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Implementation of mechanistic-empirical pavement analysis in the State of Qatar

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The State of Qatar is experiencing tremendous growth in infrastructure including road network and highways. The current methods used in design of asphalt pavements in the State of Qatar are empirical and might not be suitable for the design of long-lasting pavements. Given the significant increase in traffic, road authorities in the State of Qatar have been considering the use of mechanistic-empirical methods in the design and analysis of asphalt pavements. This study documents the results of a study in which the mechanistic-empirical pavement design guide (M-E PDG) software was used in the design of asphalt pavements with input parameters that were carefully selected to reresent local materials and climatic conditions. The selection of material properties was based primarily on specifications and design guides in the State of Qatar and on published literature about these materials. The mechanistic-empirical method was also used to assess the benefits of adopting the concepts of perpetual pavement design and also to compare the performance of pavement structures in which various bitumen grades, granular bases and chemically stabilised sub-base were used. A life-cycle cost analysis was carried out to determine the design with the highest net present value among the various options investigated. It is expected that the outcomes of this study would promote the use of mechanistic-empirical methods in the State of Qatar and the region. Inevitably, this will require significant efforts to calibrate material and damage prediction models used in the M-E PDG for more accurate representation of material properties and measured pavements performance.

Keywords: perpetual pavement design; mechanistic-empirical methods; life-cycle cost analysis; Qatar; conventional pavements

1. Introduction

The State of Qatar is experiencing tremendous economic growth accompanied by the construction of major road infrastructure. In 2012, the Public Works Authority in the State of Qatar has announced that they will invest about $14 billion in improving the road network and infrastructure by the year 2019 (The Public Works Authority 2012). In order to ensure the construction of high-quality pavements, the Public Works Authority has initiated efforts to upgrade methods for the design and evaluation of asphalt pavements. In addition, research projects have been funded by the Qatar National Research Fund in order to develop accurate material characterisation methods and to determine vital input parameters for mechanistic-empirical and mechanistic models. The outcomes of these research projects have been documented in several papers (Masad *et al.* 2011, Sadek *et al.* 2012).

The review of several reports on the anticipated traffic in major highways in Qatar revealed that 20-year design traffic load could exceed 300 million equivalent single axle loads (ESALs). This high-traffic loading necessitates considering the design and construction of perpetual or ‘long-life’ pavements. Many studies in the USA, Europe and Far East demonstrated the significantly improved performance of perpetual pavements in terms of resistance to surface distresses and deteriorations when compared with conventional or ‘Determinate Life’ pavements (Ferne 2006, Merrill *et al.* 2006, Timm and Newcomb 2006).

The European Long-Life Pavement Group (Ferne 2006) defined long-life pavements as those designed and constructed to last indefinitely without deterioration in the structural elements, provided they are not overloaded and appropriate surface maintenance is carried out. The concept of perpetual pavement design implies prevention of the onset of deterioration in the form of rutting and fatigue cracking in the structural layers, which is a result of increased traffic loading and high temperatures. This could be achieved by reducing the stress and strain in the pavement either by increasing the thickness of the pavement layers or by using stiffer materials (Merrill *et al.* 2006, Renteria and Hunt 2008).

Timm and Newcomb (2006) reported that long-lasting asphalt pavements have been designed and constructed in the USA for many years because their service life could exceed 50 years, the cost of reconstruction at the end of the structural life is low and amounts consumed of

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Table 1. AADTT for the required ESALs and traffic classes.

Traffic class[a]	ESALs (million)	Two-way AADTT (M-E PDG input)
T4	10	1594
T5	20	3188
T6	50	7970

[a] These traffic classes follow the designations used in the QHDM.

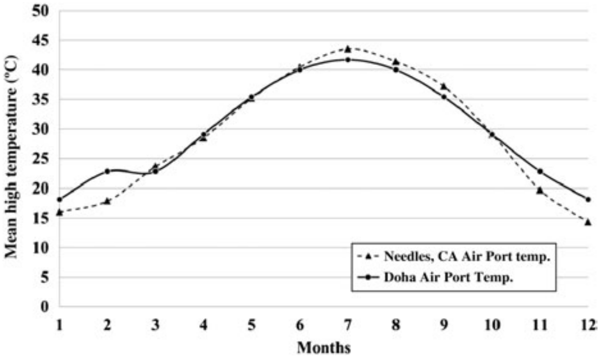

Figure 1. Yearly mean high air temperature for Qatar and Needles Airport Station in the USA.

non-renewable resources, such as bitumen and aggregate, are lower. Merrill *et al.* (2006) conducted a study on a road network in the UK to determine the relationship between thickness of the asphalt layer and rutting rate. The study found that, below an asphalt thickness of 180 mm, thickness has a clear effect on the rate of rutting while it is independent of thickness when the layer is above 180 mm.

Results from a study on road sections from the Netherlands reported by Merrill *et al.* (2006) showed that all test sections with thin asphalt layers (< 80 mm) exhibited full-depth cracking in the layer. However, for thicker pavements (> 290 mm of asphalt layer), only 28% of the sections showed cracking and that was confined to the top layers.

Timm and Priest (2006) reported the results of evaluating the performance of perpetual pavement sections with control sections that were constructed in China. Control sections were constructed with a thin asphalt layer on top of cement-stabilised granular layers; this design is commonly used in highways in China. The results demonstrated that the perpetual sections avoided the overstressing that causes early cracking that happened in the control sections.

Only few studies have been conducted in the countries within the Arabian Peninsula to evaluate the benefits of using mechanistic-empirical design and construction of perpetual pavements (Al-Abdul Wahhab and Balghunaim 1994, Al-Abdul Wahhab *et al.* 2001, Masad *et al.* 2011). Most of these studies focused on characterisation of local materials, influence of increase in traffic loading on performance and rutting due to high temperature.

2. Objective and scope of the study

The primary objective of this study was to introduce the mechanistic-empirical method to the design of asphalt

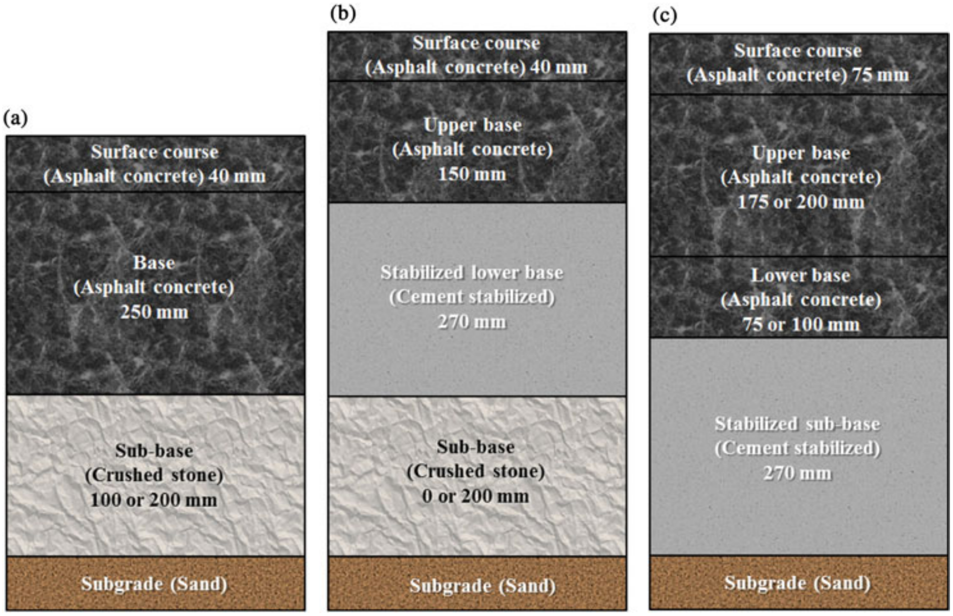

Figure 2. Typical cross sections for asphalt pavement designs: (a) AC design, (b) flexible-composite design, (c) perpetual pavement design.

Table 2. Layers, materials and properties of conventional and perpetual designs.

