Investigation of Using Concrete Pavements in Developing Countries: A Case Study for Conditions of Khartoum State in Sudan

Galal Ali, Noha Akasha
[1] School of Civil Engineering, Sudan University of Science & Technology (SUST), Khartoum, Sudan
E-mail: ga03ali@yahoo.com

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***ABSTRACT* -** Recent years have witnessed several advances in pavement industry, such as superpave and asphalt-rubber mix-design, mechanistic-empirical design and pavement recycling. Nevertheless, development is lacking search for feasibility of using concrete pavements in developing countries, while cities are seeking improvements in terms of reduced life-cycle cost, shorter construction period and less disruption of activities. This is in contrast to flexible-pavement poor performance with frequent premature failure and ever-increasing utility cuts. Although some doubts exist regarding their economics under certain conditions, those countries predominantly use flexible pavements. It appears then the cost factor is the main reason for this preference although the most two crucial parameters that govern the design of both asphalt and plain-jointed concrete pavements are soil subgrade strength and the design traffic. This paper applied popular design methods for both pavement types to compare construction and maintenance costs of typical sections over a length of one kilometer. It was found that there was difference in the respective costs justifying that it is economically viable to use rigid pavements for urban roads.

Keywords - Asphalt and concrete pavements; pavement design and performance; cost analysis and comparison.

المستخلص - هنالك شواهد فى السنوات الأخيرة عن عدة تطورات فى مجال صناعة رصف الطرق تشمل الخلطة الأسفلتية المحسنة واستخدام السيوبربيف، وإعادة استخدام مواد الرصف وتطبيق النظم العلمية الميكانيكية فى تصميم طبقات الرصف. وعلى الرغم من ذلك، لم يشمل التطور فى البحث العلمى امكانية استخدام الرصف الخرصانى فى الدول النامية، فى الوقت الذى تبحث فيه المدن عن تقليل التكلفة الكلية والفترة الزمنية للتشييد وتكرار القطوعات. و فى المقابل، هنالك الأداء غير المرضى للرصف المرن وانهياره قبل أوانه والقطوعات المتكررة التى يتعرض لها الرصف لتوصيل الخدمات. وعلى الرغم من الشكوك حول أفضلية الرصف الصلب للنواحى الإقتصادية، إلا أن هذه الدول تستخدم الطرق الأسفلتية بصفة دائمة. ومن هنا يبدو أن عنصر التكلفة يرجح كفة تبنى الرصف المرن بالرغم من أن أهم مداخل التصميم الأساسية لنوعى الرصف هى مقاومة طبقة التأسيس وحجم المرور التصميمى. وتهدف هذه الورقة إلى تصميم النوعين من الرصف بأحدث الوسائل التصميمية، ثم مقارنة تكلفة التشييد والصيانة لمقطع مماثل بطول واحد كيلومتر لكل رصف. وتوصل البحث إلى أن الرصف الخرصانى أقل تكلفة مما يدل على توفر الجدوى الإقتصادية لتبنى الرصف الصلب فى الطرق الحضرية.

INTRODUCTION

The two most important factors that govern pavement design are soil sub-grade strength and traffic loading [1,2]. Both the subgrade soil strength and the design traffic affect the layer thicknesses of flexible as well as rigid pavements. The Indian Road Congress Guidelines IRC: 37 – 2001 [3] uses CBR for sub-grade soil strength for flexible pavement design, whereas AASHTO [4] employed resilient modulus (M_R) since 1986 Design Guide and 1993 thereafter. On the other hand, both IRC: 58 – 2002 [5] and AASHTO use the modulus of subgrade reaction (k) for subgrade strength. In the design of flexible pavements, traffic load is expressed in terms of million Equivalent Single Axle Loads (ESALs); whereas it is expressed as axle load distribution (ALD) for designing rigid pavements [4,6].

