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Faculty of Engineering, Built Environment and Information Technology

Fakulteit Ingenieurswese, Bou-omgewing en Inligtingtegnologie / Lefapha la Boetšenere, Tikologo ya Kago le Theknolotši ya Tshedimošo

Inverted Pavements

Prof Wynand JvdM Steyn – HOD Civil Engineering

Acknowledgement – Eduard Kleyn, Andrew MacKellar, Michele van der Walt

11 February 2020

- Background
- Design philosophy
- Pavement mechanics
- Materials
- Affecting parameters
- Construction
- Performance
- Economics

Background

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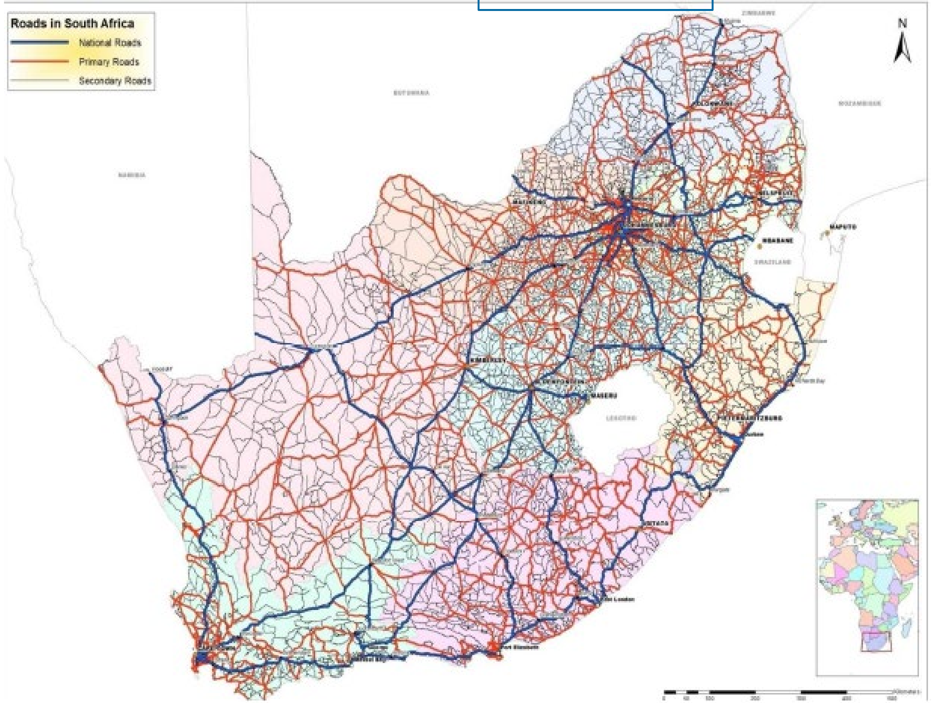
South African Road Network

Paved	Gravel	Total
153 719 km	593 259 km	746 978 km
20.6 %	79.4 %	**467 000 mi**

59 million population

South Africa road network
11th longest total
18th longest paved

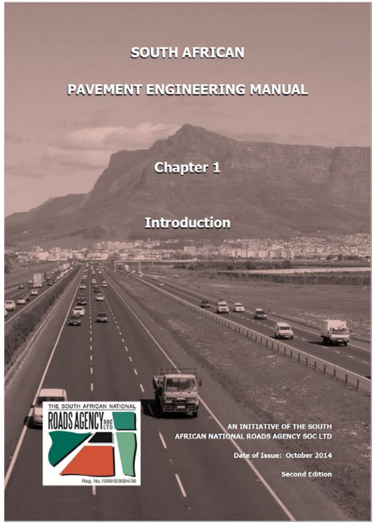
RSA road replacement
cost > US$ 1.4 Billion



Rank	Country	Road length [km]
1	United States	6,650,000
2	India	5,603,293
3	China	4,859,500
4	Brazil	1,751,868
5	Russia	1,452,200
6	Japan	1,215,000
7	Canada	1,042,300
8	Thailand	1,004,310
9	France	965,446
10	Australia	920,217
11	South Africa	750,014
29	Nigeria	193,200
32	Kenya	161,415
34	Congo, Democratic Republic of	153,497
39	Egypt	137,430
44	Algeria	113,655
45	Ethiopia	110,414
46	Ghana	109,515
48	Libya	100,024
49	Zimbabwe	97,418

Current SA Pavement environment

- SAPEM – https://www.nra.co.za/live/content.php?Item_ID=232



Using SAPEM: Do

- Do use SAPEM as a **roadmap** to guide you through a particular process in road engineering to help you access the most relevant and up-to-date approaches, methods and techniques.
- Do use the **references** provided to gain more detailed knowledge on a specific area. This will not only supplement your knowledge, but can also provide the necessary specification guidelines, test methods and available standard documentation.
- Do be aware of differences between the **requirements of road authorities**. SAPEM has been drawn up generically for the highest level of application of pavement technology. However, where possible, caveats for provincial, municipal, district and metro roads are provided.

Using SAPEM: Don't

- Don't consider SAPEM as an exhaustive compilation of all the details that you may require. SAPEM only **provides an overview,** and includes many references to the latest detailed approaches, and procedures to cover the rest. Use the references.
- Don't follow SAPEM by **rote without critical consideration** and decision making for your particular road's needs.
- Don't ignore basic engineering judgement. SAPEM can only **supplement knowledge** and cannot replace judgement.
- Don't consider SAPEM to replace mentors. Use it as a **supplementary source of guidance** and reference.
- Don't use SAPEM as the main source of information for affiliated fields that have some relation to pavements, e.g., geotechnical investigations and tunnelling. SAPEM aims to include some information on these areas for completeness, but is by **no means a definitive source of guidance** in specialist areas.

Brief history of inverted pavement development

- Definitions
  - G1 vs inverted
    - G1 – high-quality crushed aggregate base material
    - Inverted pavement – pavement structure - SAPEM definition
- 1950s/60s
  - Economic & traffic growth
  - SA visit US
  - Learn about cement stabilization
  - SA application base layer / thin surfacing – major cracking & crushing
  - Keep strong material, reduce cracks – granular on top of cemented
  - Birth of inverted pavement structure

Inverted Pavements - SAPEM 10

- An inverted pavement is when the **base layer is a high quality granular layer**, and the **subbase a cement stabilized layer**. A thin asphalt layer or seal provides the surfacing. The term “inverted” is used because the **strength of the pavement does not decrease with pavement depth**, because of the stiff cemented layer. This means that the pavement is not in balance. The idea behind an inverted pavement is that the **cemented layer provides an anvil upon which the granular base can be well compacted**. This achieves a high quality, dense base. Over time, the cemented layer weakens to an equivalent granular state. The pavement is then in balance.

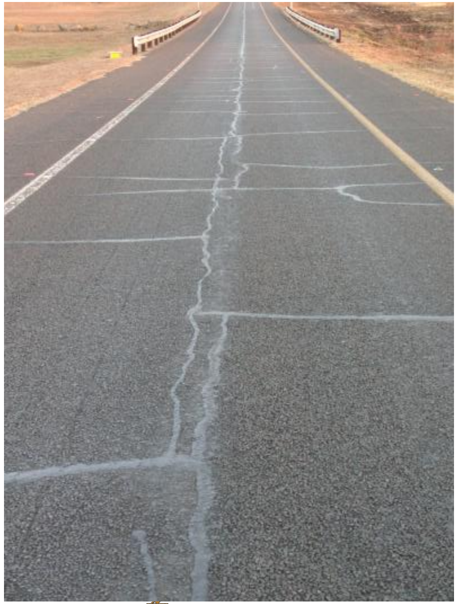
Design philosophy

Design philosophy for inverted pavements

Art of Pavement Engineering

The art of pavement design is to ensure that materials within the pavement layers are not overstressed at any time during the course of these changes in the pavement's life.

