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Viability of Concrete Pavement in Bhutan: A Review

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Abstract: The coverage, standard and the state of the road infrastructure of a country has a direct and significant bearing on the health of its economy. The choice of materials to be used for the various components in a road pavement is among the various crucial aspect of planning and design for a safe, comfortable and durable road network system. Road pavement surfaces are typically of two kinds, the all too familiar bitumen (asphalt) based surface known as the flexible pavement and the cement concrete-based surface known as rigid pavement. This review has shown that the rigid pavement roads are economical than flexible pavement over the course of the road's design life and more so when the roads are to be built over very weak underlying soil (sub- grade) condition under higher traffic loads.

Keywords: Viability, concrete pavement, economic benefit, LCCA

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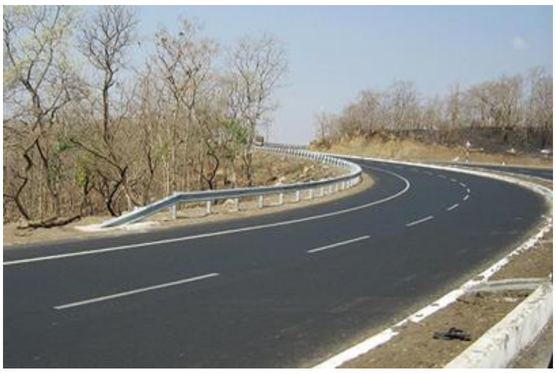
Introduction

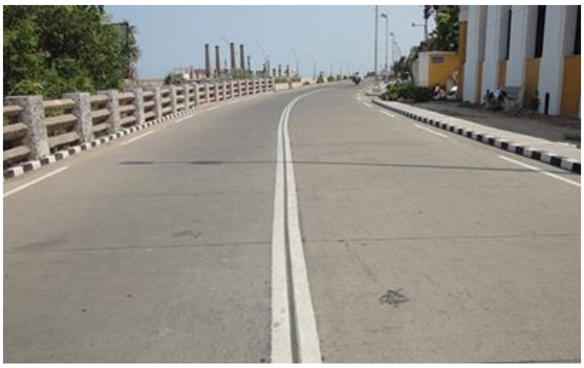
Rigid pavement road concept and construction is a recent phenomenon in Bhutan. Apart from the few isolated cases of trial stretches of few kilometers being built at Yotongla on the East West national highway and at Nanglam, the viability and the potential of the technology is yet to be explored and tapped in an earnest and concerted manner in Bhutan. Recent improvement in the design, construction and maintenance techniques have led to the rigid pavement being just as economical and under some conditions even more economical than flexible pavement. The use of rigid pavement in our road construction seems to bear multiple positive impacts in Bhutan. Our country, at present, is presented with the best circumstantial opportunity from both the demand and supply side of the equation to explore the viability of the rigid pavement as a potential option in the construction, maintenance and up gradation of our roads. On the demand front, with only 30% of the total road length of approximately 12,000 km with paved/ sealed surfaces (NTP, 2017), there is almost around 8400 km of road still to be provided with the pavement surface layer at present. A standard rigid pavement construction for this work would require around 41.58 million tons of cement. The amount of surfacing work required is only bound to rise by manifolds considering the volume of new road works envisaged in the country's Transport 2040 integrated strategic vision document. On the supply side, a key ingredient in rigid pavement construction is cement. There are several well-established states of the art high-capacity cement producing plants in the country. Considering that Dungsam Cement Corporation Limited (DCCL), one such industry alone has a production capacity of 1.36 million tons of cement per annum presents a very promising and exciting prospect. The construction of flexible pavement requires the use of bitumen as a primary material. Just in the year 2017 our country has imported 5617.706 tons of bitumen and bituminous based material worth around Nu 62.9 million (BTS, 2017). Given all the seeming benefits and the opportune timing, Druk Holding and Investment (DHI) in partnership with the College of Science and Technology (CST) and Department of Roads (DOR) has collaborated to undertake a joint project to assess and prepare a report on the viability of the rigid pavement for the roads in our country under various feasibility conditions.

The Road Pavement

Flexible and rigid pavements are typically laid for roads and are most common. A flexible pavement comprises of properly heated, mixed and compacted layers of a bitumen and mixture of aggregates laid on a bed of granular layer resting on the prepared natural soil base known as the "subgrade". In country, rigid pavement are composed of cement concrete or reinforced concrete slab which is laid on dry lean concrete (DLC) base or soil sub-grade that is well compacted as per the specification. In some cases, both the layers are required when the strength of the sub-base is very low. Sub-base, base course and bituminous surface layer forms the overall thickness of the pavement. Usually, top surface layers are composed of one or more layers call Dense Bituminous Macadam (DBM) and Asphalt Concrete AC) (Figure 1a). This pavement type is flexible to undergo deformation under traffic load as it possesses negligible flexure strength. The combined additive forces of internal grains in the granular materials substantiate the overall structural capacity of this pavement.