		Soil subgrade			Crushed stone sub-base		Asphalt surface course	Asphalt base course		Cement-stabilised base and sub-base	
Design type	Analysis case	Material	M_r (MPa)	AADTT	Thickness (mm)	M_r (MPa)	Thickness (mm)	Thickness (mm)	Asphalt bitumen	Thickness (mm)	M_r (MPa)
Asphalt concrete	1	A-2-4	120	1594	200	242	40	250	Pen 60-70	0	0
	2	A-2-4	120	1594	200	242	40	250	PG 76-10	0	0
	3	A-2-4	120	3188	200	242	40	250	Pen 60-70	0	0
	4	A-2-4	120	3188	200	242	40	250	PG 76-10	0	0
	5	A-2-4	120	7970	200	242	40	250	Pen 60-70	0	0
	6	A-2-4	120	7970	200	242	40	250	PG 76-10	0	0
	7	A-1-b	242	1594	100	242	40	250	Pen 60-70	0	0
	8	A-1-b	242	1594	100	242	40	250	PG 76-10	0	0
	9	A-1-b	242	3188	100	242	40	250	Pen 60-70	0	0
	10	A-1-b	242	3188	100	242	40	250	PG 76-10	0	0
	11	A-1-b	242	7970	100	242	40	250	Pen 60-70	0	0
	12	A-1-b	242	7970	100	242	40	250	PG 76-10	0	0
Flexible-composite	13	A-2-4	120	3188	200	242	40	150	Pen 60-70	270	2413
	14	A-2-4	120	3188	200	242	40	150	PG 76-10	270	2413
	15	A-2-4	120	7970	200	242	40	150	Pen 60-70	270	2413
	16	A-2-4	120	7970	200	242	40	150	PG 76-10	270	2413
	17	A-1-b	242	3188	0	0	40	150	Pen 60-70	270	2413
	18	A-1-b	242	3188	0	0	40	150	PG 76-10	270	2413
	19	A-1-b	242	7970	0	0	40	150	Pen 60-70	270	2413
	20	A-1-b	242	7970	0	0	40	150	PG 76-10	270	2413
Perpetual	21	A-2-4	120	7970	0	0	75	250	PG 76-10	270	2413
	22	A-2-4	120	23,910	0	0	75	250	PG 76-10	270	2413
	23	A-2-4	120	47,820	0	0	75	250	PG 76-10	270	2413
	24	A-2-4	120	7970	0	0	75	300	PG 76-10	270	2413
	25	A-2-4	120	23,910	0	0	75	300	PG 76-10	270	2413
	26	A-2-4	120	47,820	0	0	75	300	PG 76-10	270	2413
	27	A-1-b	242	7970	0	0	75	250	PG 76-10	270	2413
	28	A-1-b	242	23,910	0	0	75	250	PG 76-10	270	2413
	29	A-1-b	242	47,820	0	0	75	250	PG 76-10	270	2413
	30	A-1-b	242	7970	0	0	75	300	PG 76-10	270	2413
	31	A-1-b	242	23,910	0	0	75	300	PG 76-10	270	2413
	32	A-1-b	242	47,820	0	0	75	300	PG 76-10	270	2413

Table 3. Design limits provided in the M-E PDG for the performance criteria of pavement designs.

Performance criteria	Design limit
Longitudinal cracking	378 m/km (2000 ft/ml)
Alligator cracking	25%
Total rutting depth	19 mm (0.75 in.)
IRI	2.717 m/km (172 in./ml)

pavements in the State of Qatar. This was achieved by the evaluation of different asphalt pavement designs (i.e. perpetual and conventional designs) under climatic conditions resembling those in the State of Qatar. The input parameters analysed were extracted from specifications and design guides in the State of Qatar and from published reports about these materials. The analysis focused on performance measures such as longitudinal cracking, alligator cracking, total rutting depth and international roughness index (IRI). Life-cycle cost analysis (LCCA) was conducted on conventional and perpetual designs to identify the option with the highest net present value (NPV) among the design variety investigated.

3. General inputs and assumptions

3.1 *Traffic data inputs*

The mechanistic-empirical pavement design guide (M-E PDG) software, version 1.1 (Applied Research Associates, Inc., Arizona State University, USA), was used at level 3 in all analyses documented in this study. This level provides some default and typical values for the traffic volume adjustment factors, axle load distribution factors and axle configuration. The M-E PDG software implements a combined group of empirical models for climate, traffic and materials to predict future performance in terms of cracking, rutting, faulting, etc. Thus, this would provide more appropriate designs and better performance of pavements (Ceylan *et al.* 2008, 2009).

The analysis was carried out using three main traffic levels shown in Table 1. The conversion between the annual average daily truck traffic (AADTT) and the design

Table 4. Analysis results and percentage performance improvement of AC designs by using PG 76-10 on Pen 60-70 for subgrade class S1.

Traffic classes	T4			T5			T6		
	1	2		3	4		5	6	
Analysis cases	Pen	PG	% Improved	Pen	PG	% Improved	Pen	PG	% Improved
Longitudinal cracking (m/km)	764.2	417.7	45	641	292.6	54	172	46	73
Alligator cracking (%)	4.43	3.38	24	5.34	4.12	23	5.52	4.28	22
Rutting (mm)	16.2	13.8	15	20.4	17.2	16	23.3	19.6	16
IRI (m/km)	1.75	1.68	4	1.86	1.78	4	1.94	1.84	5

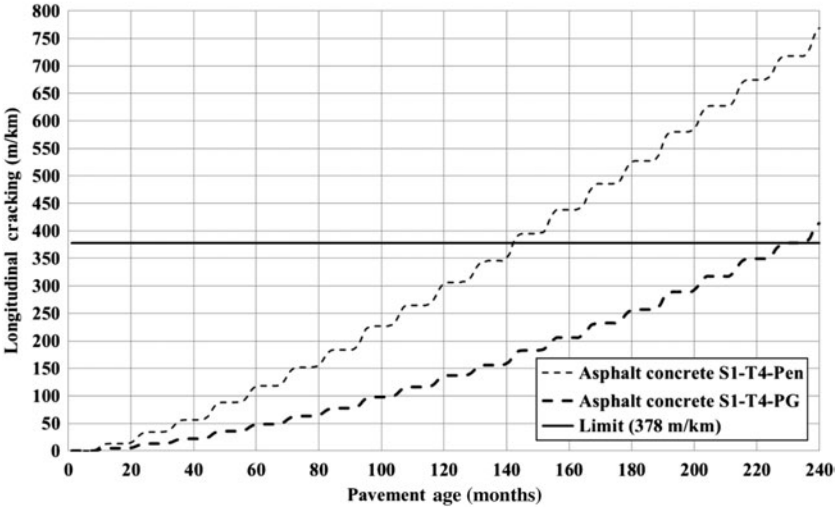

Figure 3. Longitudinal cracking graphs comparing Pen 60-70 and PG 76-10 for AC designs for traffic T4 and subgrade S1.

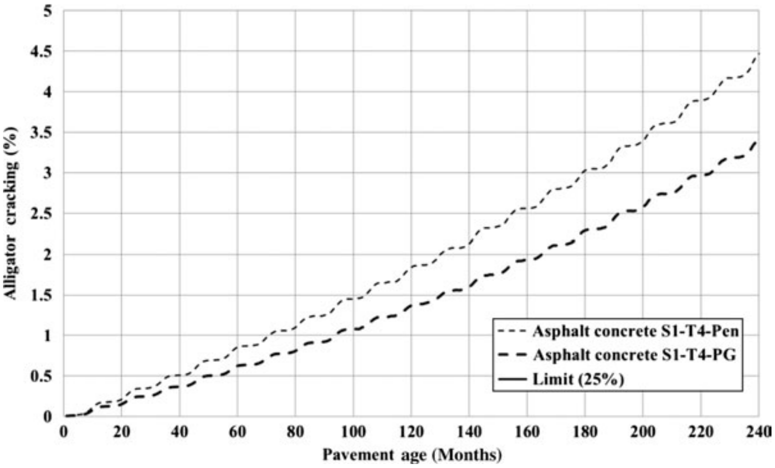

Figure 4. Alligator cracking graphs comparing Pen 60-70 and PG 76-10 for AC designs for traffic T4 and subgrade S1.

equivalent single axle load (ESAL) was made using the default traffic distribution in the M-E PDG level 3 with the following values:

- Design life (years): 20
- Number of lanes in design direction: 2
- Percentage of trucks in design direction: 50%
- Percentage of trucks in design lane: 95%
- Operational speed (mph): 60
- Traffic growth: 4%

3.2 *Climatic data inputs*

The weather in Qatar is generally hot with very little precipitation. In order to carry out the analysis in the M-E PDG software, careful examination of numerous climatic files was carried out to find out climatic data in the software with temperatures similar to those in Qatar. The climatic conditions in Needles Airport in California, USA, were found to reasonably resemble climatic conditions in Qatar. The latitude of this station is 34.46°N and the longitude is 114.37°W. Figure 1 shows a comparison of the yearly mean high air temperature profiles between both locations.

3.3 *Asphalt pavement designs*

A total of three asphalt pavement designs using 32 different cases were analysed in this part of the study. The first type is a flexible pavement design and is referred to as ‘asphalt concrete design’ in the Qatar Highway Design Manual (QHDM). This design consists of a surface course, asphalt concrete (AC) base course and granular sub-base over the subgrade. The second type is referred to as ‘flexible-composite design’ in the QHDM. This design consists of a surface course, upper AC base, cement-stabilised lower base and granular sub-base over the subgrade. The third type is the ‘perpetual pavement

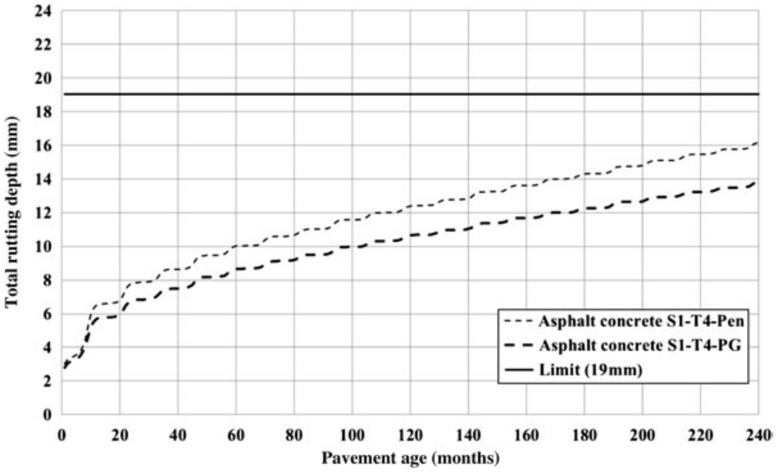

Figure 5. Total rutting depth graphs comparing Pen 60-70 and PG 76-10 for AC designs for traffic T4 and subgrade S1.