The fact that the subgrade CBR or M_R can be converted to k and the ESALs into ALD makes it possible to design the two types of pavements, flexible and rigid for similar soil and traffic conditions using appropriately related, different methods. Costs are then compared in order to investigate the feasibility of using concrete pavements on a large scale [6]. Such a study can be justified by the facts that cities are seeking improvements, reduced life cycle cost, shorter construction periods, less disruption to traffic, residents and business, and safe and manageable field activities. Additionally, utility cuts, a major concern, are becoming more frequent and increasing in number. Furthermore, poor performance is getting difficult to manage.

With its unique geographical situation in Africa surrounded by eight countries (Egypt, Libya, Chad, Congo, South Sudan, Ethiopia, Eretria and Somalia), Sudan has the advantages rarely found elsewhere, qualifying it to be the link among the African countries, particularly through the Intercontinental African Highway (Figure 1).

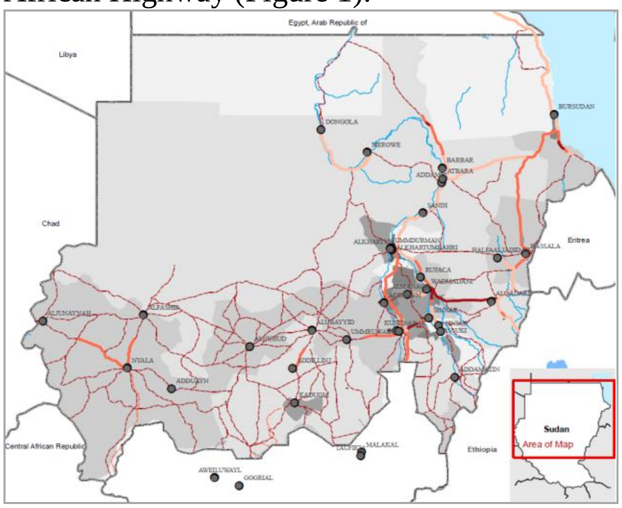


Figure 1: Sudan Road Network

MATERIALS AND METHODS

Pavement Construction Materials

Several different materials are used in the construction of each of the two pavement types. They differ in cost, quality, sustainability and environmentally friendliness, etc.

Asphalt Materials

The road industry in Sudan costs relatively high compared to several other countries, mainly due to using hot mix asphalt (HMA) for flexible pavement surface layer. All asphalt materials used in road construction are imported costing the country excessive foreign currency. The high cost of importing bitumen amounting to one thousand US dollars per ton, and the lack of paved roads for most parts of the largest country in Africa (Figure 1) led to spending huge sums of scarce resources of foreign currency. The change in climate with rising temperatures further results in adverse effects on flexible pavements manifesting distresses and surface defects, even on newly constructed roads. This situation led to considering paving alternatives in view of the current expansion in cement industry leading to possible adoption of rigid pavements Sudan.

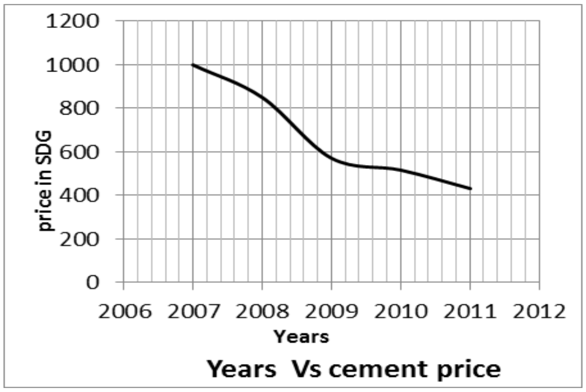
The Cement Industry in Sudan

Portland cement is made up of lime, iron, silica, and alumina. These materials are broken down, blended in the proper proportions, and then heated in a furnace at a high temperature to form“clinker.” when cooled and pulverized, the clinker, is ready for use as “Portland” cement”. By varying the materials used in cement production as well as the fineness of grinding, different cement types are produced.

