Structural Design for Sustainable Pavements

Abstract

Pavement construction is a very energy intensive process, and it results in a significant usage of water, and emission of chemicals in the environment. Maintenance and rehabilitation of pavements also utilize a significant amount of energy, time and natural resources such as aggregate. Therefore, ensuring the durability and good performance of a pavement through proper structural design is a step towards making sustainable pavements. Structural design of pavements has evolved significantly over the years, from purely empirical to mechanistic-empirical, although, in most countries around the world, the empirical design process is followed for the design of asphalt pavements, which constitute the majority of roads in most countries. This is because of the inherent complexities, uncertainties and lack of single unified theories in the case of pavements. Furthermore, because of the variations in climate and types of aggregate and asphalt binder, and possibly type of traffic, across the globe and across large countries, and the dependence of pavement behavior on the climatic conditions, it is not possible to use any specific model for all countries or an entire country. But there is no doubt that a rational structural design procedure is needed in every country to ensure that the design with the optimum combination of performance and impact on the environment is selected. This paper presents the cost and environmental implications of different structural designs, and explores the concept of structural design for sustainable pavements with an example. It is shown that similar design life could be achieved by utilizing different combinations of base/binder and surface courses of a pavement, and the use of composite pavement, with Portland cement concrete and asphalt pavement layers could very well be the most optimum solution in reducing the impact of pavement construction and maintenance on the environment.

Keywords: pavement, sustainable, life cycle, composite

Introduction

The development and proper functioning of a nation depends to a great extent on her road infrastructure. Safe, durable and smooth pavements are the lifelines of a society. However, during the construction and maintenance of roadway pavements man-made material (or processed natural material) is laid down to cover virgin (most likely arable) ground (making it un-arable from that point onwards), a significant amount of natural resources is utilized, (nonrenewable) energy is consumed, landfills are created, and different types of chemicals (in the form of gases) are emitted to the environment (all of these processes are irreversible). Thus, there is a significant environmental impact of pavement construction and maintenance activities on our environment.

The selection of the right type of pavement for a specific project is made primarily on the basis of cost – either initial only or on a life cycle cost basis. Although recycling of pavements has become more and more routine over the years, a comprehensive consideration of different impacts on the environmental and the selection of the alternative with the least environmental impact, has not started in pavement design on a regular basis. Of course, such selection has to be made in conjunction with considerations of cost also.

Pavements can be broadly classified into asphalt (or flexible) and concrete (or rigid) pavements Pavements consist of different layers, more so in the case of asphalt pavements than concrete ones. From the bottom up, these layers are known as the subgrade, subbase, base, and binder and/or surface. There are certain pavements with asphalt surface layers on top of concrete layers. The purpose of a pavement is to ensure that the load is spread out below the tire, such that the resultant stress in the existing soil (which could be stabilized), the subgrade, is low enough so as not to cause damage, in the form of excessive deformation.

Generally several layers are present in an asphalt pavement. From the bottom up, the layers are known as the subgrade, subbase, base, and binder and/or surface. Generally, the bottom most layer is soil; the subbase and/or base layers can be granular soil, or aggregates or asphalt-aggregate mixtures (mixes); and the binder and surface are asphalt mixes. While designing, adequate thickness to each layer is assigned, so as to obtain the desirable properties in the most cost-effective way. Concrete pavement may not have as many layers, and in many cases the concrete slab rests on a stabilized subgrade, which consists of soils modified with some additives.

Although all pavements consist of different types of layers and hence can be called composite, generally the term refers to those pavements, which consist of asphalt mix layer on top of a concrete pavement or a concrete layer on top of another concrete pavement. The concrete part could be Portland cement concrete (PCC), Continuously Reinforced Concrete Pavement (CRCP), Jointed Reinforced Concrete Pavement (JRCP) or roller compacted concrete. For concrete over concrete pavements, generally the lower layers consist of locally available aggregates or recycled concrete while the upper layer (which could be a porous concrete layer) contains high quality smaller size aggregates.

Objective

The objective of this paper is to present the cost and environmental implications of different structural designs of asphalt pavements, and explore the feasibility of structural design for sustainable pavements with examples.

Pavement Layers

Structural design of a pavement is conducted to determine the thickness of the different layers to prevent the occurrence of problems or distresses in the pavement due to traffic loading and the environment. Such distresses may include rutting or depressions in the wheel path and cracking. In an asphalt pavement the surface layer usually consists of the “best” and most costly materials. Also, this layer is always “bound”—that is, mixed with a “binder,” in this case asphalt binder—to prevent raveling of materials under traffic, as well as to provide a dense surface to prevent ingress of water, unless it is an open graded friction course. Therefore, the surface layer has two major components—asphalt binder and aggregates, with relatively small amounts of additive, if any. The mixture of this layer needs to be designed properly to give it adequate stiffness, strength, and durability. This mix is usually prepared by combining hot aggregates and asphalt binder (hot mix asphalt, or HMA).The next layer could be either binder or base. Generally, the binder layer is almost similar to the surface layer, except that it may consist of aggregates of larger size. The base may be made up of a bound layer or an unbound aggregate layer. The base layer has to be sufficiently strong in shear as well as bearing capacity, but need not be as good as the binder and surface course, since the stresses at this level are much lower. However, the base needs to be stiff enough to provide an overall stiffness to the pavement structure such that it does not deflect too much under load.

