decrease the stresses and strains in layers below.

2. Stiff layers attract stresses. (may lead to failure)

3. Elastic linear theory is valid, providing temperatures are not high, speed is not low, and the pavement has > thin stabilized layer.

Computer Programs:

1- CHEV5L (CHEVRON)

$\leq$ 5 layers, 1 load, Linear elastic.

2- PSAD (CHEVRON)

As CHEV5L but Non-linear

3- PSAD2A (CHEVRON)

As PSAD with 2 Loads.

4- ELSYM5 (Univ. of California)

$\leq$ 5 layers, $\leq$ 10 loads, linear elastic.

5- BISAR (SHELL)

$\leq$ 10 layers, $\leq$ 10 loads, linear can include shear forces.

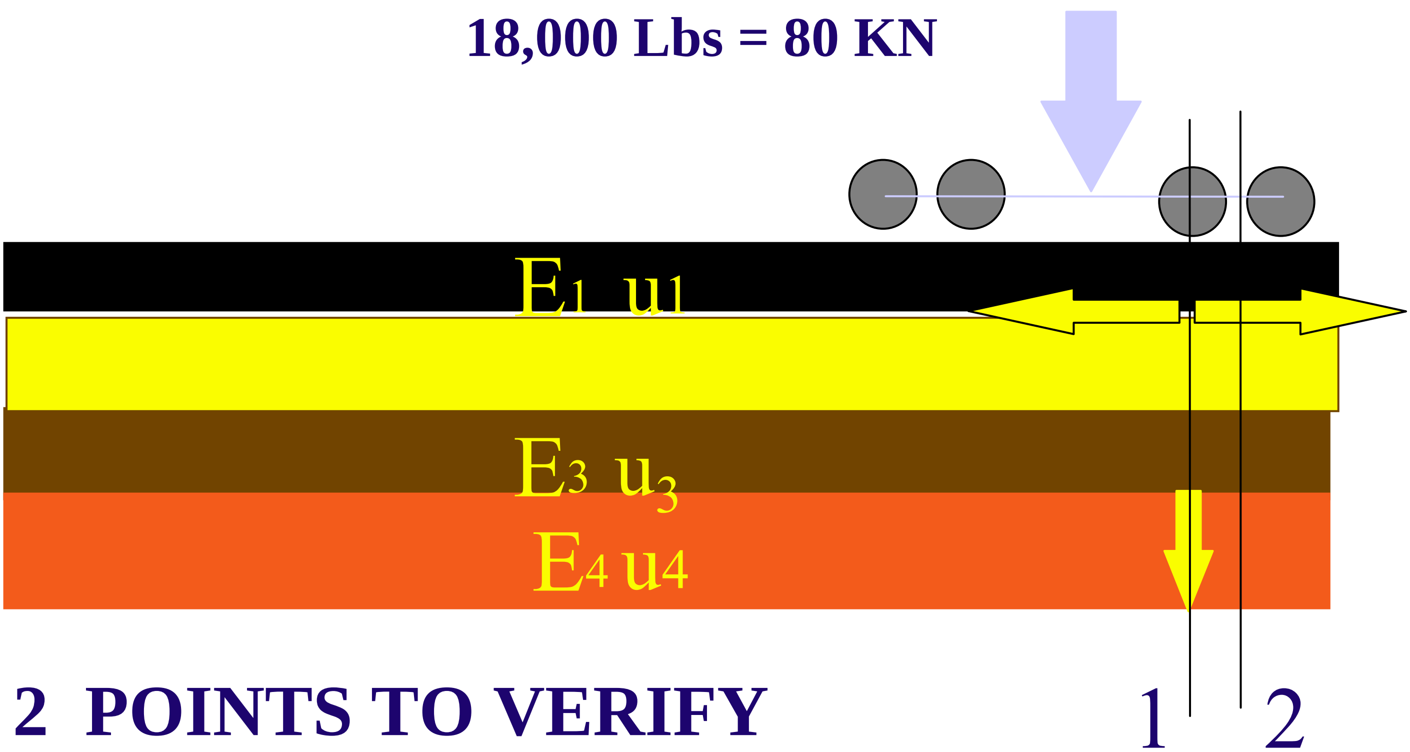
6- BOUSS (OSU)

$\leq$ 10 layers, 1 load, approx. linear.

MULTI-LAYER STRUCTURAL ANALYSIS

FHWA (ELSYM5)

18,000 Lbs = 80 KN



2 POINTS TO VERIFY