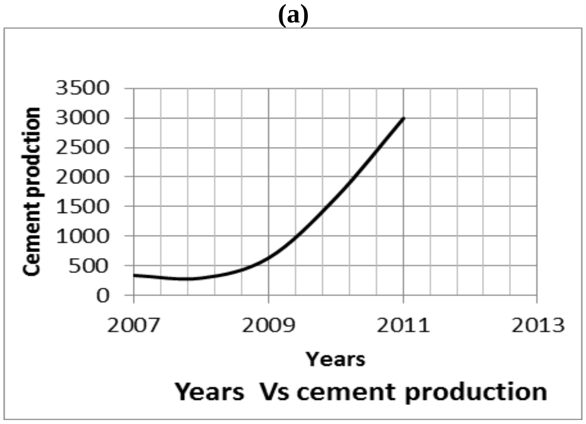
The main reasons for the development of the Portland cement industry are the abundant availability of lime stone, the main raw material, in many areas in Sudan especially in the River Nile State. The recent rapid expansion of development projects led to increase in investment in cement Industry from only 2 factories in early 70’s to 8 now with more new factories under development and construction. Table 1 and Figure 2 reflect the development of the cement industry, exhibiting increase in production with decrease in price.

Concrete Pavement Materials

Concrete is composed of coarse aggregate (crushed stone and gravel), fine aggregate such as sand, Portland cement and water. The concrete can be modified in a number of ways, including the addition of cementitious materials other than Portland cement, or through the use of admixtures, which are materials that are added to the mixture to enhance the properties of the fresh or hardened concrete, such as accelerating or retarding the rate of setting.



(a)



(b)

Figure 2: Increase in cement production with price decease (a) Price in SDG, (b) Cement production.

The most common cement type employed in rigid pavement construction in the United States is Type I, although Type III cement is gaining more widespread use, particularly in applications where high early strength is needed.

Why concrete is the best pavement choice?

Concrete pavements are by far the best long-term value because of their longer life expectancies it can be designed to last 40 years and more. Thus making concrete the best long-term pavement solution together with durability and minimal maintenance, The rigidity of concrete pavements allows them to keep their smooth riding surface long after construction, Concrete does not rut, so there is no hydroplaning and stress on an automobile's steering system, Concrete reflects 33 to 50 percent more light than asphalt, especially important for driving safely at night and can save on street lighting costs, Concrete actually gets stronger over time.

After its first month in place, concrete continues to slowly gain ten percent strength during its life, more durable and can best withstand the heaviest traffic loads. The durability of concrete minimizes the need for extensive repairs or annual maintenance. Therefore, less time is lost in traffic jams caused by road repairs. When repairs are necessary, they are typically smaller in scope than asphalt, Restoration techniques can extend the life of concrete pavements up to nine times their original design life. Concrete pavement can be built and open to traffic in as little as 12 hours

Aggregates for Pavements

In concrete, aggregate (rocks and minerals) is the filler held together by the cement paste. Aggregate forms the bulk of the concrete system they play a very important role in concrete pavements in addition to the usual skeletal function they perform in all concrete aggregate strongly influences concrete’s fresh properties (particularly workability) and long-term durability, Well-graded aggregate (wide range of aggregate sizes) has less space between aggregate particles that will be filled with the more chemically reactive cement paste.

It also contributes to achieving a workable mix with a minimum amount of water. Many kinds of aggregate can be used, but granite and limestone are common in concrete pavements. The cost of flexible pavement construction is high in some areas of Sudan, such as Aljazeera, White Nile and the Upper Nile states due to scarcity of query sources for crushed stone and hence long haulage of stone over long distances. However, the availability of natural aggregate in many areas of the country gives preference to using rigid pavement which can be constructed with natural aggregate which is generally considered the most cost effective in concrete mixes.

There are many type of rigid pavement Jointed plain concrete pavement (JPCP), Jointed reinforced concrete pavement (JRCP) and continuously reinforced concrete pavement (CRCP). Jointed plain concrete pavement (JPCP) is the most common type of rigid pavement made up of coarse and fine aggregates. Since aggregates make up between 60 and 75 percent of the total volume of a concrete mix [7], the properties of the aggregate significantly affect durability and performance of jointed plain concrete pavements (JPCPs).