- Need stronger layers for higher traffic
- Cemented base causes block cracks
- Granular on granular - difficult to compact
- Granular on cemented
  - **Anvil for compaction & support**
  - higher density / bearing capacity / stiffness
- Cemented still cracks
  - Fatigue after longer time – lower σ deeper down
  - Crushing not a problem below base



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Pavement mechanics

Inverted pavements - Pavement mechanics

Art of Pavement Engineering
The art of pavement design is to ensure that materials within the pavement layers are not overstressed at any time during the course of these changes in the pavement's life.

- Pavements team effort
- Boussinesq example

	Stiffness [MPa]		
	AC, G1, C4, G5	**AC, G1, G2, G5**	**AC, C4, G1, G5**
E1/E2	0.3 (1)	1 (3)	3.3 (9)
Base / Subbase σ ratio	0.7	0.5	0.3

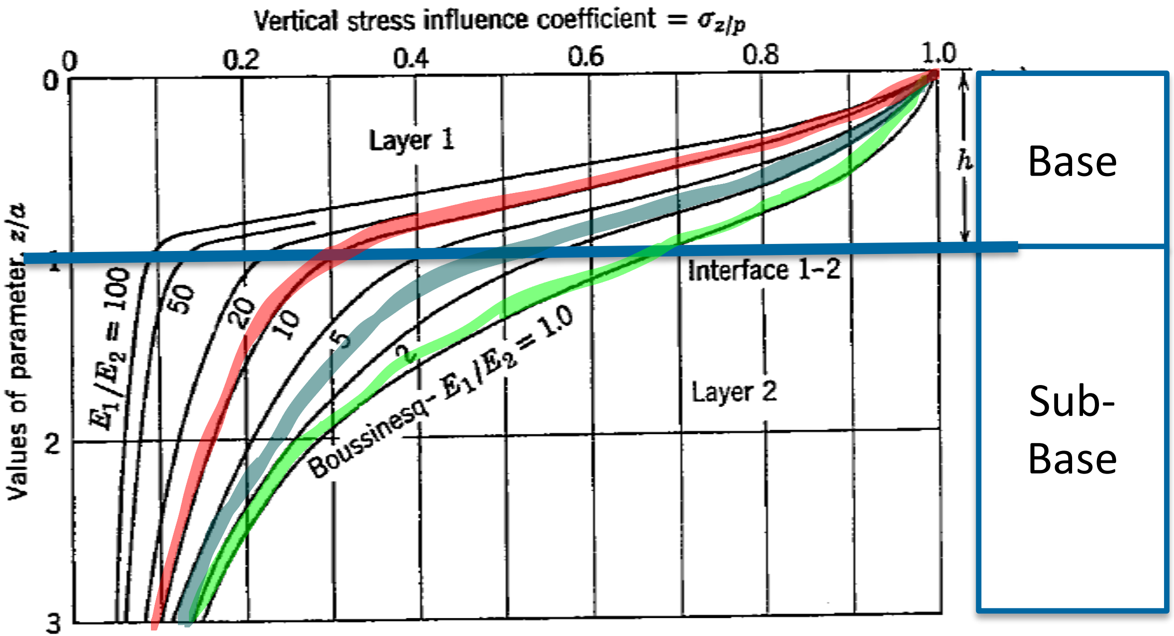


Figure 2.6. Basic pattern of Burmister two-layer stress influence curves. (From Burmister, Highway Research Board Bulletin 177.)

Inverted pavements - Pavement mechanics

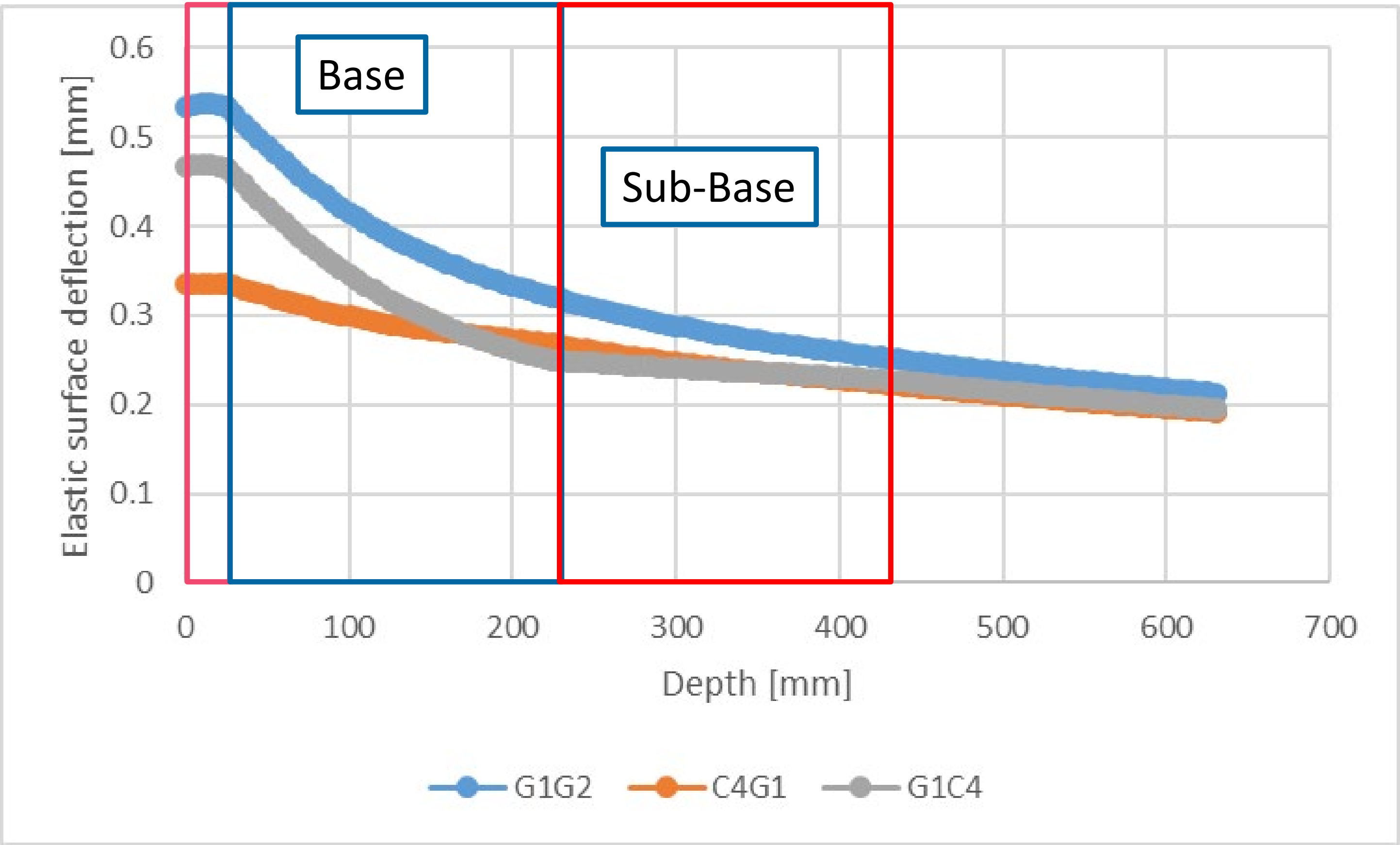
- meGAMES examples
  - **G1 on G2** - 25 AC, 200 G1, 200 G2, 200 G5
  - **C4 on G1** - 25 AC, 200 C4, 200 G1, 200 G5
  - **G1 on C4** - 25 AC, 200 G1, 200 C4, 200 G5
- Dual tire single axle 20 kN, 800 kPa / tire

	Stiffness [MPa]		
	AC, G1, G2, G5	**AC, C4, G1, G5**	**AC, G1, C4, G5**
AC	3 500	3 500	3 500
Base	300	1 000 / 100	300
Subbase	250	300	1 000 / 100
Support	200	200	200