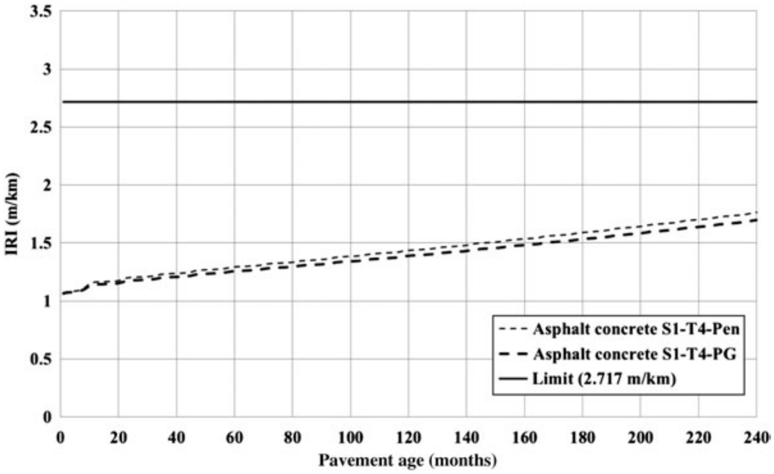

Figure 6. IRI graphs comparing Pen 60-70 and PG 76-10 for AC designs for traffic T4 and subgrade S1.

design' and it consists of a surface course, AC upper base, AC lower base and cement-stabilised sub-base over the subgrade. The typical cross sections of these design varieties can be seen in Figure 2.

Three conventional pavement designs that are being used in Qatar for traffic classes T4, T5 and T6 were analysed and evaluated using M-E PDG. The analysis was carried out using an unmodified bitumen Pen 60-70, which is graded as PG 64-22 using the Superpave system, and a modified bitumen PG 76-10 which is proposed to be used in Qatar (Sadek *et al.* 2012). The Pen 60-70 bitumen has been in use for many years to produce hot-mix asphalt mixtures in Qatar as well as in other countries in the region such as in Saudi Arabia, United Arab Emirates, Oman, Yemen and Jordan. Several studies showed this binder grade is not suitable for the prevailing climatic conditions (Al-Abdul Wahhab and Balghunaim 1994, Bubshait 2001, Asi 2005, Hassan and Al-Jabri 2005, Naji and Asi 2008). The PG was selected based on analysis of climatic conditions in the State of Qatar and on evidence reported in regional studies indicating the advantages of harder or modified bitumen to withstand high temperatures and resist cracking and rutting (Fatani *et al.* 1992, Al-Abdul Wahhab and Balghunaim 1994, Al-Hadidy and Tan 2011).

The perpetual pavement designs were analysed and evaluated using minimum thicknesses of 75 and 175 mm for the upper and lower asphalt base courses, respectively. The analysis was also conducted using maximum thicknesses of 100 and 200 mm as shown in Figure 2. Details of traffic, layer thicknesses, bitumen and all other material properties used in the 32 different pavement design cases are summarised in Table 2.

3.4 *Material properties*

The properties of the materials used in this study were carefully selected by the authors based on the data available in QHDM, Qatar Construction Specifications (QCS 2010) and experimental measurements of local materials (Masad *et al.* 2011, Sadek *et al.* 2013). These properties are discussed in the following sections.

3.4.1 *AC surface course*

For the surface course, the analysis was carried out using Pen 60-70 and PG 76-10 bitumen for conventional

Table 5. Analysis results and percentage performance improvement of AC designs by using PG 76-10 on Pen 60-70 for subgrade class S3.

Traffic classes	T4			T5			T6		
	7	8		9	10		11	12	
Analysis cases	Pen	PG	% Improved	Pen	PG	% Improved	Pen	PG	% Improved
Longitudinal cracking (m/km)	1169	849	27	1059	693	35	608	273	55
Alligator cracking (%)	3.18	2.37	25	3.63	2.73	25	3.5	2.7	25
Rutting (mm)	14.7	12.4	16	18.8	15.7	16	22	18	17
IRI (m/km)	1.68	1.62	4	1.79	1.71	4	1.9	1.8	5

Table 6. Analysis results and percentage performance improvement of flexible-composite designs by using PG 76-10 on Pen 60-70 for subgrade class S1.

Traffic classes	T5			T6		
	13	14		15	16	
Analysis cases	Pen	PG	% Improved	Pen	PG	% Improved
Longitudinal cracking (m/km)	1.17	0.20	83	51.0	4.1	92
Alligator cracking (%)	0	0	0	0	0	0
Rutting (mm)	23.9	19.9	17	32.5	26.8	18
IRI (m/km)	1.91	1.81	5	2.12	1.98	7

designs. Modified bitumen PG 76-10 was used for the asphalt surface course in the case of perpetual pavement design. An effective bitumen content of 5%, air voids of 6% and Poisson's ratio of 0.35 were used in the analysis of conventional and perpetual designs. These volumetric properties were selected based on typical mixtures used in the State of Qatar.

3.4.2 *AC base course*

Timm and Priest (2006) stated that using extra-flexible asphalt mixtures can resist fatigue cracking in the lower asphalt base course. In addition, the upper asphalt base course was designed to resist traffic load and rutting which can be achieved by using bitumen with the appropriate high-temperature grading. Consequently, the analysis was carried out using Pen 60-70 and PG 76-10 bitumen for conventional designs, while for perpetual pavement designs, modified bitumen PG 76-10 was used for the asphalt mixture layers with bitumen content of 6% and air voids of 5%.

3.4.3. *Cement-stabilised base and sub-base course*

The cement-stabilised base (or sub-base) was used only in flexible-composite and perpetual pavement designs. This material comprises sand, gravel or crushed rock that is mixed with cement either in-place or in an off-road mixer. The resilient modulus value for this material was determined to be 2413 MPa (350,000 psi) using the relationship M_r (MPa) ≈ Compressive strength (MPa) × 750. The compressive strength was assumed to be 3.2 MPa. The modulus of rupture was 1 MPa (150 psi) and Poisson's ratio was 0.2, based on data provided by field testing reports.

3.4.4 *Granular sub-base course*

Granular materials are used for the sub-base course in conventional designs. The granular material may consist of crushed stone or gravel. QHDM specifies a minimum of 60% California bearing ratio (CBR) value for the sub-base layer. The modulus was calculated to be 242 MPa (35,100 psi) using the relationship M_r (MPa) ≈ 17.6 $(\mathrm{CBR})^{0.64}$ (AASHTO T193) and Poisson's ratio of 0.35 for the crushed stone was used.

3.4.5 *Subgrade*

The State of Qatar generally has high-strength natural soils consisting of weathered limestone or sand. Therefore, silty or clayey gravel and sand 'A-2-4' and stone fragments, gravel and sand 'A-1-b', based on AASHTO Soil Classification System, were used in this study. These two soils are referred to as S1 and S3, respectively, in the QHDM. The resilient moduli are given in Table 2. Poisson's ratio of 0.35 was used for the subgrade soils.

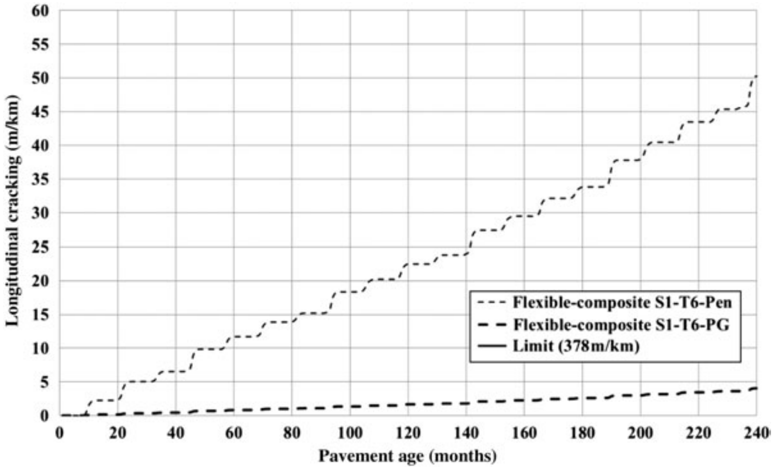

Figure 7. Longitudinal cracking graphs comparing Pen 60-70 and PG 76-10 for flexible-composite designs for traffic T6 and subgrade S1.