Concrete Recycling and Recovery

Concrete pavement recycling is a relatively simple process that involves breaking, removing and crushing hardened concrete from an acceptable concrete pavement source to produce Recycled concrete aggregate (RCA) Concrete recycling has been used extensively in Europe since the 1940's and in the U.S. since the 1970's (NHI1998). The availability of demolished concrete for use as recycled concrete aggregate (RCA) is increasing. Using the waste concrete as RCA conserves virgin aggregate, reduces the impact on landfills, decreases energy consumption and can provide cost savings.

The primary applications of RCA have been as base and subbase materials, but it also has been used in concrete and asphalt paving layers, high-value "rip-rap" embankment, and other applications. Concrete pavements being 100% recyclable, concrete recycling for paving applications is now performed in at least 41 states in USA. The process has the support of the Federal Highway Administration which states that reusing the materials already used to build the original highway system makes sound economic, environmental, and engineering sense. It is estimated that about 25 billion tons of concrete are manufactured globally every year. This means about 6.4 million truckloads a day or over 3.8 tons per person worldwide each year. Twice as much concrete is used in construction around the world than the total of all other building materials. Concrete is the second most consumed material after water.

It is estimated that in 2006 between 21 and 31billion tons of concrete, containing 2.54 billion tons of cement, were consumed globally compared to less than 2to 2.5 billion tons of concrete in 1950 including 200 million tons of cement [7]. China and India alone produce and use over 50% of the world's concrete. Many countries have recycling schemes for construction and demolition waste (C&DW).concrete with very high levels of recovery being achieved in countries such as Japan and several European countries. Recovered concrete from C&DW can be crushed and used as aggregate, road subbase being the predominant use in addition to new concrete. Over 125 million tones are generated each year in the developed world. Some key benefits of concrete recycling include reduction of waste, substitution for virgin resources and reduction in associated environmental costs of natural resource exploitation, reduced transportation costs, and employment opportunities.

Pavement Design Methods Selected

The TRL Design Method

The Transport Research Laboratory (TRL) design method is the dominating design procedure for most of Sudan roads with using subgrade CBR values and traffic (ESALs) as the main design parameters in spite of its empirical nature (Design Catalogue). The detailed methodology can be found elsewhere (8). The range of the design parameters used are shown in Table 2. Recently, the AASHTO and Asphalt Institute methods were introduced for flexible pavement [4,9], while AASHTO and the Portland Cement Association methods were preferred for rigid pavements [1,10]. In this paper, the average design of asphalt pavement was obtained for cost computations using TRL and AASHTO methods, whereas the PCA method was applied to design concrete pavement.

The AASHTO method

In recent years some highways in Sudan were designed by AASHTO procedure [4] which accounts for more design factors that affect pavement performance. The design equation modified for subgrade and environmental conditions is given in Eq. (1),

$$\log W_{18} = Z_R S_0 + 9.36\log(SN+1) - .2 + \frac{\log\left[\frac{\Delta PSI}{4.2-1.5}\right]}{0.4+1094/(SN+1)^{5.19}} + 2.32\log M_R - 8.07 \quad (1)$$

In which W_{18} is the number of 18-kip (80-kN) single-axle load applications to time *t*, *p*is the terminal serviceability index and M_R is the effective roadbed soil resilient modulus. Taking local precipitation and drainage conditions into account, structural number SN of pavement is given as

$$SN = a_1D_1 + a_2D_2m2 + a_3D_3m_3 \quad (2)$$

Where a_1, a_2, and a_3 are layer coefficients for the surface, base and subbase, respectively, andD_1, D2, and$D_3$are the thicknesses of the surface, base and subbase, respectively. The values of a_2 and a_3 are related to elastic moduli E_2 and E_3 by Eqns. (3) and (4), respectively.

$$a_2 = .249(\log E_2) - 0.977 \quad (3)$$

$$a_3 = 0.227(\log E_3) - 0.839 \quad (4)$$

With reference to Eqn (2) above, the layer coefficients a_1 a_2 and a_3 are used to determine the layer thicknesses D_1, $D_2$and D_3 of the respective layers knowing the structural number SN from Eqn (2) or the corresponding monograph (4) and the .drainage coefficients $m_2$and m_3 of the base and subbase courses, respectively. The basic procedure: includes the following steps:

- Determine the design traffic (ESAL)
- Compute the effective subgrade modulus (M_R)
- Select the performance level (ΔPSI)
- Solve for the SN required to protect the underlying layer
- Design the pavement thickness applying Eqn (2)

Rigid Pavement Design Methodology

The Portland Cement Association's (PCA's) thickness-design procedure for concrete pavement was published in 1984, superseding that of 1966. The method can be applied to jointed plain concrete pavement (JPCP), jointed reinforced concrete pavement (JRCP), and continuously reinforced concrete pavement (CRCP). A finite element computer program called JSLAB (1, 10) was employed to compute the critical stresses and deflections which were then used in conjunction with specified design criteria to develop the design tables and charts. The design criteria are based on pavement performance, and research experience, including relationships to faulting and performance of pavements in the AASHO Road Test. The design can be worked out manually using tables and charts or by a microcomputer program available from PCA.

The design criteria in the new design procedure include erosion analysis, in addition to fatigue. Fatigue analysis recognizes that pavements can fail by concrete fatigue. In erosion analysis, pavements fail by pumping, erosion of foundation, and /or faulting.

Depending on whether doweled joints and concrete shoulders are to be used, the design thicknesses governed by the following four major design factors:

1. Concrete modulus of rupture, MR
2. Subgrade and subbase support,
3. Design period, and
4. Traffic.

RESULTS AND DISCUSSION

Cost Comparison between Rigid and Flexible Pavements

Scope and Main Objectives

The process of comparing costs was a major objective of undertaking this study in an attempt to determine the economic feasibility of using rigid pavement by comparing its cost with that of flexible pavement. As indicated before, TRL and AASHTO methods were used to design flexible pavement, while the concrete pavement was designed by the PCA method. The available soil strength parameter in terms of CBR and the corresponding values for k and MR were used.

An Application of using Rigid Pavement in Sudan

A private Contractor has been working in the industry of exploration, development, production and transportation of crude oil located in a total concession area of 72,420 sq km. The field is in a swampy area of expansive soil with high plasticity resulting high cost of construction cost for the oil field infrastructure including roads and pad well foundation. The following difficulties and problems were encountered in the construction of asphalt pavement:

1. In addition to crushing plant which was installed as the unique source at a distance of 150 km from construction site, the special equipment consisting of plant, distributor tanker, asphalt paver and compaction machinery for the surface layer of HMA needed to be mobilized. The cost of mobilization of such equipment through very swampy track would be very high to construct small internal road system.
2. If the road were to be constructed in the oil field where the pavement would be subjected to spoiling of a variety of hydrocarbon materials within the carriageway thereby damaging the surface layer.

3- More skilled labor would be needed in addition to the normal labor working in concrete works.

Because of the above conditions and construction problems, the design development engineer modified the road design to rigid pavement by using concrete for surface course as in Figure 3.

Figure 3: SUDAN Rigid-pavement trials

Detailed Cost Analysis and Comparison

After the pavement crosssections were determined from the design phase, the costs for construction of one km of fleaxible and rigid pavements were computed using 2011 prices.. Eight levels of design traffic ranging from $0.3*10^6$ to $30*10^6$ ESALs were used; 6 CBR values varied between 2 and 30 making a total of 48 combinations.

The results of cost computations for 48 different combinations of traffic level and subgrade soil strengrh are presented in Table 3. However, only 4 levels of traffic (07, 3.0, 10 and $30*10^6$) are shown in the table for clarity. For discussion purposes, the results of Table 4 are further reduced to Low and High CBR and Low, Medium and High traffic (Table 5). Examination and analysis of the results presented in Figures 4 to 7 reveal that the difference in cost between rigid and flexible pavements is in favor of concrete ranging from 14.4% at low traffic and high strength to a maximum of 55.5 % at low strength and high traffic.