	Estimate life [million E80s]		
	AC, G1, G2, G5	AC, C4, G1, G5	AC, G1, C4, G5
AC	0.06		
Base	[illegible]		
Subbase			
CRITICAL Life (excluding AC)	8.4		

ONLY AN EXAMPLE FOR ILLUSTRATION

Elastic vertical deflection [mm]



Materials

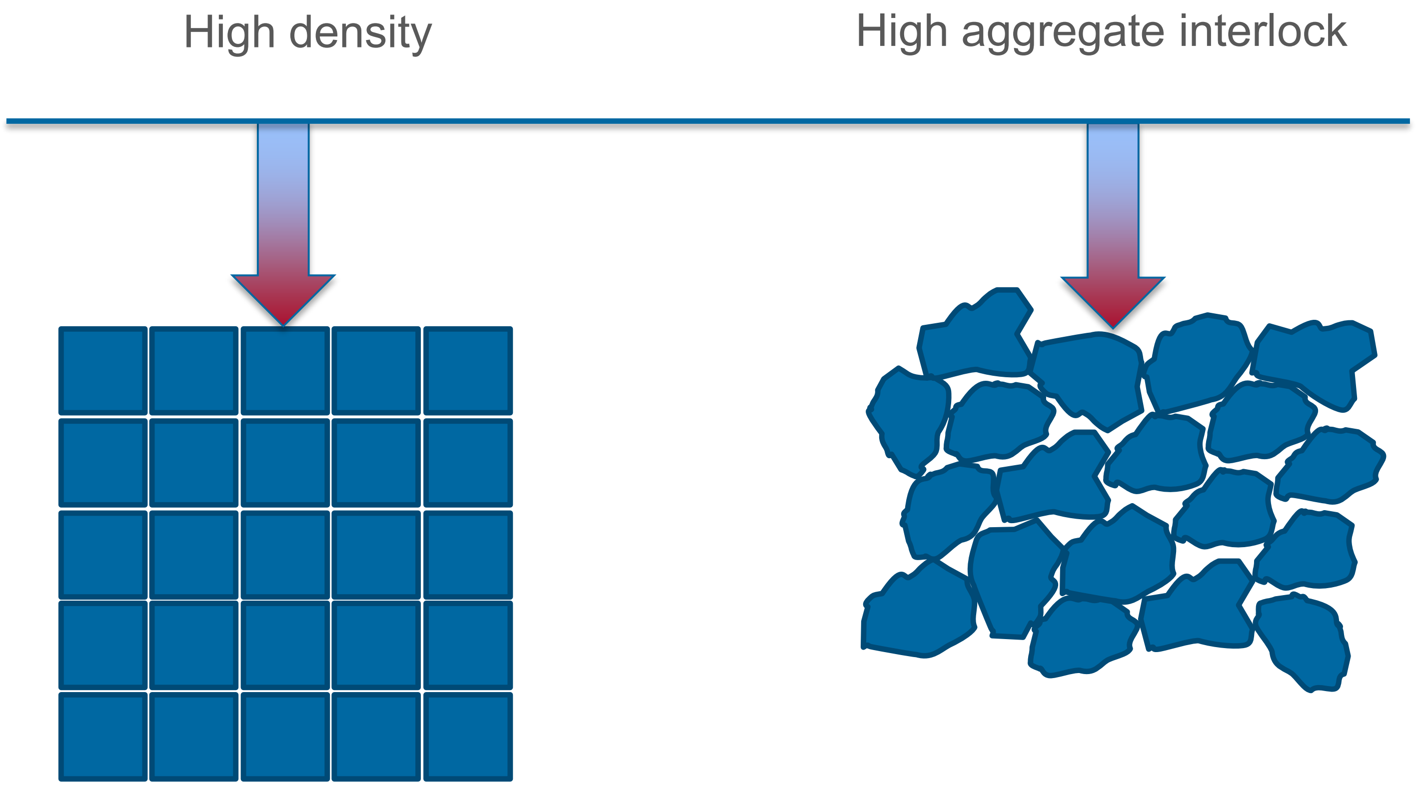
Factors influencing shear properties of a material

- **Grading**
  - maximum particle size, packing characteristics, number of contact points, irregular paths that the shear plane has to navigate through
- **Aggregate strength**
  - aggregate crushing value (ACV)
- **Particle shape**
  - rounded particles less shear resistance than angular particles
- **Particle texture**
  - coarser texture generate higher friction than smooth particles
- **Compaction**
  - number of contact points and inter-particle friction increase as the density of a material increases
- **Degree of support from underlying layer**
  - influences stiffness modulus that granular material develops

Materials selection

- "**Parent material** - Sound rock from an approved quarry, or clean, sound mine rock from mine dumps, or clean sound boulders."
- **Material selection**
  - Aggregate Interlock
- G1 is a **layer of**
  - Continuously graded, -37,5 mm crushed aggregate
  - Slush-interlocked to refusal
- **Minimum density**
  - 88% of Solid / Apparent Relative Density (SRD / ARD)

