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Performance based pavement design and construction

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Abstract. Pavement designs for roads have evolved from empirical approaches whose origins lie in AASHTO road trials in the 1950's. These are embodied in AASHTO guidelines from USA, the British Road note 29 and 31 as well as Arahah Teknik JKR guidelines. This approach constrains the designer and the contractor to use "standard" materials which were assumed in the empirical approach since these were the materials used in the trials. Any materials that are "nonstandard" cannot be utilised in the empirical approach. This leads to expensive pavement designs. With the development of mechanistic pavement design principles along with equipment to measure performance criteria such as stiffness, roughness, surface texture, friction etc performance-based pavement design and construction has become possible. This paper outlines the mechanistic approach with a case history of such pavement along with other important factors to be considered such as drainage of pavements which are essential for better pavement performance. Based on past successful history of performance-based pavement designs and construction there is a strong case that pavement designs can be done by mechanistic designs and the performance criteria be defined in specifications by way of roughness, stiffness, friction, surface texture in all road works contracts.

1. Introduction

The development of pavement engineering is growing from year to year and helps to provide better perspective on present and future practice. Previously, most of the pavement designs were based on empirical approaches whose origins lie in AASHTO road trials in the 1950's. However, the last three decades have seen a shift to mechanistic design methods. Unlike an empirical approach, a mechanistic design approach seeks to explain phenomena by reference to physical causes such as stress, strain and deflections (pavement response) [1]. The mechanistic analysis theory for pavement stresses have developed extensively in Denmark and Australia. Along with this, the ability to measure stiffness by Falling Weight Deflectometer (FWD) has allowed the design of pavements based on stiffness. This approach also allows the stiffness of conventionally designed pavements to be compared to stiffness-based pavement designs. In addition, the stiffness-based approach also allows the use on "non-conforming" materials in pavements and to model them in the mechanistic design approach and later validate the stiffness by FWD. This paper outlines the approach and illustrates with a case history of such pavement design along with other important factors such as drainage of pavements which are essential for pavement performance. Examples of how performance is defined in major highway contracts in Australia are presented along with a case history from Malaysia.



2. History of Pavement Design Development

The Romans have built roads which were initially utilised for military purposes to connect the military camps which were located far apart [2]. With regards to this primary purpose, no basic standard in designing the road was specified. These roads produced high noise levels and were rough. The initial design of Roman road consisted of 4 layers with a total thickness of about 0.9m.

With the extension of masonry knowledge to bridge building, Thomas Telford introduced a new pavement design approach using Tresaguet's theories (use of cubical stone blocks) consisting of 3 layers [3]. The total pavement thickness was reduced to between 350mm to 450mm with the bottom layer comprising of large stones (100mm size). On top of this, the smaller size of stones is placed (65mm size) and followed by a wearing course of gravel about 40 mm in size.

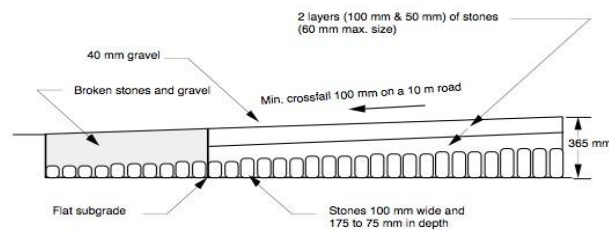


Figure 1. Thomas Telford's pavement cross section (Courtesy of www.pavementinteractive.org).

Then, moving on to the Macadam era, the angular aggregates were used over well compacted subgrade as it would be bound together by fines generated by traffic [4]. The subgrade was designed slightly with a gradient unlike Telford pavements which had flat grades. Macadam pavement allowed better drainage and performed substantially better. The typical thickness of Macadam pavement is 250mm and consisted of 3 layers. Two layers with a total thickness of 200mm comprised of angular aggregates (75mm particle size) and wearing course of 50 mm thickness with aggregates size of 25mm were placed at the top.