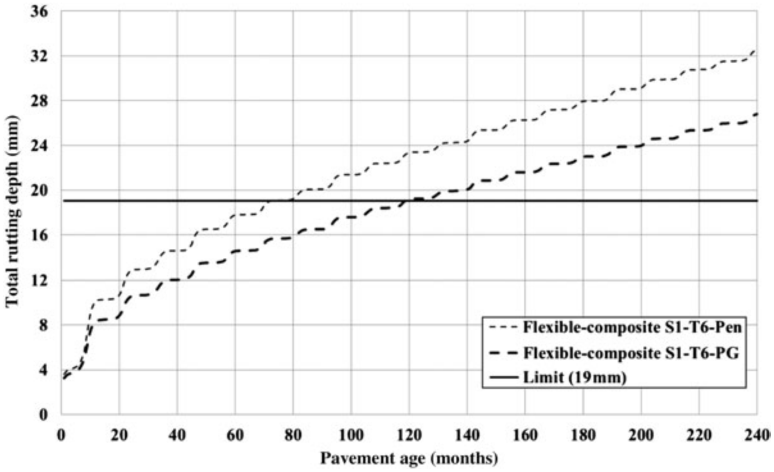

Figure 8. Total rutting depth graphs comparing Pen 60-70 and PG 76-10 for flexible-composite designs for traffic T6 and subgrade S1.

4. M-E PDG results and discussions

The performance of conventional and perpetual pavement designs in terms of surface distresses: longitudinal cracking, alligator cracking, total rutting depth and IRI, was examined. Each performance criterion has a design limit in the M-E PDG as given in Table 3. In this section, the analysis results for the 32 cases of pavement designs are presented and discussed.

4.1 *Effect of bitumen type on the performance of conventional pavement design*

In the first part of this study, AC designs (flexible designs) and flexible-composite designs were evaluated using the M-E PDG in which each design was assessed by comparing the performance of using unmodified bitumen Pen 60-70 and modified bitumen PG 76-10. The comparison also concentrated on subgrade class S1 and S3 to evaluate the effect of using high-modulus subgrade.

4.1.1 *Analysis results of AC designs*

Subgrade class S1. Results of cases 1–6 are shown in Table 4 and Figures 3–6. It can be seen that the use of modified bitumen PG 76-10 improved the performance of this conventional pavement design for subgrade class S1, especially for longitudinal cracking, which decreased by 45%, 54% and 73% for traffic classes T4, T5 and T6, respectively. On average, alligator cracking decreased by 23%, total rutting depth decreased by 16% and IRI decreased by only 4%.

Subgrade class S3. The results of analysis cases 7–12 are presented in Table 5. It is clear from the results that the use

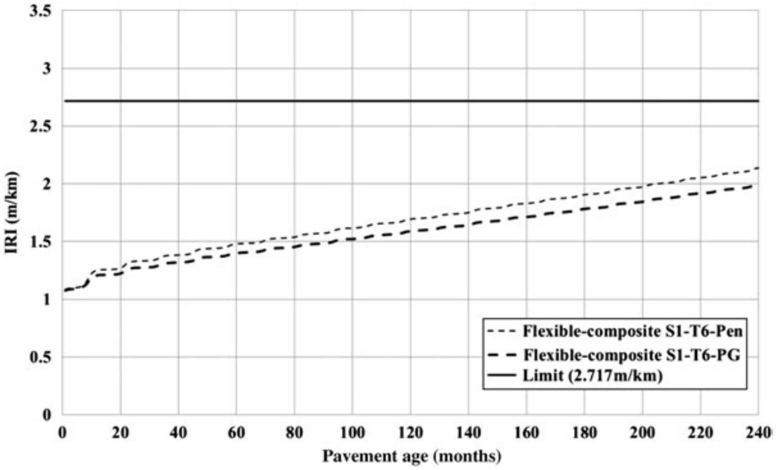

Figure 9. IRI graphs comparing Pen 60-70 and PG 76-10 for flexible-composite designs for traffic T6 and subgrade S1.

Table 7. Analysis results and percentage performance improvement of flexible-composite designs by using PG 76-10 on Pen 60-70 for subgrade class S3.

Traffic classes	T5			T6		
	17	18		19	20	
Analysis cases	Pen	PG	% Improved	Pen	PG	% Improved
Longitudinal cracking (m/km)	18.1	6.8	62	224.5	39.3	82
Alligator cracking (%)	0	0	0	0	0	0
Rutting (mm)	22.4	18.6	17	30.9	25.3	18
IRI (mm/km)	1.85	1.75	5	2.06	1.92	7

of PG 76-10 instead of Pen 60-70 enhanced the performance of pavements with subgrade S3, especially for longitudinal cracking, which decreased by 27%, 35% and 55% for T4, T5 and T6, respectively. On average, alligator cracking decreased by 25%, total rutting depth decreased by 16% and IRI decreased by 4%.

4.1.2 *Analysis results of flexible-composite designs*

Subgrade class S1. As shown in Table 6 and Figures 7–9, the use of PG 76-10 as a replacement of Pen 60-70 improved the performance of flexible-composite pavement designs in cases 13–16, especially for longitudinal cracking, which decreased by 83% and 92% for traffic classes T5 and T6, respectively. On average, total rutting depth decreased by 17% and IRI decreased by only 6%. There was no alligator cracking for both bitumen types. This could be due to the existence of the stabilised lower base layer just beneath the AC layer which prevents any cracks to start from the bottom to the top of the pavement section.

Subgrade class S3. The analysis results for cases 17–20 of flexible-composite pavement designs are given in Table 7. The results indicated that using PG 76-10 enhanced the performance of this pavement design for subgrade class S3, especially for longitudinal cracking, which decreased by 62% and 82% for traffic classes T5 and T6, respectively. On average, total rutting depth decreased by 17% and IRI decreased by only 6%. However, similar to the case in subgrade S1, there was no alligator cracking for both PG 76-10 and Pen 60-70.

In general, the use of high-modulus subgrade S3 for both conventional designs, AC and flexible-composite, improved the performance. However, it increased longitudinal cracking significantly compared with the use of subgrade class S1.

4.2 *Perpetual pavements versus conventional pavements*

A total of three traffic loadings, T6 (50 million ESALs), three times T6 (150 million ESALs) and six times T6 (300 million ESALs), were used to analyse the performance of conventional and perpetual designs using the M-E PDG. Unmodified bitumen Pen 60-70 and modified bitumen PG 76-10 were used for conventional and perpetual pavements, respectively.

4.2.1 *Traffic class T6*

The results for cases 21, 24, 27 and 30 of perpetual pavements compared with those for conventional pavements under T6 traffic load are shown in Table 8 and Figures 10–13. The use of perpetual pavements significantly improved the performance of the pavement designs against surface distresses, particularly in the case of 300-mm-thick asphalt base course.

4.2.2 *Traffic class 3 × T6 (150 million ESALs)*

Table 9 summarises the analysis results for cases 22, 25, 28 and 31 of perpetual pavements. Performance results of

Table 8. Analysis results for conventional and perpetual pavements for traffic T6.

Design type	Flexible-composite designs		AC designs		Perpetual pavement designs			
Performance after 20 years	S1	S3	S1	S3	250 mm		300 mm	
					S1	S3	S1	S3
Longitudinal cracking (m/km)	51	224.5	172	608	32.0	122	0	0
Alligator cracking (%)	0	0	5.52	3.5	0	0	0	0
Rutting (mm)	32.5	30.9	23.3	22.0	14.9	13.6	11.8	10.5
IRI (m/km)	2.12	2.06	1.94	1.90	1.69	1.63	1.61	1.56