(**a**)



(**b**)

Figure 1. Types of road pavement (**a**) Flexible pavement-asphalt concrete; (**b**) Rigid pavement-cement concrete (Picture courtesy: www.nbmcw.com)

The traffic loads get disseminated (e.g., like truncated cone) through the layers of the base, sub base, sub grade courses, and then ultimately to the ground. Since the stress induced by traffic loading is highest at the top, the top surface layer should be of the highest quality. The sub grade layer is responsible for transferring the load from the above layers to the ground. Thickness of the flexible pavements' layers are designed in such a way that the load that reaches the sub grade does not exceed the bearing capacity of the sub grade soil. Based on the strength of the sub-surface soil and the traffic load in consideration, the thickness of the pavement is estimated.

Rigid pavements (Figure 1b) are so named because of the high flexural rigidity of the concrete slab. The pavement structure deflects very little under traffic loads due to the high modulus of elasticity of concrete slab. The concrete slab acts like a rigid plate/slab resting on a flexible base. In rigid pavement, the depth of the bearing slab and the number of the pavement layers can be minimized or optimized because of its high flexural strength which is capable of distributing traffic loads to a large area. At joints, dowel and tie bars are mostly employed. A smooth reinforcing bars that runs in transverse direction are called dowel bars which functions as mechanical connection and transfers the load between the slab. This provision restricts the horizontal movement of the slab panels. On the other hand, tie bars which are normally deformed steel bars are used in longitudinal direction and holds the faces of abutting slabs that are in contact. With the minimal load transfer that happen through the tie bars, they are not designed to act as load transfer devices and are simply used to 'tie' the two concrete slabs together. The key difference between the two pavements is presented in Table 1.

Table 1. The key differences between the two pavements (Courtesy: www.theconstructor.org)

Features	**Rigid Pavement**	**Flexible pavement**
Composition	Consist of one layer of cement concrete slab (Usually OPC)	Consist of series of layers of bitumen aggregate mix and granular material with the highest quality material at the surface
Surface Deformation	Rigid and able to bridge over localized failure and area of inadequate support	Flexible and reflects the deformation of the sub grade and subsequent layers and deformation
Source of Strength	Strength provided by the slab through beam action	Strength provided by aggregate interlock and particle friction and cohesion
Key Design Parameter	Flexural strength of concrete Fatigue life of Concrete Modulus of sub grade reaction	Soil Sub grade Strength CRB value of Sub grade
Effect of Temperature	Temperature variation induces high stresses	No additional stress induced
Service Life	30-40 years	10 - 15 years

The Review

Sound and Noise

Traffic noise pollution has become a growing problem which effect the human phycology and living environment (Li et al., 2016). Tires of heavy vehicle that have distinct blocks and gaps which is usually called the tread pattern exhibits louder noises compared to small passenger cars (Ramussen et al., 2007). Tire-pavement noise, which is dominant contributor of overall noise emitted as a result of the interaction of tires and the pavement surface (Sirin, 2016). Porous asphalt concrete of one or more layers pavements has been shown to improve the noise reduction capability (Meiarashi & Ishida, 1996); (Sandberg, 1999); (Nelson et al., 2008). According to (Donavan & Rymer, 2003) such porosity provide a 5 to 10 dB reduction in tire or pavement noise over conventional surfaces of various types. Also, the noise level can be reduced to 2 to 3 dBA by addition of rubber (Tehrani, 2015). Primarily, noise level is highly dependent on porosity, thickness, gradation and texture of the pavement surface (Abo-qudais, 2004); (Hanson et al., 2004); (Parnell & Samuels, 2006); (Cackler et al., 2006); (Rasmussen & Sohaney, 2012); (Rochat & Read, 2013). We conclude from this review that concrete pavement produces more noise than the asphalt pavements. For highways with noise issues, diamond ground surfaces are the solution of choice for producing quiet concrete pavements with less expenses (Bennert et al., 2005).