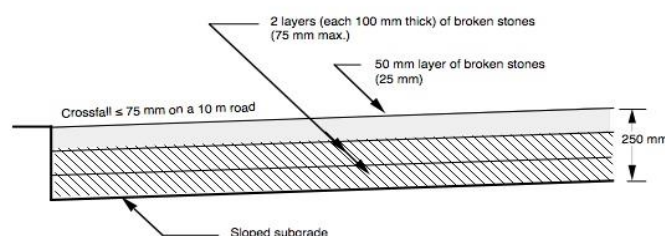


Figure 2. Macadam's pavement cross section (Courtesy of www.pavementinteractive.org).

History has showed that pavement designs have gone through many phases of enhancement before asphalt and Portland Cement Concrete (PCC) pavement was introduced. However, as reported by Agg and McCullough [5] to the Iowa State Highway Commission (1916), this PCC pavement has some issue with its performance. Then, extensive experiments were carried out by AASHTO in 1959 and eventually the empirical based guideline was produced.



Figure 3. AASHTO Road Test carried out in Ottawa (Courtesy of www.explorer.acpa.org).

The empirical design approach has been widely used in pavement structural design procedures. The pavement performance is evaluated based on the experimentation and experience or with combination of both. [6]. However, initially this empirical design guideline produced by AASHTO is solely depending on the AASHTO Road Test carried out in Ottawa, IL from 1956 – 1961 [7]. In this guideline, only the specified material (granite) shall be used in pavement design. The California Method is one of many empirical design approaches that were commonly used during the early 1940s. Therefore, for Malaysian conditions the applicability of this method is quite questionable as Malaysia has different climate and soil characteristics resulting in variable soil and rock types and characteristics.

3. Mechanistic Pavement Design Developments

The main consideration in mechanistic-empirical method is the actual response of the pavement when it is subjected to load. Unlike the empirical design method, this mechanistic design method seeks to explain phenomena of only by reference to physical causes such as stress, strain and deflections [1]. Empirical design elements are also used along with mechanistic method to determine the values of the calculated stresses, strains and deflections result in pavement failure. The performance-based pavement design and construction has the following advantages;

- Enables the use of marginal materials with modifications and the ability to model these modified materials in the mechanistic design.
- Saves cost by allowing local “non-standard” materials to be used.
- Reduces the risk of pavement life reduction due to poor quality construction because stiffness can be measured rapidly and economically by FWD testing.
- Better long-term life can be obtained by specifying and ensuring roughness.
- Safer road (especially during rains) can be obtained by measuring Surface texture and Friction as construction acceptance testing.
- This method can be used for both existing pavement rehabilitation and new pavement construction.

The most special value of the mechanistic design method is it allows a rapid analysis of the impact of changes in input items such as changes in traffic and materials. This method also can accurately characterize in situ material using the portable device that is called Falling Weight Deflectometer (FWD). FWD testing is used to evaluate the structural condition of pavement by predicting the layer moduli of the pavement [8].

The stiffness of the pavement sub grade is denoted by the FWD deflection, D_0 . It is widely accepted that the D_0 deflection and the life of the pavement are well correlated. Deflection measurements by FWD and pavement life prediction using deflection measurements have been in practice in Malaysia for more than a decade.

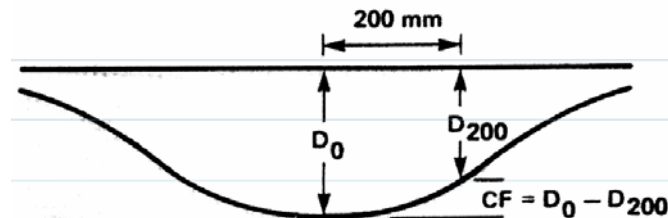


Figure 4. Typical deflection bowl under FWD test plate.