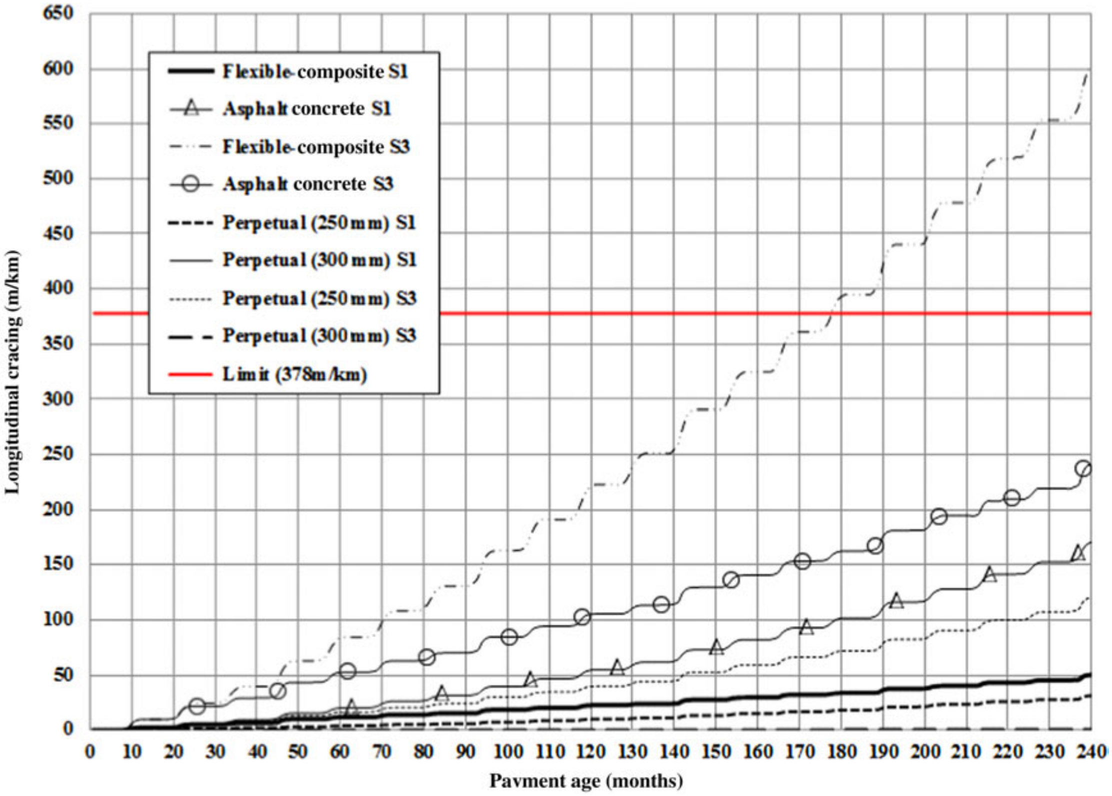

Figure 10. Longitudinal cracking for conventional and perpetual pavements for traffic T6.

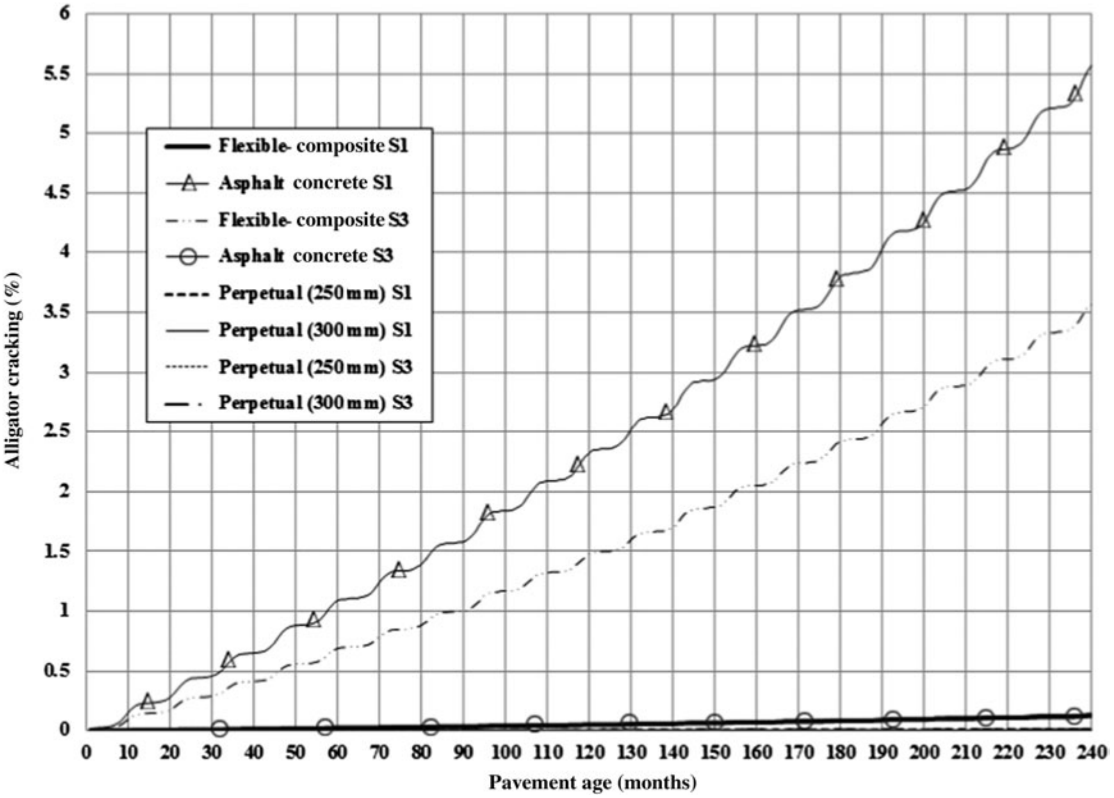

Figure 11. Alligator cracking for conventional and perpetual pavements for traffic T6.

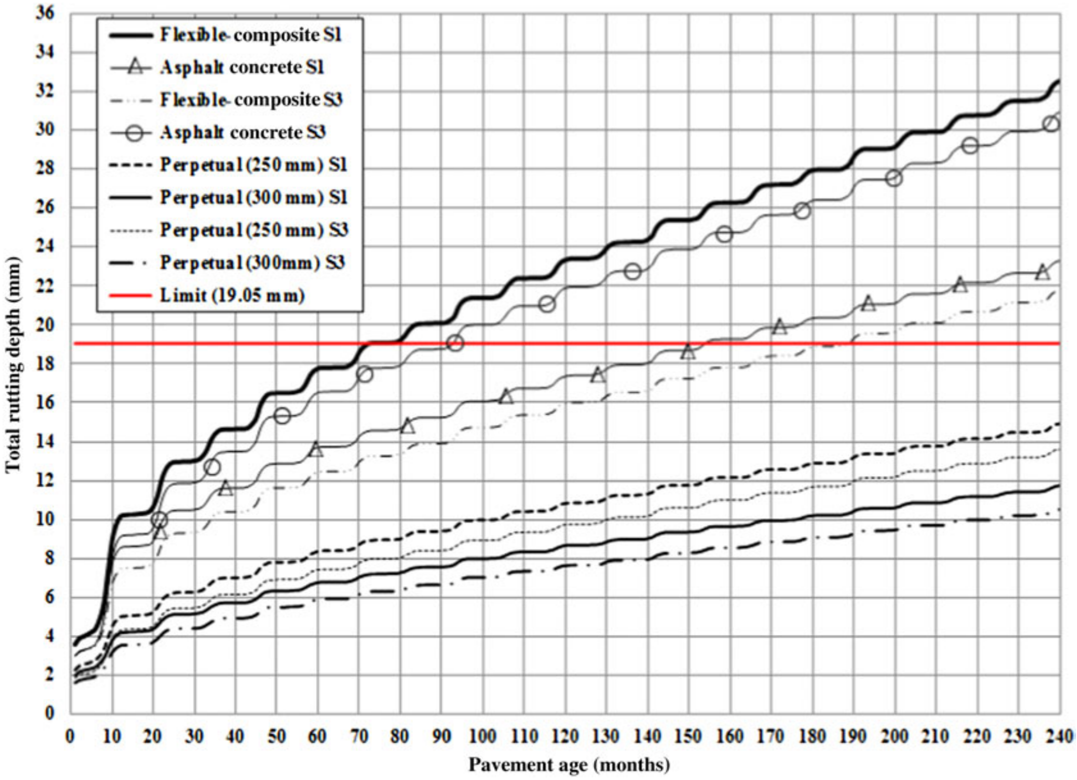

Figure 12. Total rutting depth for conventional and perpetual pavements for traffic T6.

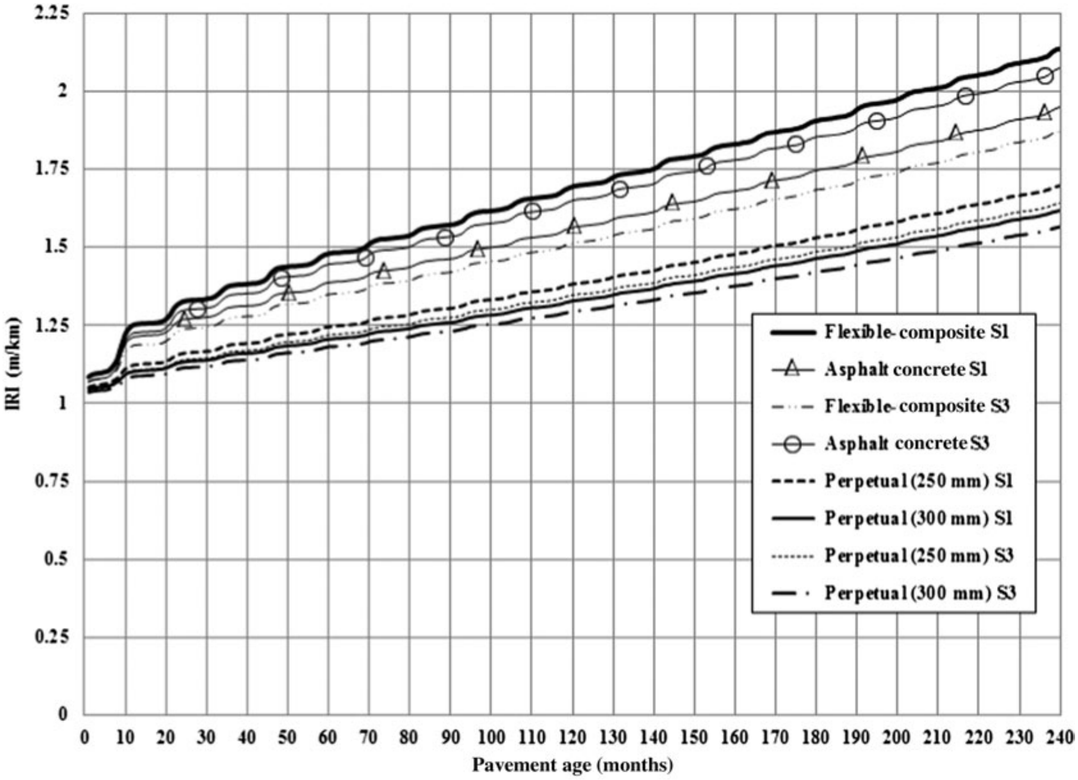

Figure 13. IRI for conventional and perpetual pavements for traffic T6.