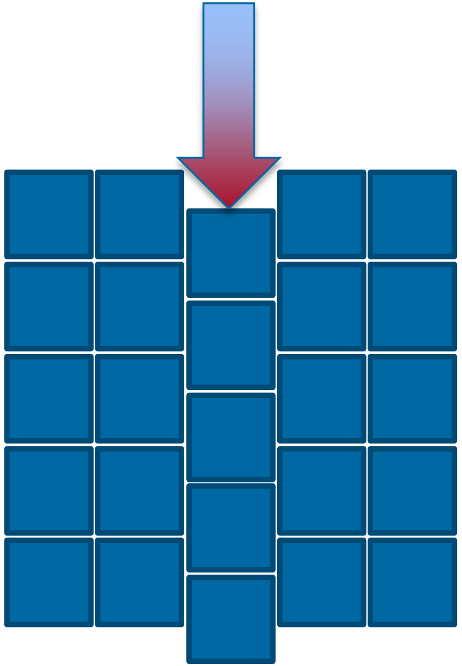
Good particle size distribution

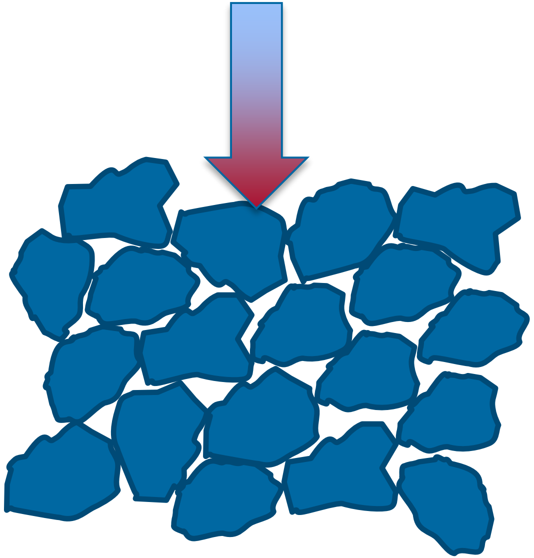


High density
High aggregate interlock

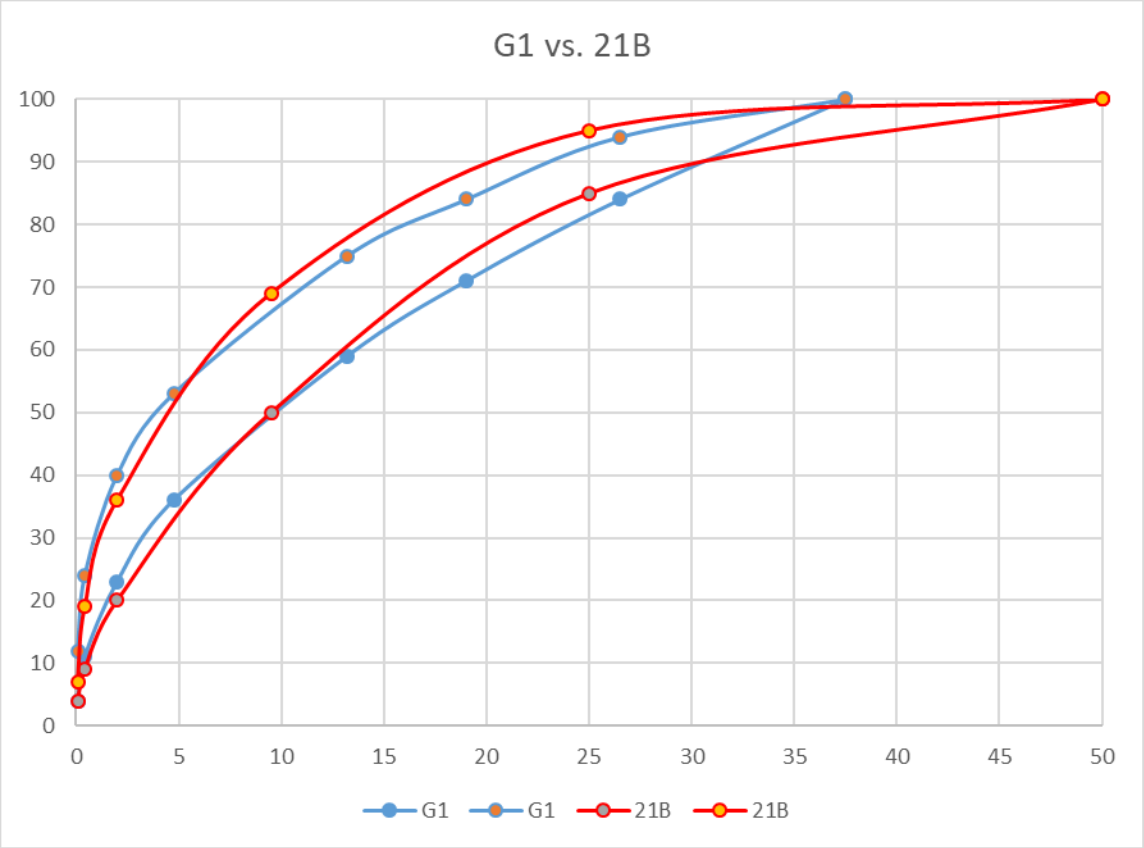
High density

High aggregate interlock





US grading vs G1 grading



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Affecting parameters

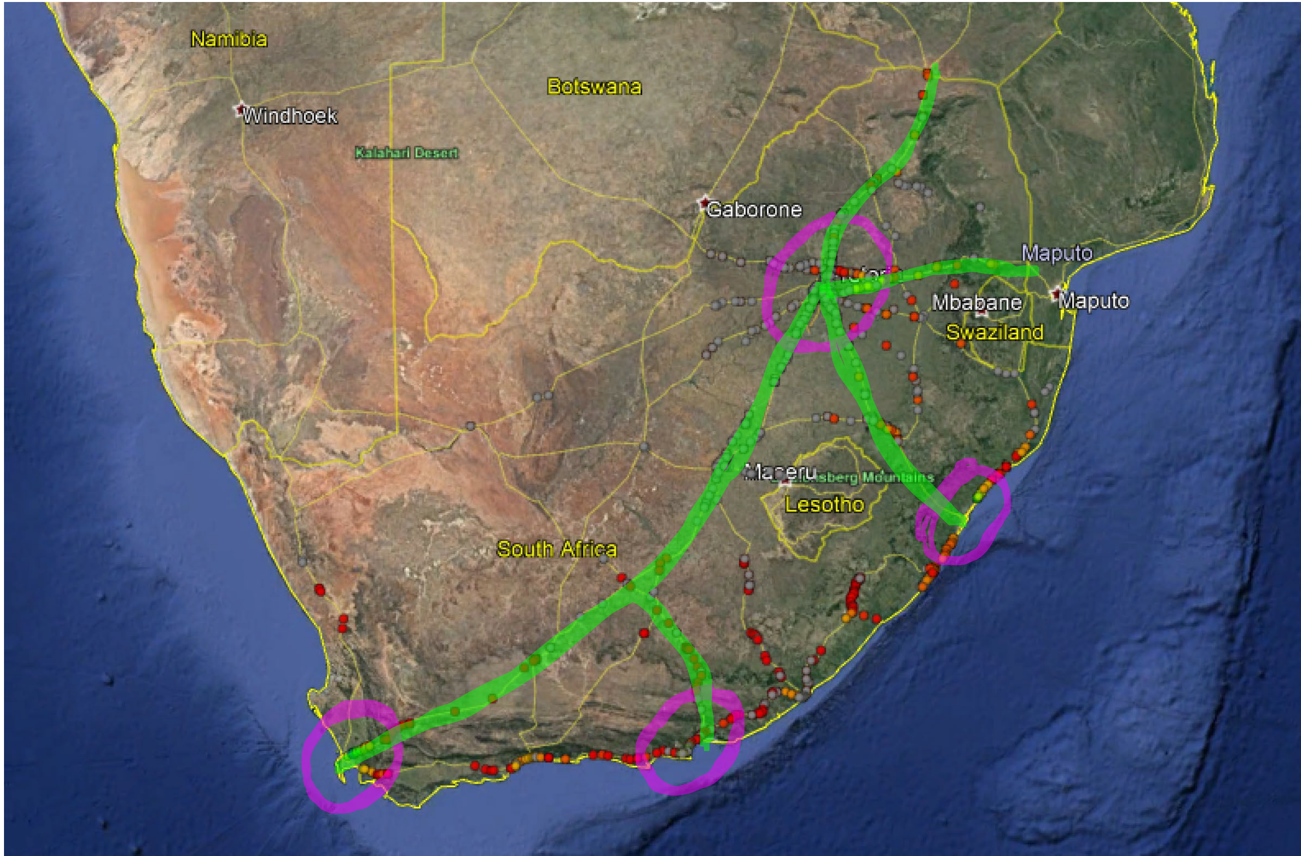
Inverted pavement – affecting parameters