D_0 = maximum deflection for a test point

$D_0 - D_{200}$ = deflection measured where the test load is 200mm from the point of maximum deflection (in the direction of travel).

The deflection (D_0) of the pavement represents the strength, while the curvature ($D_0 - D_{200}$) represent the asphalt fatigue. The smaller value of the D_0 , the stiffer the pavement it can be. The design surface deflection (D_0) and design curvature ($D_0 - D_{200}$) against design traffic or Equivalent Standard Axles (ESA) can be estimated based on the graph in Figure 5 and Figure 6 (Austroads, 2004) [9]. The Austroads (2004) design deflections for traffic loading less than 10^6 ESAs were derived from research undertaken by Scala in the early 1960s. These design deflections were based on field measurements of the dependence of Benkelman Beam deflections on granular thickness and subgrade CBR, and the relationship between pavement composition and design traffic loading.

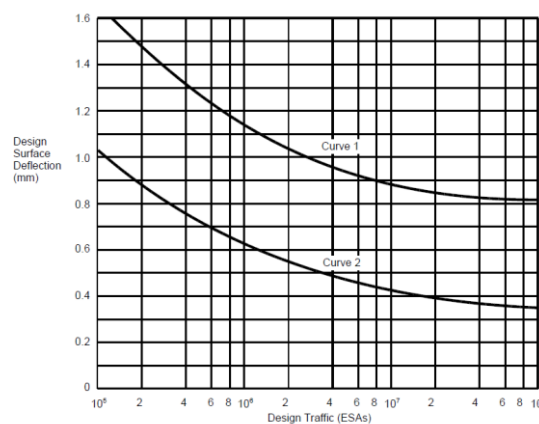


Figure 5. Design deflection levels design traffic (ESA) (Austroads Pavement Design Guide, 2004).

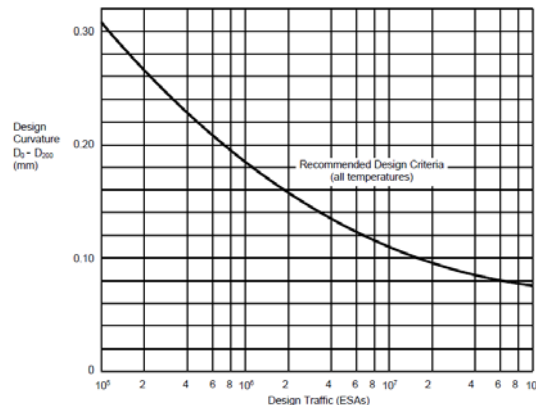


Figure 6. Design curvature function design traffic (ESA) (Austroads Pavement Design Guide, 2004).

4. Pavement performance parameters

Unlike the empirical design method, the mechanistic design method can be evaluated using the in-situ testing. Several performance criteria can be evaluated to determine the pavement performance.

Table 1. Pavement Performance Criteria.

No.	Performance Criteria	Descriptions
1	Rutting	Rutting is when pavement deform due to sub grade strain and mix design issue that cause surface depression in the wheel path.
2	Skid Resistance	The friction force developed between tyre and pavement to prevent the vehicles from sliding - TRRL Pendulum to Laser Profilometer Test.
3	Surface Texture	Pavement surface texture is texture wavelength. Adequate surface texture will provide proper drainage of tyre grooves and reduce water spray when moving at high speed – Sand Patch Test and Laser Profilometer Test
4	Roughness	Pavement roughness is defined as microscopic undulating of the pavement that affect the ride quality of vehicles – Bump Integrator and Laser Profilometer Test.
5	Strength	The maximum deflection (D_0) is noted as the strength of the pavement - Benkelman Beam and Falling Weight Deflectometer Test
6	Stiffness	Deflection ratio (D_{250}/D_0) is used to indicate the stiffness of the pavement structure - Benkelman Beam and Falling Weight Deflectometer Test. ➤ > 0.8 indicates CTB or CTSB bound pavement ➤ $0.6 - 0.8$ indicates good quality unbound pavement ➤ < 0.6 indicates a possible weakness in the pavement materials
7	Fatigue	Pavement fatigue is determined from the curvature function ($D_0 - D_{200}$) to predict the fatigue life of an applied asphalt surfacing overlay or an existing asphalt surfacing - Benkelman Beam and Falling Weight Deflectometer Test.