Table 9. Analysis results for conventional and perpetual pavements for traffic 3 × T6.

Design type	Flexible-composite designs		Asphalt concrete designs		Perpetual pavement designs			
Performance after 20 years	S1	S3	S1	S3	250 mm		300 mm	
					S1	S3	S1	S3
Longitudinal cracking (m/km)	244.5	854.7	670	1409.1	158	514	1.2	0
Alligator cracking (%)	0.4	0.46	15.8	10.5	0	0	0	0
Rutting (mm)	52.2	50.4	35.8	34.2	23.0	21.5	17.8	16.3
IRI (m/km)	2.61	2.54	2.33	2.22	1.89	1.83	1.76	1.70

conventional and perpetual pavement designs were compared when 3 × T6 traffic loading was used. It can be seen from the table that the use of perpetual pavement designs enhanced significantly the performance against surface distresses, particularly in the case when the asphalt base layer is 300-mm thick.

4.2.3 *Traffic class 6 × T6 (300 million ESALs)*

Analysis results in the case of using 6 × T6 traffic loading are provided in Table 10. It can be concluded that the use of perpetual pavement design in cases 23, 26, 29 and 32 improved the performance against surface distresses, mainly in the case of 300 mm-thick asphalt base course.

In general, the use of high-modulus subgrade S3 for both conventional and perpetual designs improved the performance slightly. However, it increased longitudinal cracking significantly compared with the use of subgrade class S1.

5. Life-cycle cost analysis

In the previous sections, eight different asphalt pavement designs were evaluated based on performance and damage criteria. Performance was evaluated for three levels of traffic loading (T6, 3 × T6 and 6 × T6). Curves were produced to show the evolution of damage with pavement age and when it reached the design limits (Figures 10–13). Results indicated that the most effective design is the perpetual pavement with a 300-mm-thick base course and S3 (A-1-b) as subgrade soil.

This part of the study is concerned with evaluating the cost of constructing each of the eight pavement designs. The cost of construction was used in the LCCA to obtain the NPV. The NPV was used in capital budgeting to analyse the profitability of a project or investment. A comparison was made to evaluate the optimised NPV to enable selection of the most viable design for a traffic level of 300 million ESALs of 6 × T6.

LCCA was conducted with consideration of the construction and rehabilitation costs. These costs were gathered based on information from local road construction companies in the State of Qatar. The prices were supplied per square metre for all layer thicknesses available in the study. The rehabilitation cost included both milling of existing layers and overlaying of new layers. LCCAExpress software, version 2.0 (2011), was used for conducting the LCCA.

5.1 *Assumptions and limitations*

To simplify the analysis, some indirect costs such as work zone user costs were deactivated from the software. In addition, some assumptions were made to limit the comparison with the construction and rehabilitation costs only. The assumptions were as follows:

- The road geometry was assumed to be 1609 m (1 mile) long and 7.32 m (24 ft) wide.

Table 10. Analysis results for conventional and perpetual pavements for traffic 6 × T6.

Design type	Flexible-composite designs		Asphalt concrete designs		Perpetual pavement designs			
Performance after 20 years	S1	S3	S1	S3	250 mm		300 mm	
					S1	S3	S1	S3
Longitudinal cracking (m/km)	573.7	1372.5	1174.3	1755.6	397	1001	3.4	10.2
Alligator cracking (%)	0.84	0.97	28.1	19.7	0	0	0	0
Rutting (mm)	69.3	67.5	47.5	46.0	30.7	29.0	23.5	21.8
IRI (m/km)	3.04	2.97	2.75	2.60	2.08	2.00	1.90	1.84

Table 11. Layer type and thickness for pavement design cases.

Pavement design	Case no.	Thickness of layer (mm) Surface course (AC1)	Upper base (AC2)	Lower base (AC3)	Stabilised base	Sub-base (crushed stone)	Soil subgrade	Code
Perpetual design	P1	75	175	75	270	–	S1 (A-2-4)	S1-6T6-P-250
	P2	75	200	100	270	–	S1 (A-2-4)	S1-6T6-P-300
	P3	75	175	75	270	–	S3 (A-1-b)	S3-6T6-P-250
	P4	75	200	100	270	–	S3 (A-1-b)	S3-6T6-P-300
Flexible-composite design	F1	40	150	–	270	200	S1 (A-2-4)	S1-6T6-F-Pen
	F2	40	150	–	270	–	S3 (A-1-b)	S3-6T6-F-Pen
Asphalt Concrete design	A1	40	250	–	–	200	S1 (A-2-4)	S1-6T6-A-Pen
	A2	40	250	–	–	100	S3 (A-1-b)	S3-6T6-A-Pen

- There were two lanes in each direction.
- Lane width was 3.66 m (12 ft).
- Speed limit was 96.56 km/h (60 mph).
- Overlay thickness was considered the same as the milling thickness.
- Same asphalt mix design was used for all cases.
- Discount rate used in the software was 4%.

5.2 *Cases used for analysis*

The eight cases that were included in the LCCA are summarised in Table 11.

5.3 *Cost of construction and rehabilitation*

Average unit prices for construction, milling and overlay operations obtained from construction companies in Qatar and used in the LCCA are given in Table 12. The cost of construction and overlay for perpetual pavement was ~20% more than that of conventional pavement due to the use of polymer-modified bitumen.

5.4 *Rehabilitation*

Using the analysis results from M-E PDG, each design had a different rehabilitation method based on the type of damage and when it occurs within the design period of 20 years. Tables 13 and 14 show the time, in months, when each type of damage occurs. The effect of rehabilitation on the AC layer for three cases can be seen in Figures 14–16.

Table 12. Average unit prices obtained from construction companies in Qatar.

Description		Materials and construction $/tonne	$/m^3	Milling $/m^3	Overlay $/m^3
Asphalt concrete	Pen 60-70	96	240	58	225
	PG 76-10	115	288	58	270
Cement stabilised		26	65	–	–
Crushed stone		21	36	–	–

5.5 *LCCA results and discussions*

Results from the LCCAExpress software are displayed as NPV. Table 15 and Figures 17 and 18 show the initial construction NPV and the recurring maintenance NPV added together to obtain the total NPV.

As shown in Figure 17, despite the fact that the lowest initial construction cost is for case F1 ($954,522), the recurring maintenance cost is the highest ($8,872,691) and maintenance should be conducted almost annually during the pavement service life. The lowest recurring maintenance cost is for case P2 ($834,359) and maintenance should be carried out only once after 14 years. Case P1 has less initial construction cost ($1,438,328) than case P2

Table 13. Number of months needed to reach the limits in longitudinal and alligator cracking.

Pavement design	Case no.	Number of months to reach the limit of Longitudinal cracking	Alligator cracking
Perpetual design	P1	238	Below limit
	P2	Below limit[a]	Below limit
	P3	96	Below limit
	P4	Below limit	Below limit
Flexible-composite design	F1	165	Below limit
	F2	45	Below limit
AC design	A1	83	215
	A2	34	Below limit

[a] 'Below limits' means that the damage in the case does not reach the limit within 20 years.

Table 14. Number of months needed to reach the limits in rutting for each layer.