- Standard parameters affecting most pavements
  - Climate
  - Traffic

Inverted pavements – Major locations

Economic hubs

Trade / Import / Export Routes



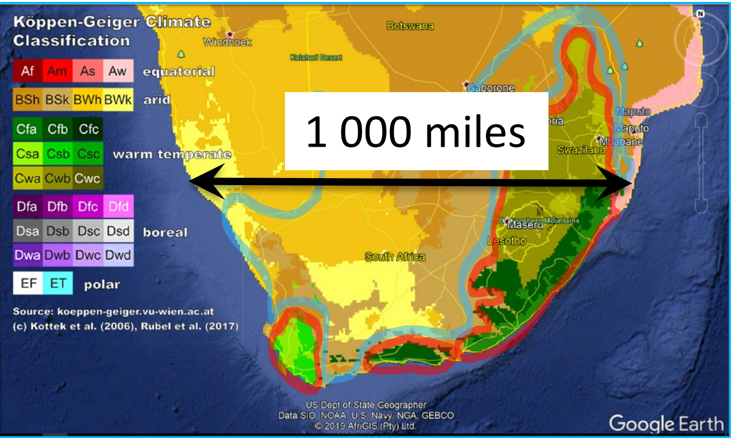
Inverted pavements - Climate

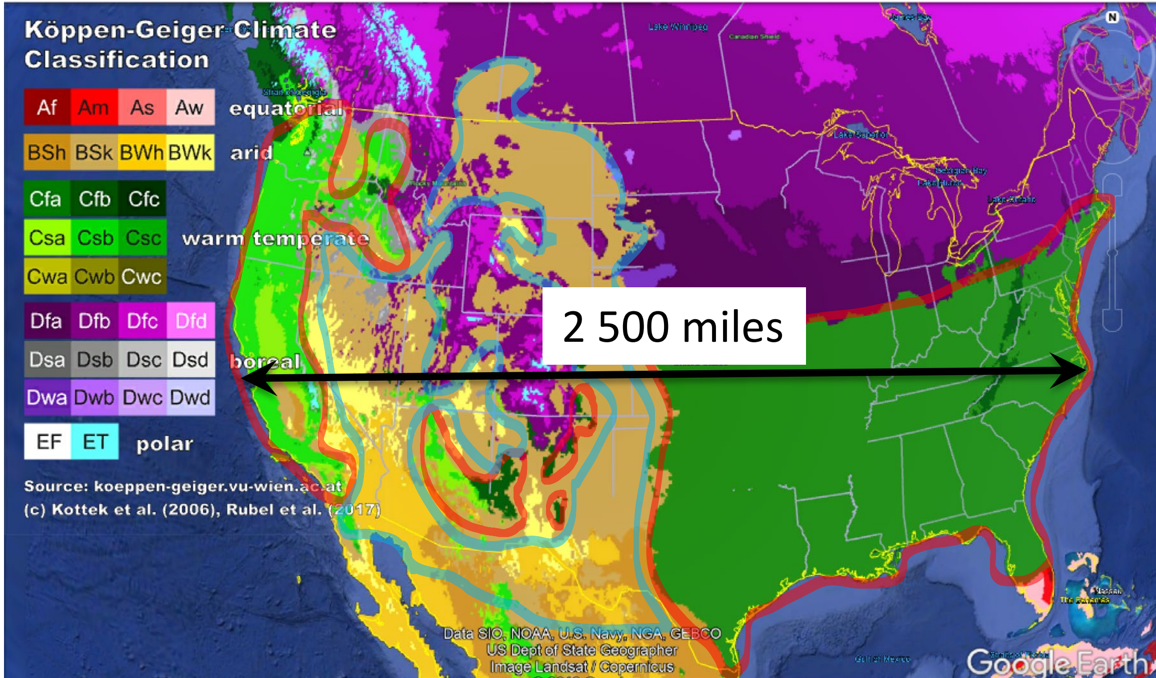
- Comparative climate
  - **Köppen climate classification**
  - 5 main climate groups
    - seasonal precipitation & temperature patterns
  - 1^{st} - A (tropical), **B (dry), C (temperate)**, D (continental), E (polar)
  - 2^{nd} - seasonal precipitation type
  - 3^{rd} - level of heat

- **SA**
  - CS/CW (Temperate Dry Summer / Winter); BS/BW (Arid Desert / Steppe)
- **USA**
  - CS/CF (Temperate Dry Summer / without); BS/BW (Arid Desert / Steppe); Also Boreal / continental

Inverted pavements – Climate: Köppen-Geiger map

- SA – CS/CW; BS/BW
- USA – CS/CF; BS/BW





Inverted pavements - Climate

- Average rainfall
  - Pretoria – 23”
  - Durban – 40”
  - Kimberley – 11”
  - Cape Town – 31”

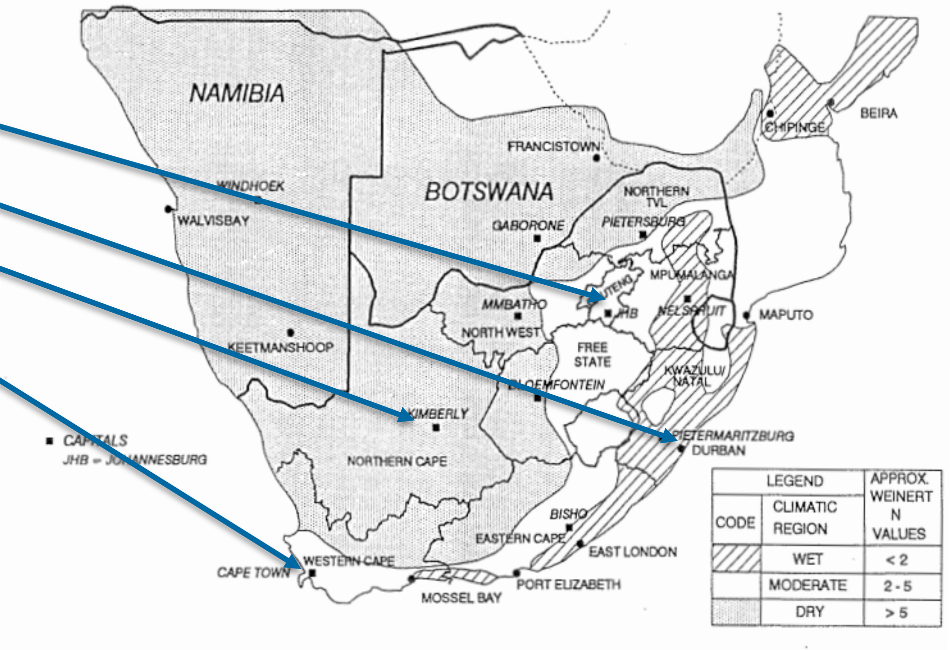
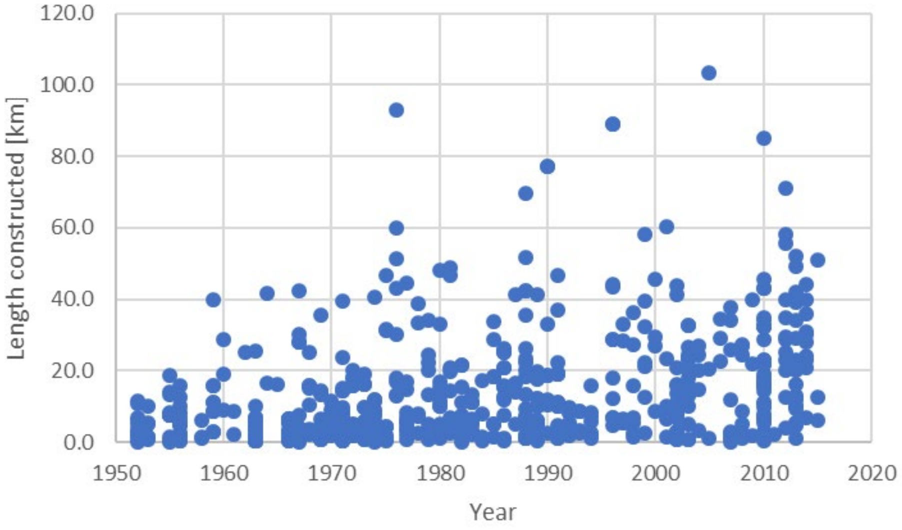


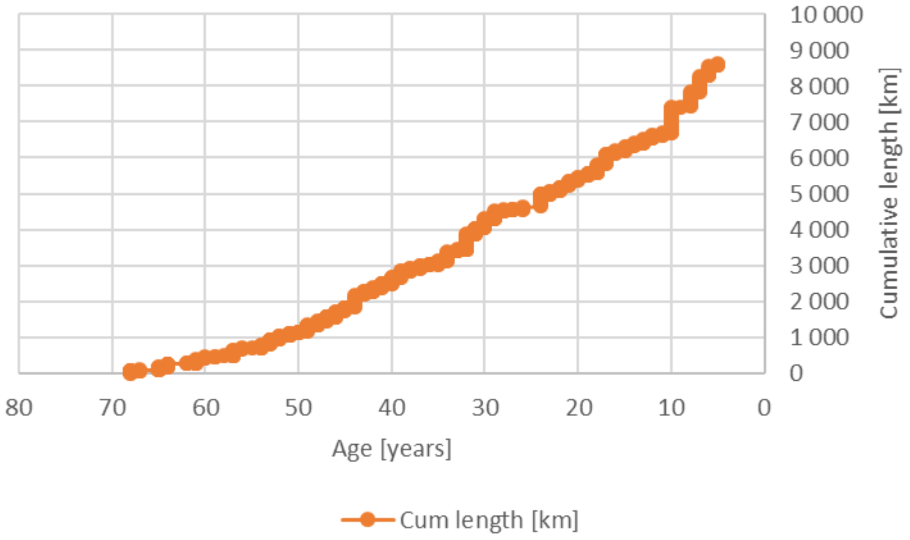
FIGURE 4: MACRO CLIMATIC REGIONS OF SOUTHERN AFRICA
(Adapted from Weinert, 1980)