The above performance criteria need to be controlled and monitored during pavement construction. In mechanistic design method, Benkelman Beam and Falling Weight Deflectometer Test are two common tests to determine the stiffness for each layer of the pavement. However, the proper drainage design must be strictly taken into consideration to prevent failure of pavement in long term period.

Based on specifications from Main Road Western Australia – Contract 89/13 [10], the pavement condition is measured based on criteria specified in table below.

Table 2. Performance Measure requirements prior to Practical Completion (Main Roads Western Australia – Contract 89/13).

Pavement Category	Component	Measure	Acceptable Standard
New construction	Structural Capacity	Pavement deflection – FWD (at 700 kPa)	For granular Pavements: mean Segment value $\leq$ 0.60mm
		Pavement curvature – FWD (at 700 kPa)	For granular Pavements: mean Segment value $\leq$ 0.23mm
	Functional Capability	Pavement roughness	95th percentile lane value < 40 counts/km and no segment value > 50 counts/km
		Surface shape	3mm maximum
		Texture Index	Segment value not greater than 0
		Texture depth	Measured at any point on the surface must be greater than 1.0 mm

5. Case History of Performance-Based Pavement

The design and construction Senai Desaru Expressway (SDE) pavement for Package 1 and 2 was designed by Infra Tech Projects using the mechanistic design method. Before the actual pavement was constructed, the trial pavements of various thicknesses on subgrade which was compacted by HIEDYC (High Impact Energy Dynamic Compaction) as compared to the original designed where the subgrade was conventionally compacted as per the JKR Design was constructed [11]. Table 3 show the pavement trial sections constructed by Infra Tech.



Figure 7. HIEDYC carried out at SDE.

Table 3. Trial pavements for SDE.

Pavement Option	Pavement Thickness (Each layer)		Targeted FWD deflection, D_0	Sub-grade Compaction
P1 450mm	ACWC14	40 mm	D_0 - 0.45mm	HIEDYC
	ACBC28	50 mm		
	BMR28	60 mm		
	CRB	300 mm		
P 2 480mm	ACWC14	40 mm	D_0 - 0.460mm	HIEDYC
	ACBC28	50 mm		
	BMR40	90 mm		
	CRB	300 mm		
P 3 530mm	ACWC14	40 mm	D_0 - 0.47mm	HIEDYC
	ACBC28	50 mm		
	BMR40	90 mm		
	CRB	350 mm		
P4 590mm	ACWC14	40 mm	D_0 - 0.58mm	HIEDYC
	ACBC28	50 mm		
	BMR40	100 mm		
	CRB	400 mm		
P5 790mm	ACWC20	50 mm	D_0 - 1.29mm	Conventional compaction
	ACBC28	60 mm		
	DBM40	100 mm		
	WMM	280 mm		
	SB	300 mm		

These trial pavements were used to determine the stiffness and resilience modulus, E_R of each layer of the pavement. The validation test using FWDT was carried by IKRAM and the result as shown in table below.

Table 4. Pavement deflection, D_0 and strength modulus, Mpa.