		Number of months to reach maximum rutting on each layer [limit is 19 mm (0.75 in.)]					
Pavement design	Case no.	Surface course (AC1)	Upper base (AC2)	Lower base (AC3)	Stabilised base	Sub-base (crushed stone)	Total rutting (all layers)
Perpetual design	P1	200	Below limit	Below limit	Below limit	Below limit	93
	P2	Below limit	Below limit	Below limit	Below limit	Below limit	164
	P3	201	Below limit	Below limit	Below limit	Below limit	106
	P4	Below limit	Below limit	Below limit	Below limit	Below limit	189
Flexible-composite design	F1	141	58	Below limit	Below limit	Below limit	11
	F2	141	59	Below limit	Below limit	Below limit	14
AC design	A1	Below limit	153	Below limit	Below limit	Below limit	23
	A2	Below limit	153	Below limit	Below limit	Below limit	33

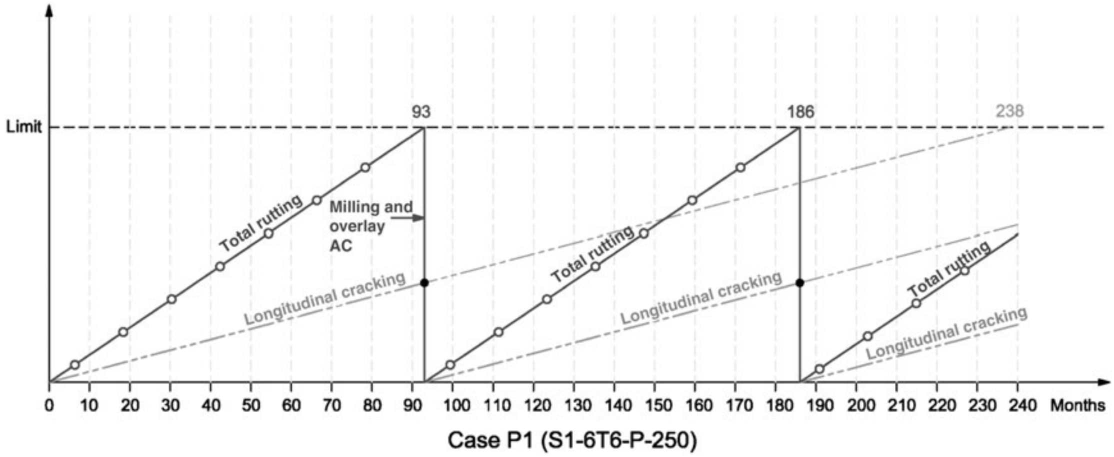

Figure 14. Effect of rehabilitation for the total rutting in the AC layer on longitudinal cracking of the same layer for case P1.

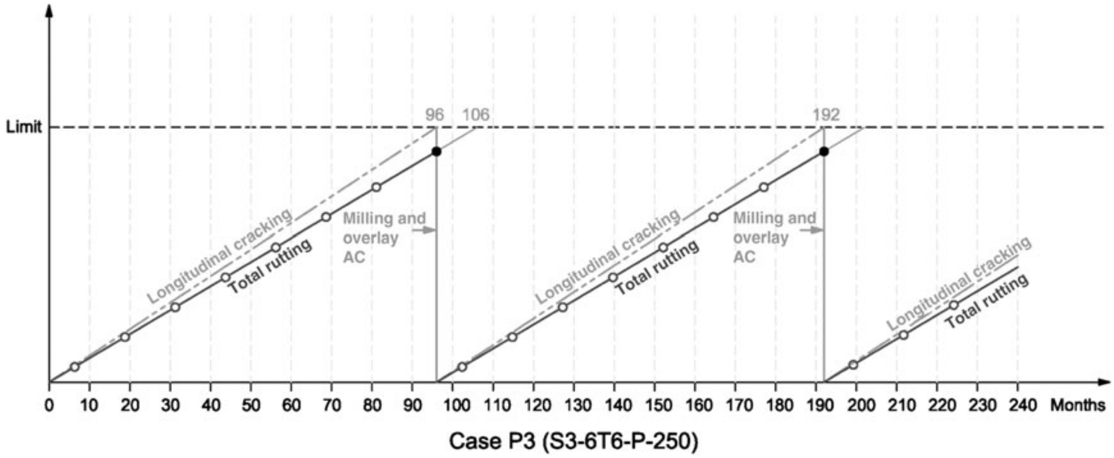

Figure 15. Effect of rehabilitation for longitudinal cracking in the AC layer on the total rutting of the layer for case P3.

($1,627,775), but recurring maintenance for case P1 is higher ($1,583,247). Initial construction cost for case A1 ($1,037,100) is almost the same as for case F1, but the recurring maintenance cost ($6,421,416) is lower and should be carried out biennially during the pavement service life.

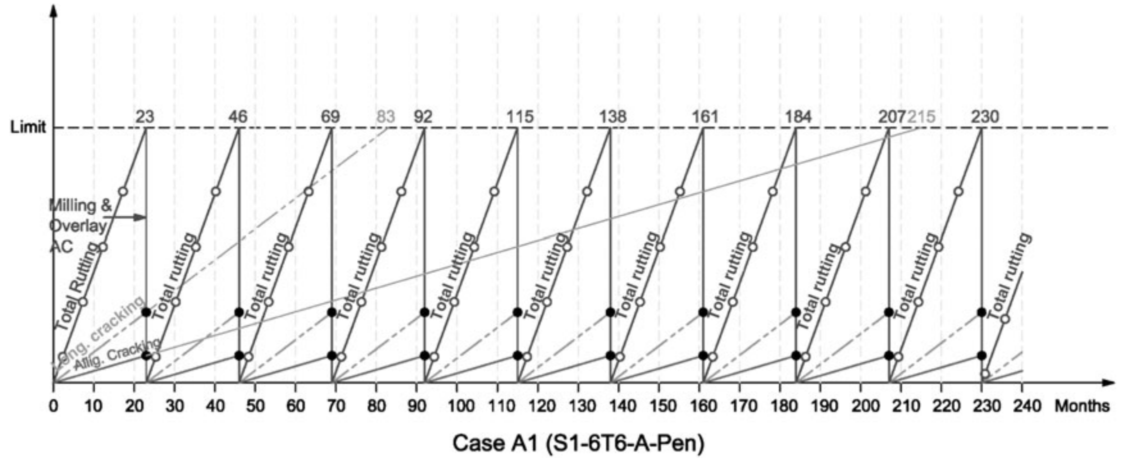

Figure 16. Effect of rehabilitation for the total rutting in the AC layer on longitudinal and alligator cracking for case A1.

Table 15. NPV for initial construction, recurring maintenance and the total NPV for each case.

Case no.	Code	Initial construction NPV	Recurring maintenance NPV	Total NPV
P1	S1-6T6-P-250	\$1,438,328	\$1,583,247	\$3,021,575
P2	S1-6T6-P-300	\$1,627,775	\$834,359	\$2,462,134
P3	S3-6T6-P-250	\$1,438,328	\$1,583,247	\$3,021,575
P4	S3-6T6-P-300	\$1,627,775	\$771,412	\$2,399,187
F1	S1-6T6-F-Pen	\$954,522	\$8,872,691	\$9,827,213
F2	S3-6T6-F-Pen	\$819,044	\$7,057,934	\$7,876,978
A1	S1-6T6-A-Pen	\$1,037,100	\$6,421,416	\$7,458,516
A2	S3-6T6-A-Pen	\$968,504	\$4,366,487	\$5,334,991

Figure 18 illustrates that the lowest initial construction cost is for case F2 (\$819,044). However, the recurring maintenance is the highest (\$7,057,934) and should be carried out almost annually during the pavement service life. The lowest recurring maintenance cost is for case P4 (\$771,412) which should be executed every 16 years during its service life, but its initial construction cost is the highest (\$1,627,775). Case P3 has lower initial construction cost (\$1,438,328) than case P4, but with higher recurring maintenance cost (\$1,583,247). Case A2 has higher initial construction cost (\$968,504) than case F2, but less recurring maintenance cost (\$4,366,487) and

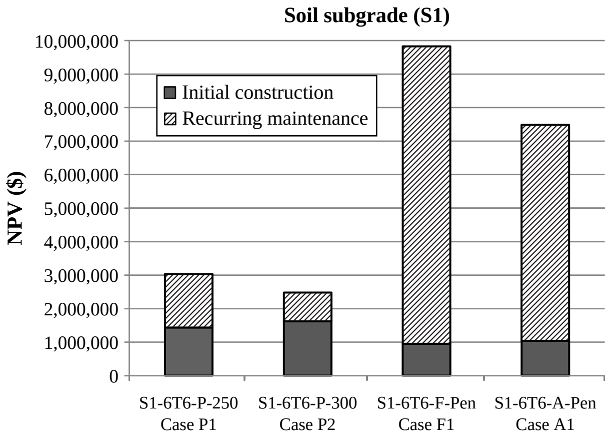

Figure 17. Total NPV for cases with soil subgrade (S1).

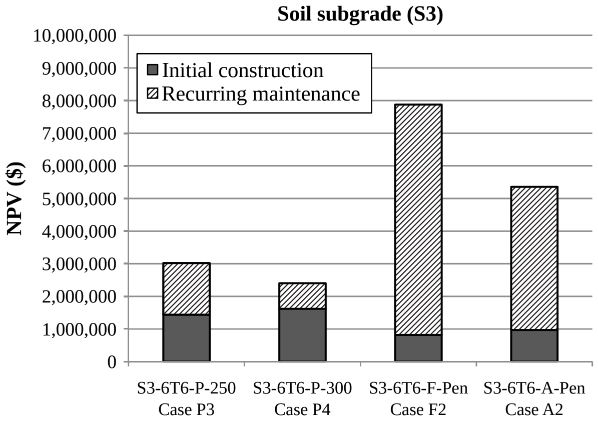

Figure 18. Total NPV for cases with soil subgrade (S3).