Business and Cost Parameter

We present economic viability of the rigid pavement in comparison to flexible in this section. The cost of the pavement grossly depends on soil condition or strength of the subgrade expressed in terms of California Bearing Ratio (CBR), traffic load and fuel cost among others. Study indicates that no significant variation in the thickness of the rigid pavement with increase in the value of CBR, while cost of flexible pavement decreased with increase in the value of CBR but the cost of flexible pavement increases with increase in traffic (Jain et al., 2013); (Naik & Sachdeva, 2017). Construction cost for flexible pavements is cheaper than rigid pavements, however with the strength increase in subgrade the asphalt pavement costs and rigid pavement costs get closer and with the increase in the fuel prices, the cost of asphalt pavements will be even higher (Akakin et al., 2013). The fuel cost saving for passenger car on concrete pavement is 3.2% less than on flexible pavement (Bienvenu & Jiao, 2013).

The findings from a study (Satish Chandra, 2017) on cost comparison conducted in India on a 1.0 km stretch of some 90 pavements for a two-lane road with 7.0 m carriageway and 1.5 m wide shoulders on either side on varying values of soil sub grade CBR and design traffic load is discussed here. The soil sub grade CBR ranges from 2 percent to 10 percent and design traffic range from 1 msa to 150 msa was considered in the study. The points of equal cost on the CBR vs msa graph is plotted (Figure 2) to infer the condition for equal cost for the two pavements. In upper portion of the plot, the rigid pavements are inclined more towards economic zone against the flexible pavements at the lower portion of the graph.

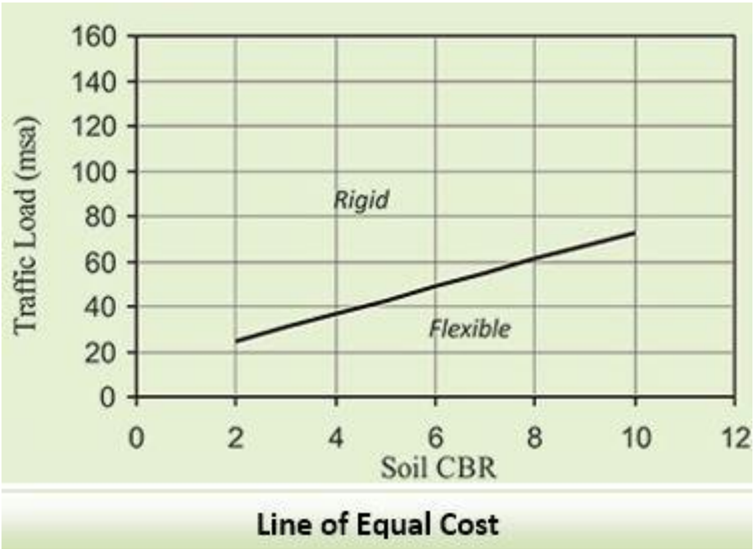


Figure 2. Line of equal cost for flexible and rigid pavements ((Satish Chandra, 2017)

Rigid pavement is more economical for areas with lower soil strength and higher traffic load is anticipated and Flexible pavement in areas with better soil condition and lower traffic volumes. Most study reveal similar observation. There is a need for a proper comparative study based on relevant design parameters to determine the better choice. The following equations captures the impact on cost of varying CRB and traffic values.

$$\mathrm{Cost} = -16.98 + (12.136 x CBR^{-0.3}) + (15.476 x msa^{0.10)} \quad (1)$$

$$\mathrm{Cost} = 8.284 + (4.719 x CBR^{0.9}) + (20.83 x msa^{0.15}) \quad (2)$$

For (msa < 12.48 + 6.05 x CBR); the flexible pavements are more economical

For (msa > 12.48 + 6.05 x CBR); the rigid pavements are more economical

For (msa = 12.48 + 6.05 x CBR); Both the pavements have equivalent cost

Initial cost of rigid pavement is usually more than twice the flexible pavement, however, due to lesser repair maintenance cost, a cost of $105,526.13 USD per kilometer will be saved for an analysis period of 40 years (Ketema et al., 2016) with economical finding during the service life of rigid pavement by (Khurshid et al., 2008); (Jain et al., 2013); (Taher et al., 2020) and reported economically sustainable (Moretti et al., 2012). Life Cycle Cost Analysis (LCCA) also show economical benefit of rigid pavement (Crarnecki et al., 2017); (Babashamsi et al., 2016) with some finding up to 38% (Hamim et al., 2020) to 55% (Ashok & Ashwini, 2017). Also, LCCA show concrete pavement most sustainable and preferable alternatives in terms of reducing negative environmental impact, economic and social impact as well (CCAA, 2010); (Choi et al., 2016). In Bangladesh, it is found evident that 1km of flexible pavement costs 3 times to 1km rigid pavement in 20-year Life Cycle (Ur, 2015). A study conducted by (Abbasianjahromi et al., 2020) mentions that the economic risk are lower for concrete pavement due to high probability of change in fuel price.