Pavement Option	D_0 mm 95% (85%)	95% (85%) Modulus, MPa				Sub Grade Compaction
		AC	BMR	CR	SG	
P1 450mm	0.65 (0.62)	4864 (5990)	259 (344)	113 (117)	93 (100)	HIEDYC
P 1 450mm	1.56 (1.45)	2957 (3181)	218 (389)	41 (42)	32 (33)	No HIEDYC
P 2 480mm	0.45 (0.42)	4276 (5211)	413 (527)	141 (181)	142 (149)	HIEDYC
P 3 530mm	0.46 (0.42)	5194 (5648)	401 (480)	186 (189)	144 (156)	HIEDYC
P4 590mm	0.58 (0.54)	3443 (3990)	310 (389)	137 (144)	122 (126)	HIEDYC
P5 790mm	1.28 (1.23)	927 (978)	96 (108)	67 (70)	60 (63)	No HIEDYC

The alternative pavement designed by mechanistic method was constructed using similar materials that was used for pavement designed by Arahan Teknik JKR. From the table above, it shows that the stiffness for the alternative pavement where the subgrade was compacted by HIEDYC is higher than the conventional compaction method and pavement designed using Arahan Teknik JKR. The targeted deflection, D_0 for alternatives is lower than the conventional pavement. In conclusion, empirical design method allows innovation to be adopted and modelled into the design and construction process and reduce the cost as well as long term maintenance. However as explained below other important considerations must be taken into account in pavement designs.

Subsequent to the trial, the pavements for SDE packages 1 and 2 were quality controlled using the Falling Weight Deflectometer to validate the pavement stiffness of each lane of the highway. The slow lane was tested at 50m intervals while the fast lane was tested at 100m intervals with the 95th percentile deflection targeted to be 0.8mm or less.

6. Important Factors in Pavement Design

In order to ensure the pavement condition can be sustained for long period, several factors need to be taken into account during design and construction stage. Adequate assessment need to be carried out on the subgrade conditions especially when dealing with problematic soil or rock material (variably weathered soil subgrades, swelling soils, collapsing soil, soft soil and etc).

Issues such as surface and subsurface drainage must be looked into at the design stage and then modified where necessary based on site observations of geological features and water seepage when the site is opened up during construction stage. All parties must accept that construction stage modifications will be necessary based on the variabilities observed in subgrade strength, water seepage and such issues that can have an effect on the pavement performance. While it may be possible that surface drainage can be reasonably addressed during design stage it is almost impossible to address sub surface drainage until when the site is opened up during construction. If Clients, Consultants and Contractors do not allow for this, this can be the single highest contributory factor for pavement distress.

Proper compaction needs to be done to ensure the subgrade is highly compacted and no major post-construction settlement will occur after the road is opened for public. It is very important to identify the location and the maximum value critical stress and strain so that the pavement can be designed with adequate strength and thickness to prevent pavement failure under actual loading [12].

Other than that, subsurface drainage is essential for economical, long term performance of roads and highways. Excessive and uncontrolled subsurface water has been cause for many slope failures, pavement failures, and unsatisfactory projects. Subsurface drainage is essential for economical, long term performance of roads and highways. The primary objective of the drainage is to channel out the water along and across the road conveniently without any obstruction in water flow [13]. If groundwater and seepage are not identified and adequately addressed, it can cause severe problem to the pavement in its constructability, pavement performance and slope failure along the construction area.

7. Conclusion

With the use of mechanistic design methods availability of pavement performance measuring equipment such as Laser Profilometers, Falling Weight Deflectometers, Light Weight Deflectometers, it is not only feasible for performance-based specifications but also performance-based construction and quality control of new works as well as maintenance works. Based on past successful history of performance-based pavement designs and construction there is a strong case that pavement designs can be done by mechanistic designs and the performance criteria be defined in specifications by way of roughness, stiffness, friction, surface texture in all road works contracts. However, important factors in pavement design as addressed in Section 6 need to be considered. Other than that, good interaction among the highway agency engineers to identify the proper input parameters for the design is necessary. Even if the designs are done using empirical methods, the pavement construction specifications should be based on roughness, stiffness, friction, surface texture. It is of utmost importance that the sub soil drainage and surface drainage issues be addressed as the project site is opened, since these issues cannot be adequately addressed at the design stage based on limited site investigations. This will lead to better roads and tighter quality control.

8. References

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