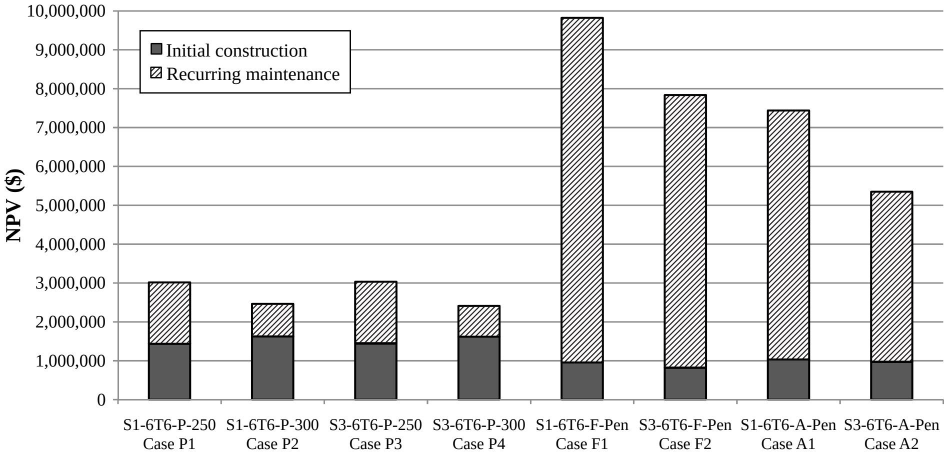

Figure 19. Total NPV for all cases.

Table 16. Number of maintenance activities and years between each of them.

Case no.	Code	Number of maintenance cycles in 20 years	Number of years between each maintenance cycle
1	S1-6T6-P-250	2	~8
2	S1-6T6-P-300	1	~14
3	S3-6T6-P-250	2	8
4	S3-6T6-P-300	1	~16
5	S1-6T6-F-Pen	21	~1
6	S3-6T6-F-Pen	17	~1
7	S1-6T6-A-Pen	10	~2
8	S3-6T6-A-Pen	7	~3

should be conducted almost every 3 years during the pavement service life.

By studying the LCCA results, it can be noticed that the lowest NPV of all cases is for case P4 ($2,399,187). This is in agreement with performance results obtained using the M-E PDG and presented earlier in this study. All perpetual pavement design cases have higher average initial construction cost than conventional flexible-composite and AC designs cases by almost 30%. However, this increase of initial construction cost is compensated for and can be justified by the significant reduction of the recurring maintenance costs by almost 6.5 times. As shown in Figure 19 and Table 16, case F1 can be considered as the worst case because it had the highest NPV and it needed recurring maintenance almost annually during its 20 years of service

6. Conclusions

The main focus of this study was to introduce the use of mechanistic-empirical analysis method in evaluating the performance of perpetual pavements in the State of Qatar. The analysis considered various conventional and perpetual pavement designs with different levels of traffic loading. Significant care was taken in the selection of material model parameters based on the properties described in the QHDM and testing results in reports and research studies.

The analysis results evidenced the effectiveness in replacing unmodified bitumen Pen 60-70 with modified bitumen PG 76-10 for pavements in Qatar and countries in the region with similar climatic conditions. In particular, longitudinal cracking was significantly less in pavements with modified bitumen PG 76-10.

Analysis of the conventional designs showed that an increase in the subgrade strength improved pavement performance whereby the magnitudes of alligator cracking, total rut depth and IRI all decreased after 20 years. In contrast, longitudinal cracking increased, indicating that the increase in subgrade strength in certain structures should be approached with caution. This issue can be overcome by using modified bitumen to increase resistance to fatigue cracking.

The results showed that the use of perpetual designs makes pavements much more accommodating than conventional designs for increase in traffic loading without causing excessive damage. In addition, LCCA of conventional and perpetual designs demonstrated that the initial cost of perpetual pavements is about 30% more than conventional pavements. However, perpetual pavements are still more economical because they require much less maintenance or rehabilitation work, especially when the AC base layer is 300 mm thick. LCCA conclusions matched the performance analysis results from M-E PDG and supported the importance of implementing perpetual designs in Qatar. This is a very important finding for the State of Qatar where there is a tremendous increase in traffic loading. Future work will focus on measuring the properties of various materials and also on the calibration of the models used in the M-E PDG for the prevailing conditions in Qatar. This will be achieved by monitoring field performance of asphalt pavements and by the construction of test sections that will be subjected to accelerated loading.

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References

American Association of State and Highway Transportation Officials (AASHTO) T193, 2010. Standard method of test for the California bearing ratio. Washington, DC: Single User Digital Publication.

Al-Abdul Wahhab, H.I., Asi, I.M. and Ramadhan, R.H., 2001. Modeling resilient modulus and temperature correction for Saudi roads. *Journal of Materials in Civil Engineering*, 13 (4), 298–305.

Al-Abdul Wahhab, H.I. and Balghunaim, F.A., 1994. Asphalt pavement temperature related to arid Saudi environment. *Journal of Materials in Civil Engineering*, 6 (1), 1–14.

Al-Hadidy, A.I. and Tan, Y.-q., 2011. Performance of SMA mixes made with various binders. *Construction and Building Materials*, 25 (9), 3668–3673.

Asi, I.M., 2005. Laboratory comparison study for the use of stone matrix asphalt in hot weather climates. *Construction and Building Materials*, 20 (10), 982–989.

Bubshait, A.A., 2001. Quality of pavement construction in Saudi Arabia. *Practice Periodical on Structural Design and Construction*, 6 (3), 129–136.

Ceylan, H., Coree, B. and Gopalakrishnan, K., 2008. Design of rigid pavements in Iowa using the mechanistic-empirical pavement design guide. *Baltic Journal of Road & Bridge Engineering*, 3 (4), 219–225.

Ceylan, H., Coree, B. and Gopalakrishnan, K., 2009. Evaluation of the mechanistic-empirical pavement design guide for implementation in Iowa. *Baltic Journal of Road & Bridge Engineering*, 4 (1), 5–12.

Fatani, M., *et al.*, 1992. *National research project: evaluation of permanent deformation of asphalt concrete pavement in Saudi Arabia*. Riyadh, Saudi Arabia, Final Report King Abdulaziz City for Science and Technology.

Ferne, B., 2006. Long-life pavements – a European study by ELLPAG. *International Journal of Pavement Engineering*, 7 (2), 91–100.

Hassan, H.F. and Al-Jabri, K.S., 2005. Effect of organic fibers on open-graded friction course mixture properties. *International Journal of Pavement Engineering*, 6 (1), 67–75.

LCCAExpress, 2011. *Version 2.0.* Developed by Timm D. H.

Masad, E., Kassem, E. and Little, D., 2011. Characterization of asphalt pavement materials in the State of Qatar: a case study. *International Journal of Road Materials and Pavement Design*, 12 (4), 739–765.

M-E PDG, 2009. *Version 1.1*. Applied Research Associates – Transportation, Arizona State University, USA.

Merrill, D., Dommelen, A.V. and Gáspár, L., 2006. A review of practical experience throughout Europe on deterioration in fully-flexible and semi-rigid long-life pavements. *International Journal of Pavement Engineering*, 7 (2), 101–109.

Naji, J.A. and Asi, I.M., 2008. Performance evaluation of asphalt concrete mixes containing granular volcanic ash. *Journal of Materials in Civil Engineering*, 20 (12), 754–761.

Qatar Construction Specifications (QCS), 2010. The State of Qatar.

Qatar Highway Design Manual (QHDM) – Section 9, 1997. The State of Qatar.

Renteria, R.A. and Hunt, E., 2008. SUPER related. *Roads & Bridges*, 46 (6), 47–51.

Sadek, H., *et al.*, 2012. The implementation of mechanistic-empirical pavement design method to evaluate asphalt pavement design in Qatar. *5th Eurasphalt & Eurobitume Congress*, 13–15 June 2012, Istanbul, Turkey. Paper No. P5EE-53.

Sadek, H., *et al.*, 2013. Evaluation of mechanical properties of alternative pavement designs for the State of Qatar. *2nd MESAT conference*, 5–7 Februray 2013, Sharjah, UAE. Paper No. MESAT-039.

The Public Works Authority (Ashghal), The State of Qatar. Available from: http://www.ashghal.gov.qa/Arabic/Ashghal/News/Pages/ [Accessed 1 June 2012, created 30 April 2012].

Timm, D.H. and Newcomb, D.E., 2006. Perpetual pavement design for flexible pavements in the US. *International Journal of Pavement Engineering*, 7 (2), 111–119.

Timm, D. and Priest, A., 2006. Year of the pavement. *Roads & Bridges*, 44 (9), 38–41.