Impact, Smoothness and Comfort

Impact of vehicles on rigid pavement mainly focuses on the performance and lifespan of rigid pavements. The performance can be affected by farm equipment's (S. Wang et al., 2012), dynamic loading (Stoner et al., 1990); (Izquierdo et al., 1997), and variation in velocity (Darestani et al., 2006). Dynamic wheel loading can cause more stress in corner. The highest stress occurred on the transverse and longitudinal edges of the slab using the design axle and an axle with the maximum allowed weight. The most unfavorable effect caused by stress in the middle of the slab was from the non-standard axle with stress achieving a value of 23.32% higher than the stresses from the design axle (Bartosova, 2002). Precaution needs to be taken to design the corner section in order to achieve zero maintenance pavement. Subbase erosion phenomenon is more pronounced relating to deflection and subsequent distresses in concrete pavement under dynamic loadings (Stoner et al., 1990); and modelling of dynamic vehicle loads is recommended (Stoner et al., 1990); (Gillespie et al., 1992).

Standard tool for evaluating the pavement roughness is scaled with reference to International Roughness Index (IRI) which defines ride comfort and IRI (Cackler et al., 2006); (Izevbekhai et al., 2007) (Chen et al., 2020). In some studies, threshold value of 4.50 m/km was indicative to achieve smoothness of the pavement (Chen et al., 2020). According to (F. Wang & Easa, 2016), ride comfort primarily related to weighted root mean square of acceleration (a_w), weighted value of subjective comfort (C_w), root mean square of successive heartbeat interval differences (RMSSD) which is accounted as function of IRI. The experimental and analytical method indicate comfort ride in light passenger car up to IRI 4.0 mm/m. (Holloway, 1956) recommends the following roughness index based on the research caried out for Indiana concrete pavement for new high type pavement construction as shown in Table 2.

Often some indices such as Ride Number, Michigan Ride Quality Index (RQI), Minnesota Ride Quality Index and frequency-weighted vertical acceleration, a_{wz}, according to

ISO 2631 frequently used to evaluate ride quality level sensed by the users (Loprencipe & Zoccali, 2017). In general, flexible pavement provide smooth riding surface than concrete, however, slip-form paving yielded improved smoothness of the concrete pavement (Rizenbergs et al., 1973). We reviewed that while designing a rigid pavement emphasis should be given on dynamic loading, roughness of the surface, stress distribution especially in the corner section and the type of vehicles.

Table 2. Roughness Index for corresponding riding qualities

Roughness Index (in per mile)	Riding Qualities
Below 75	Good (Acceptable)
75 to 90	Fair (Acceptable)
Above 90	Poor (Not Acceptable)

Quality, best practices in similar climatic conditions and orography

Joints in Jointed Plain Concrete Pavements (JPCP) are the weaker zones that crack during summer due to temperature variation. An option to improvement is to make saw-cuts deeper with Relative Joint Depth (RJD) of 45% for Effective Slab Length (ESL) of 4m with the exception of temperature variation of 2°C with stronger coarse aggregates (Pradena & Houben, 2016). (Mammeri et al., 2015) highlighted that there is a significant impact of different thermal parameters like heat transfer coefficient and thermal conductivity of layers, and daily temperature variation causing thermal cracking of the pavement. Also, studies show temperature effects are largely notable to effect on pavement performance among other climate change parameters (Gudipudi et al., 2017). Review also indicate that temperature difference exceeds the failure load defined by $0.4\times\sqrt{f_{cu}}$ as a result of thermal-expensive stresses and overall, the impacts are severe under climate change projections which increases the likelihood of cracking (Chai et al., 2012). Literatures emphasized that concrete pavements are the best pavements with longer service life, except due to its distress, which are manageable. It was also highlighted that distress are due to traffic and thermal stress. Thus, thermal distress needs to be studied and incorporated in design along with mechanical stresses which are extensively compared and studied (Tayabji, 2010). The safer, smoother and long-lasting pavements widely used in United States with a service life of more than 40 years. Concrete pavement fails over a period of time due to distresses like cracking due to poor design and construction practices, Joint faulting due to load transfer at transverse joints, spalling due to poor joint sawing practices and quality of concrete, Roughness due to other stresses and during construction, surface texture loss due to high volume and speed applications. However, he suggested that the distress developed is manageable by incorporating sound design, durable materials and quality construction practices (Tayabji, 2010) and the threshold value are recommended as presented in Table 3.