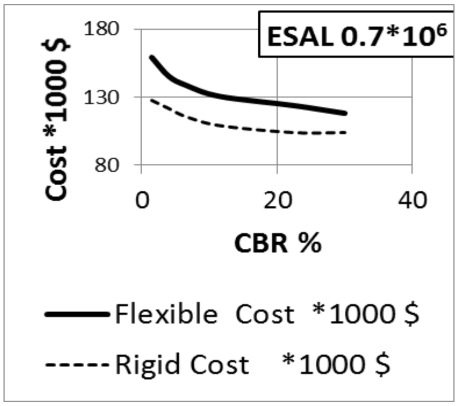


Figure 4: Variation of cost vs. CBR at 0.7*106 ESALs

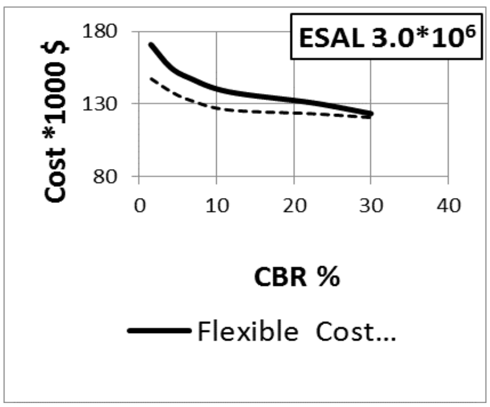


Figure 5: Variation of cost vs. CBR at 3*106ESALs

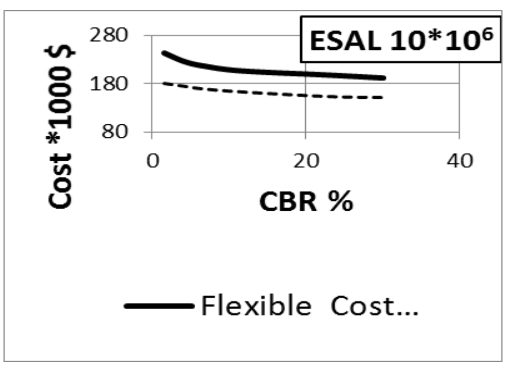


Figure 6: Variation of cost vs. CBR at 30*106 ESALs

Studies in India [2] and Turkey [11] reported comparable results. Thus, it can be seen that concrete pavement may cost as low as half of flexible pavement at certain combinations of design factors.

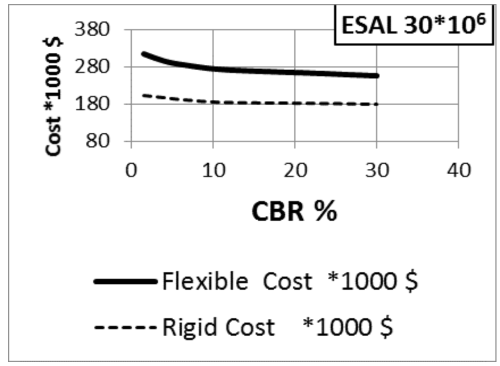


Figure 7: Variation of cost vs. CBR at 10*106 ESALs

This is due to the nature and characteristics of the respective construction materials used in each case, respectively. Concrete can withstand heavy traffic while not being much affected by week foundation. On the other hand, asphalt pavements require strong subgrade to resist heavy traffic and reflect good performance. The fact that base and sub-base courses are rarely used in concrete pavements gives additional preference to rigid pavement regarding construction cost. Furthermore, the design life for concrete pavement could be 1.5 times to twice longer than that of flexible pavement thereby providing lower life-cycle cost.

SUMMARY AND CONCLUSIONS

In this paper the following design methods were presented and applied: TRL and AASHTO for asphalt pavement, while the PCA was adopted for concrete pavement. Having developed the structural designs of both pavement types under similar traffic and subgrade strength conditions, a thorough analysis of economic feasibility study was carried out. The following conclusions and recommendations pertain within the scope of this research:

1. Using rigid pavement reduces construction costs by 10 to 35 percentage depending on subgrade strength and ESAL compared to flexible pavement which is the dominating pavement type commonly adopted in Sudan.
2. The natural ground in most residential areas targeted with road projects is black cotton

soil with high plasticity. Considering the factor of cost for comparison between flexible and rigid pavement, it was shown that using rigid pavement would reduce the overall construction cost.