- Standard moisture related issues for wet areas
- Require
  - impermeable surfacing
  - dense, well-graded, relatively layer
- Crack development in surfacing / inadequate drainage / maintenance
- Require good maintenance

Inverted pavements – Length & Age in SA

National network





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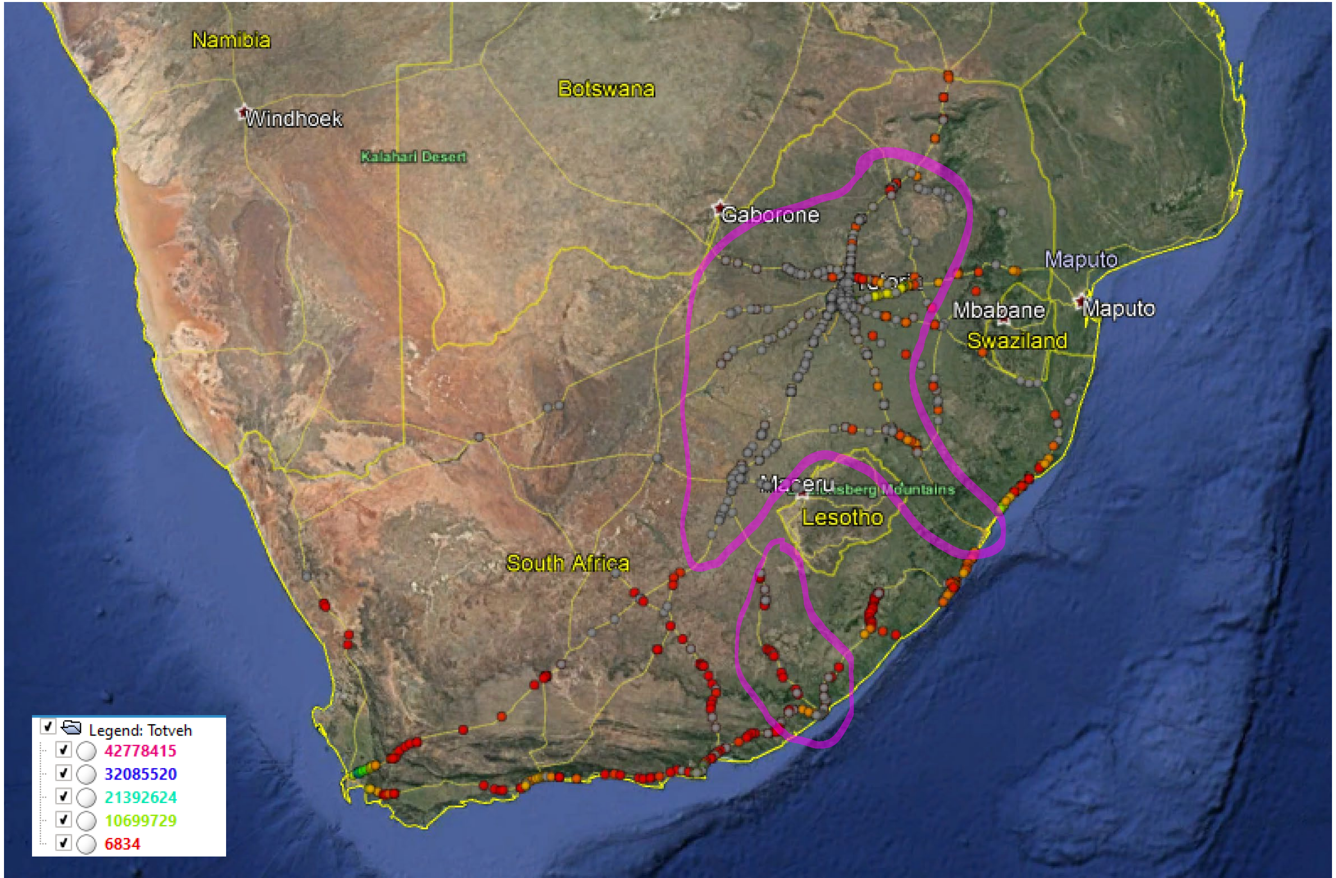
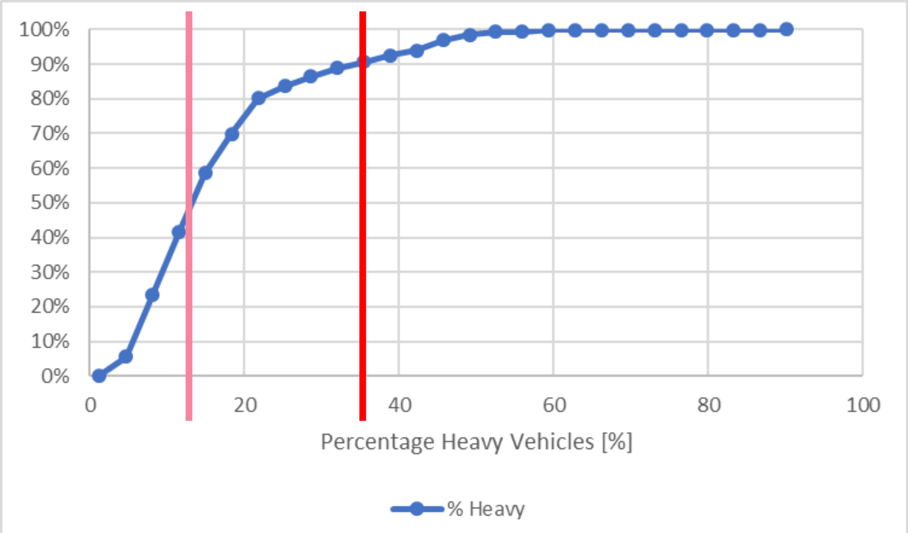
Inverted pavements - Traffic