Table 3. Recommended threshold values for concrete pavement distresses

Distress	Threshold value
Cracked slabs, % of total slab	10 to 15
Faulting, mm	6 to 7
Smoothness (IRI), m/km	2.5 to 3.0
Spalling (length, severity)	Minimal
Materials related distress	None

Rigid pavement is also susceptible to damage due to frost penetration depth, and the number of freeze/thaw cycles experienced by the pavement apart from pavement's surface temperature. The Freezing index is a common metric for determining the freezing severity of the winter season and estimating frost depth for mid-latitude regions, which is useful for determining the depth of shallow foundation construction (Bilotta et al., 2015).

Most critical failure mode in AASHO (1962) test sections was erosion of subbase or subgrade materials, whereas, the predominant failure modes in many rigid pavements are faulting and fatigue cracking (Highway Research Board, 1962).

Carbon Footprint

With global challenges of climate change and environmental degradation the impact on the environment is also a very crucial parameter to judge a technology's viability. Some key measuring yardsticks are the carbon footprint and the embodied energy (Huang et al., 2016). Like any construction materials, road construction consumes energy (embodied energy) in five phases: a) Manufacturing of construction materials, b) Site preparation; c) construction of roads and transportation, d) Maintenance of road and, e) Energy consumed in demolition and recycling. According to (Associated Schools of Construction, 2018), when 50-year life-cycle GHG production was compared, concrete pavement and asphalt pavement produced approximately 1610 CO_2e tons/km and 500 CO_2e tons/km respectively indicating that for every 1,000 kg of Portland cement, about 730 kg of CO_2 is produced. According to (Espinoza et al., 2019), after an LCCA study, it was determined that the construction of the hot mix asphalt (HMA) layer generates a carbon footprint of 65.8 kg of CO_2e per km of road. Similar studies and review findings are also indicative of high carbon footprint in overall life cycle of concrete pavement construction (Häkkinen & Mäkelä, 1996); (Santero et al., 2010); (Mukherjee & Cass, 2011); (Kar et al., 2015); (Ma et al., 2016); (Zainab Ali Hulail, Afizah Ayob, 2016); (Utomo Dwi Hatmoko et al., 2020); (Singh et al., 2020).

This section a illustrates the study covered by Prof. Satish Chandra, Ph. D. Director, CSIR-Central Road Research Institute, Delhi (https://www.nbmcw.com/) (Satish Chandra, 2017) on the comparative study conducted between two pavements. The study was carried out on a pavement of 1 km stretches with a 7.0 m wide carriageway designed for a sub grade CRB value of 8% and a traffic loading of 100 msa with standard pavement specifications. It revealed that 96 percent of total greenhouse emission for rigid pavement comes from the embodied energy of the material. Substantial amount of energy is consumed during the construction of flexible pavement. Assuming, equivalency in embodied energy of materials like cement and steel bars and considering primary emission during construction, the lower emission is evident for rigid pavement. Considering that the cement is manufactured regardless of whether it is to be used for pavement construction or not in Bhutan, rigid pavement construction will have a lower adverse impact on the environment. However, this is based on data available for the first three phases of the road lifecycle as data on energy consumed for the maintenance and demolition phase were not available. It is vital to analyses the maintenance impact as rigid pavement will require less maintenance than flexible pavement because of their longer service life.

Table 3. Life cycle carbon footprint of pavement per km

Source	**Emission in tons of CO_2 equivalent**	
	Rigid pavement	**Flexible pavement**
Raw material embodied energy	1246.00	95.00
Construction stage	6.60	84.00
Transportation and logistics	46.70	40.70
Maintenance	NA	NA
Demolition/removal	NA	Na
Total	**1299.30**	**219.70**

Conclusion

The design traffic load and the sites subgrade condition govern the choice of a pavement type for any stretch of a road. In cases where the soil sub grade is weak (like clay) and places with heavy precipitation and proper drainage conditions are difficult to maintain, rigid pavement is the better choice. But at sites with good quality soil sub grade and where traffic is also not very heavy, flexible pavements are more economical. Therefore, the assessment of the site CRB value and forecasting of the anticipated traffic volume and load is vital to determine the choice of the two pavements. Considering the CBR value, traffics load and cost, it is indicative that the rigid pavement is more sustainable as compared to flexible pavement due to durability and capacity to take much heavier loads. Project specific comparative cost analysis is also very important as prices of materials and equipment and labor are subject to change based on the prevailing economic condition of the region. However, LCCA through the review indicate sustainability of rigid pavement up to 40 years provided right implementation of technology and quality. To the best of author's knowledge, the topographical condition of a region still remains a challenge. It is important that geometric designs are aligned to the topographical features of the route.

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