3. The availability of natural aggregate (gravel and sand) in many areas in the country will further reduce the cost of pavement compared to flexible pavements due to their suitability for use in rigid pavement. On the other hand, for asphalt pavement, which uses crushed aggregate, quarry must be sought for sources suitable for production of crushed stone.
4. With the availability of concrete construction equipment such as concrete plant, concrete pump and trans-mixer, only a few specific equipment in road paving needs to be provided for the application of rigid pavement in Sudan.

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Table 1: Annual Increase in cement production with decease in price

No.	Year	Price in SDG* per ton	The production
1	2007	1000	328.779
2	2008	850	282.188
3	2009	570	624.506
4	2010	515	1646.365
5	2011	430	2987.216

***Sudanese Ginaih (SDG) ~ 6 US$**

Table 2: TRL Method (Road Note No. 31)

(a) ESAL factors Equivalence factors for different loads

Wheel load(single & dual) (10^3kg)	Axle load (10^3kg)	Equivalence factor
1.5	3	0.01
2	4	0.04
2.5	5	0.11
3	6	0.25
3.5	7	0.50
4	8	0.91
4.5	9	1.55
5	10	2.50
5.5	11	3.83
6	12	5.67
6.5	13	8.13
7	14	11.30
7.5	15	15.5
8	16	20.7
8.5	17	27.2
9	18	35.2
9.5	19	44.9
10	20	58.5

(b) Traffic classes and ESAL (esa)

Case	13	14	15	16	17	18	19	20	21	22	23	24
ESAL *106	10	10	10	10	10	10	30	30	30	30	30	30
CBR, %	2	4	7	12	23	30	2	4	7	12	23	30
Modified k, pci	81	158	193	210	275	333	81	158	193	210	275	333
Flexible Cost *1000 $	244	227	217	207	198	192	314	294	284	271	262	255
Rigid Cost *1000 $	181	175	170	163	153	151	202	196	190	183	181	178

(c) Classes of subgrade strength

Traffic classes	
Traffic classes	Range (106esa)
T1	< 0.3
T2	0.3-0.7
T3	0.7-1.5
T4	1.5-3.0
T5	3.0-6.0
T6	6.0-10
T7	10-17
T8	17-30

Table 3: Cost of flexible and rigid pavements for different soil strength and traffic

Subgrade strength classes	
classes	**Range (CBR٪)**
S_1	**2.0**
S_2	**3.0-4.0**
S_3	**5.0-7.0**
S_4	**8.0-14**
S_5	**15-29**
S_6	**30**

Table 4: Continued. Cost of flexible and rigid pavements for different soil strength and traffic

Case	1	2	3	4	5	6	7	8	9	10	11	12
ESAL $*10^6$	0.7	0.7	0.7	0.7	0.7	0.7	3.0	3.0	3.0	3.0	3.0	3.0
CBR %	2	4	7	12	23	30	2	4	7	12	23	30
Modified k	81	158	193	210	275	333	81	158	193	210	275	333
Flexible Cost *1000 $	159	146	139	131	124	119	171	155	148	138	131	123
Rigid Cost *1000 $	128	122	116	109	104	104	147	139	133	126	123	121

Table 5: Cost and % difference of flexible and rigid pavements At low-high CBR and low-med-high traffic (*US $1000)

ESAL	Low ($0.7*10^6$)	Med ($10*10^6$)	High ($30*10^6$)
Low Subgrade Strength (CBR = 2)			
Rigid Pavt Cost	128	181	202
Flex Pavt Cost	159	244	314
% FP Increase in Cost	28	34.8	55.5
High Subgrade Strength (CBR = 30)			
Rigid Pavt Cost	104	151	178
Flex Pavt Cost	119	192	255
Increase in Flex Pavt Cost, %	14.4	27.2	43.3