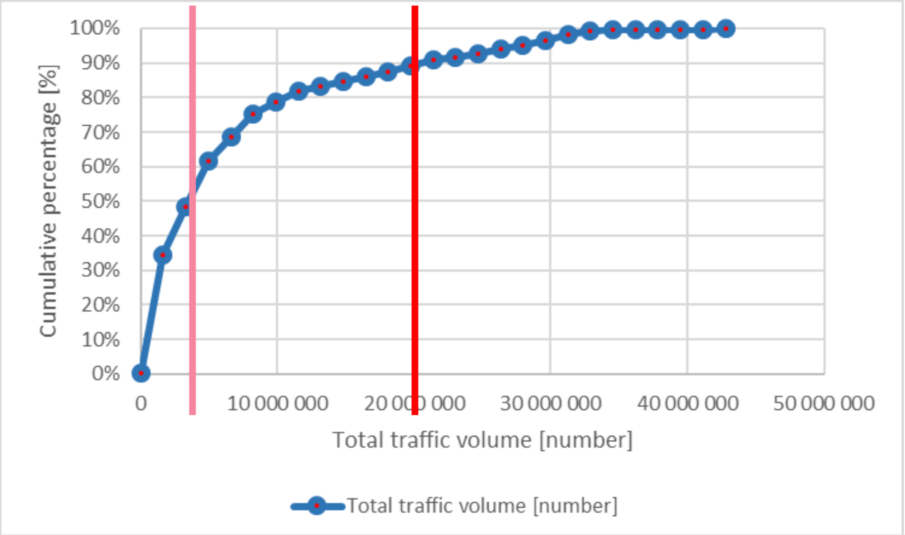
Up to 50 million ESALs OK



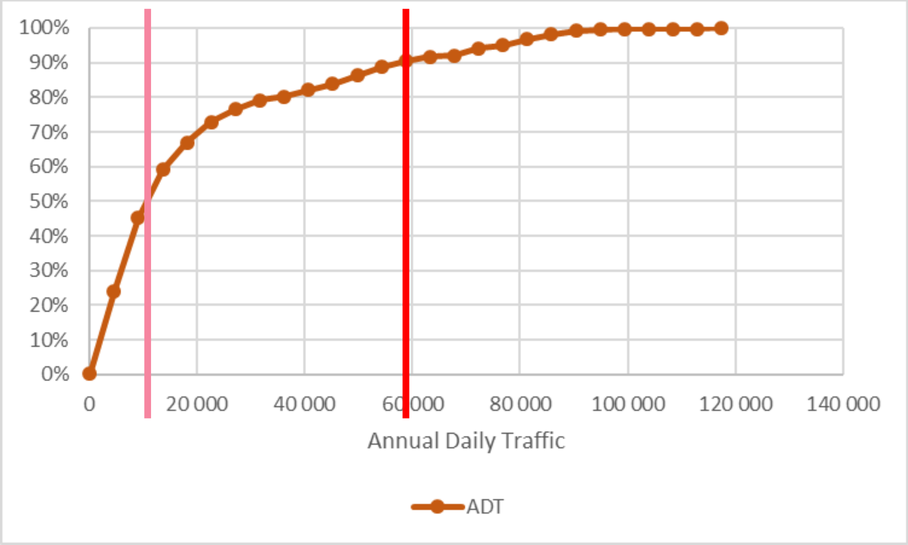
Traf



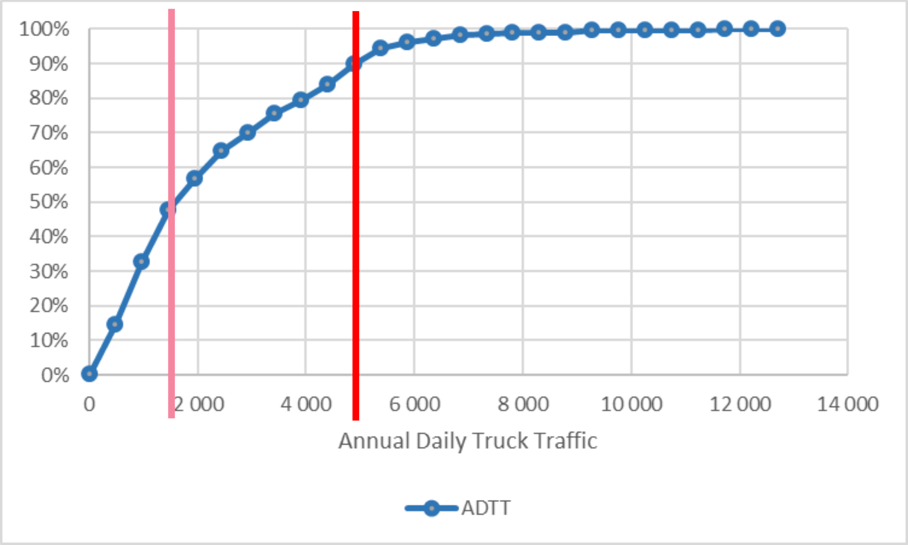
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
20
40
60
80
100
Percentage Heavy Vehicles [%]
% Heavy



Cumulative percentage [%]
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
10 000 000
20 000 000
30 000 000
40 000 000
50 000 000
Total traffic volume [number]
Total traffic volume [number]



100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
20 000
40 000
60 000
80 000
100 000
120 000
140 000
Annual Daily Traffic
ADT



100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
2 000
4 000
6 000
8 000
10 000
12 000
14 000
Annual Daily Truck Traffic
ADTT

Construction

Inverted pavements - Slushing

- **Slushing**
  - watering layer thoroughly - rolling with vibratory rollers without vibration / pneumatic rollers / static rollers - squeezing fines to surface
  - fines broomed off road surface
- **Purpose of slushing**
  - ensure all aggregate particles **interlock** with one another
  - form dense integrated mass of particles

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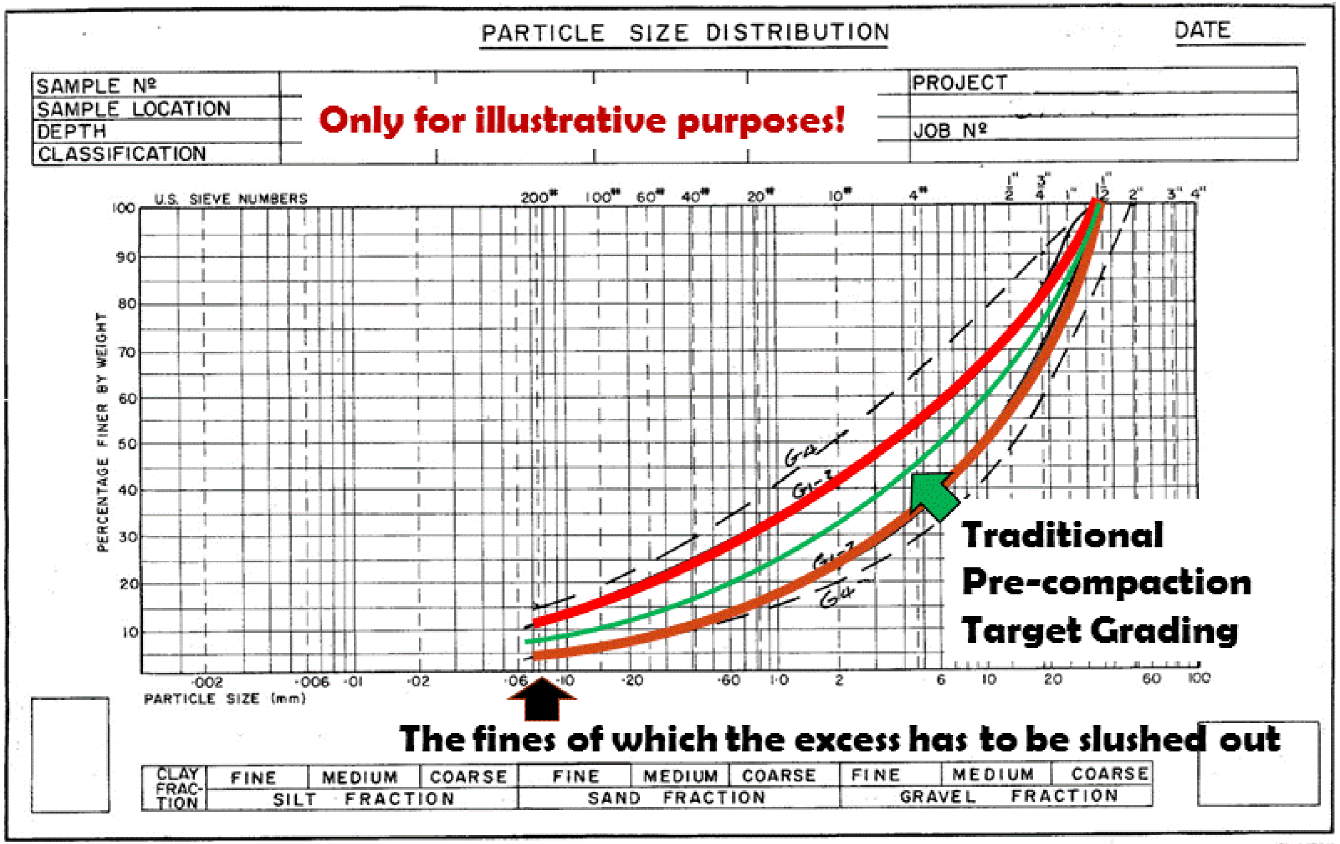
Slushing - Before & After grading of G1 aggregate

Only excess fines (<0,075 mm) slushed out

- Only toe of grading curve changes
- Negligible change in grading occurs during slush-compaction

- **Lubrication – fines NB**

Traditional grading for G1 aggregate (COLTO 1998)



Layer ready for slush-compaction

Slush-compact with lots of water

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Excess fines being expelled as slush from layer

Air being expelled from layer during slush-compaction

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Slush run-off along road

Dried slush run-off

G1 crushed stone ready for "ping-test"

- No more air bubbles escaping during slushing
- Expelled water clearing up substantially
- Well-knit mosaic visible through surface water
- Road surface does not heave under heavy roller
- Do interlock & density acceptance control – Visual & Ping Tests

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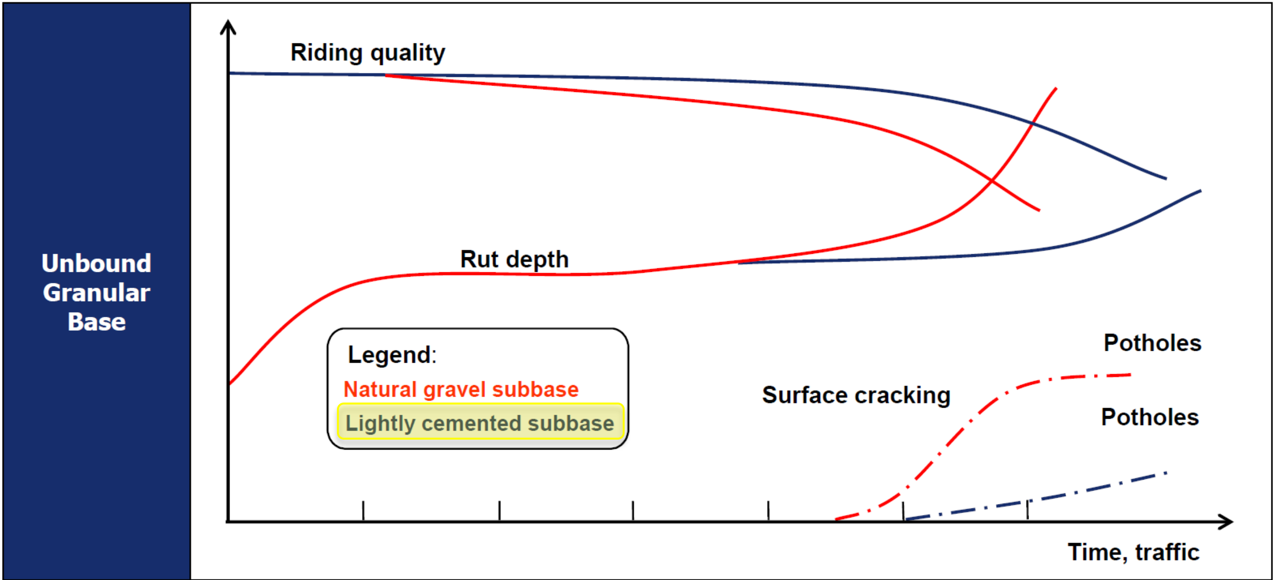
Performance

Typical - performance & failure mechanism

- Many good years – if well maintained surfacing & drainage



Economics

Production rates

Table 21. Typical Production Rates

Construction Process	Typical Production Unit (per day)	
Single seal	10 000 – 20 000 m^2 (full width)	
Double seal	10 000 – 12 000 m^2 (½ width)	
Asphalt surfacing	350 – 400 tons	
Asphalt Base	400 – 600 ton	**Ratios**
G1 base	2 500 – 3 000 m^2	1
BSM base	3 000 – 4 000 m^2	1.273
Cemented subbase	3 000 – 4 500 m^2	1.364
Natural gravel layers	4 000 – 5 000 m^2	1.636
Waterbound macadam (hand placed)	400 m^2	
Prime/tack	15 000 – 50 000 m^2	
Concrete – JRCP (220 mm hand placed) – CRCP (180 mm hand placed)	 420 m^2 480 m^2	
UTFC	6000 - 8000 m^2 (400 tons)	

Cost comparison

- BE VERY CAREFUL WITH COMPARISONS
- Understand assumptions & local costs & issues
- 1998 study – Rust, Mahoney, Sorenson
  - RUST, FC, JP MAHONEY and J SORENSON (1998). **An International View of Pavement Engineering.** The Bearing Capacity of Roads and Airfields Conference, Trondheim, Norway.
  - https://researchspace.csir.co.za/dspace/handle/10204/1369?show=full
- Compared US / SA pavement engineering
- Conducted cost comparison – similar traffic demand & climates

Table 14 : Cost of comparable South African and US pavement designs

South African Designs									
Million ESALS	1 to 3			3 to 10			30		
Subgrade type	Layer type	Thick-ness	Cost	Layer type	Thick-ness	Cost	Layer type	Thick-ness	Cost
Weak, CBR = 5	AC	40	$3.18	AC	40	$3.18	AC	50	$3.98
	G2	150	$0.52	G2	150	$0.52	G1	150	$3.17
	G5	150	$0.89	C3	250	$3.19	C3	300	$3.83
	G5	300	$1.78	G5	300	$1.78	G5	300	$1.78
		Total :	$6.37			$8.67			$12.75
Strong, CBR = 15	AC	40	$3.18	AC	40	$3.18	AC	50	$3.98
	G2	150	$0.52	G2	150	$0.52	G1	150	$3.17
	G5	150	$0.89	C3	250	$3.19	C3	300	$3.83
		Total :	$4.60			$6.90			$10.97
Caltrans Designs									
TI Class	9			12			13.5		
Million ESALS	0.8 to 1.27			9.5 to 13.5			26.1 to 35.6		
Subgrade type	Layer type	Thick-ness	Cost	Layer type	Thick-ness	Cost	Layer type	Thick-ness	Cost
Weak, CBR = 5	AC	152	$12.13	AC	183	$14.56	AC	213	$16.98
	G5	107	$0.63	G5	198	$1.17	G5	213	$1.26
	G6	259	$1.53	G6	351	$2.07	G6	396	$2.35
		Total :	$14.29			$17.80			$20.59
Strong, CBR = 15	AC	137	$10.92	AC	183	$14.56	AC	183	$14.56
	G5	137	$0.81	G5	198	$1.17	G5	107	$0.63
	G6	107	$0.63	G6	107	$0.63	C3	168	$2.14
		Total :	$12.36			$16.36			$17.33
WSDoT Designs									
Million ESALS	1			10			30		
Subgrade type	Layer type	Thick-ness	Cost	Layer type	Thick-ness	Cost	Layer type	Thick-ness	Cost
Weak, CBR = 5	AC	105	$8.36	AC	105	$8.36	AC	105	$8.36
	G3	280	$3.69	BC	135	$8.82	BC	230	$15.02
				G3	170	$2.24	G3	135	$1.78
		Total :	$12.04			$19.41			$25.15
Strong, CBR = 15	AC	105	$8.36	AC	105	$8.36	AC	105	$8.36
	G3	75	$0.99	BC	60	$3.92	BC	115	$7.51
				G3	105	$1.38	G3	135	$1.78
		Total :	$9.34			$13.66			$17.64

Cost comparison

- BE VERY CAREFUL WITH COMPARISONS
- Understand assumptions & local costs & issues
- G1 currently - $40/m^3 to $60/m^3

SA			California			Washington		
ESALS 30			ESALS 26.1 to 35.6			ESALS 30		
Layer type	Thick-ness	Cost	Layer type	Thick-ness	Cost	Layer type	Thick-ness	Cost
AC	50	$3.98	AC	213	$16.98	AC	105	$8.36
G1	150	$3.17	G5	213	$1.26	BC	230	$15.02
C3	300	$3.83	G6	396	$2.35	G3	135	$1.78
G5	300	$1.78						
		$12.75			$20.59			$25.15

Conclusions / Summary

- Well-used system due to specific technical requirements
- Understanding of pavement system
- Specific construction procedure
- Not maintenance-free
- Not magical solution


WBHO
WBHO

Discussion