The function of the subbase is almost similar to that of the base, except that it could be of lower quality materials, since the stress is even less at this level. Generally, it is made up of aggregates only. The sub-base layers also serves as a drainage layer. The subgrade is made up of the existing soil or the soil mixed with some additives to enhance its properties. It serves as the foundation of the pavement and should be of such quality as to resist excessive deflection under load.

The desirable thickness of the layers over the subgrade are determined from the consideration of their stiffness/resistance to deformation properties (such as with the use of the test property California Bearing Ratio, or CBR), as well as the change in the properties that can be expected due to a change in the environmental conditions, primarily moisture and the effect of temperature on moisture. However, note that in a pavement structure, the stress in the subgrade or subbase/base is governed by the imposed stress (vehicle load) as well as the thickness of the layers above them. Therefore, if the subgrade/subbase or base is known to be relatively weak, it should be protected by a proper selection of binder/surface mix and layer thickness. On the other hand, if the base could be made stiffer, then a relatively thin surface layer would suffice. It follows that the structural design process in pavements is an iterative process that balances the availability of materials and the cost of the total pavement structure.

The basic purpose of the structural design process is to combine the different layers in such a way so as to result in the most cost-effective functional pavement structure. This can be achieved by primarily two different techniques: (1) by using empirical methods—that is, charts and equations developed from experimental studies carried out with a set of traffic, environment, and pavements; or (2) by using a mechanistic method, in which concepts of mechanics are used to predict responses and performance of the pavement. Note that a purely mechanistic approach is not possible at this time—the responses can be predicted by employing concepts of mechanics, but the performance has to be predicted by empirical models. Hence, it is more appropriate to say that pavements can be designed either by using the empirical approach or by using the mechanistic-empirical approach (ME). Structural design of concrete pavements is based on the concept of limiting stresses to prevent excessive damage and deterioration of the pavements. Distresses are caused by stresses in rigid pavements. These stresses are imposed by traffic through wheel loads, temperature and moisture variations (causing warping, and expansion and shrinkage stresses), and volume changes in the base and subgrade.

In this paper, analysis and design are presented for asphalt pavements only.

Design criteria

In most mechanistic-empirical design procedures of design of asphalt pavements, the tensile strain at the bottom of the asphalt mix layer and the vertical strain on top of the subgrade are considered as primary responses that lead to fatigue cracking and rutting, respectively. The responses are predicted from layered elastic models, whereas the deterioration models relating life to responses (number of repetitions to failure for a specific strain, for example) are determined from laboratory tests (empirical part) (***1, 2, 3, 4***). Obviously, a suitable structure needs to be designed to prevent both fatigue cracking and rutting, and therefore, in many cases, a design that is ultimately adopted for one mode of failure (say, rutting) is over-conservative for the other (say, fatigue cracking), and hence, the selection of a pavement structure with the least cost and least environmental impact becomes complicated.

An alternative to this approach is the consideration of a single response, the deflection at the surface of a pavement, that could account for both modes of failure (***5, 6***). The benefit is that a pavement structure could be optimized against a single response and then optimized for the reduction of its cost as well as environmental impact. From a practical standpoint, the benefits also include the facts that unlike strains, the surface deflection could be measured relatively easily in the field, and hence the structural condition of a pavement could be determined easily, and relationships between surface deflection and tensile strain/compressive strain could be developed. Considering these advantages, the surface deflection approach has been utilized for analysis in this paper.

Standard and Alternative Pavement Structures

The Indian Road Congress (IRC) (***7***) provides a catalog of standard pavement structures for different combinations of soil stiffness (characterized by the California Bearing Ratio, CBR) and traffic (expressed in million standard axles, msa). Although the adoption of a catalog makes the process empirical, in essence, the designs have been developed on the basis of mechanistic-empirical procedures, with due consideration of temperature and traffic data from different parts of India.

Four standard pavements (from the IRC catalogs) are considered here, for different soil and traffic conditions. For each case the standard Indian Road Congress (IRC) specified structure is analyzed and the vertical deflection at the surface is determined. These four cases were selected to include low, medium and high stiffness soil (CBR of 2, 6 and 10) and low and high traffic volumes (10 and 150 msa). Next, an alternative was sought for each case, which would provide significant reduction in materials, which could potentially lead to a significant reduction in environmental impacts.

Based on a literature review, the “inverted pavement” concept was selected for utilization in the alternative pavement structures. The concept of “inverted” pavements has been used successfully in many countries, specifically South Africa, to provide good performing roads with long life. In such pavements, an aggregate base layer is provided over a cement treated base (CTB) layer, and the demand for good quality crushed aggregate is minimized. The CTB layer provides a strong platform on which the unbound aggregate base course materials (commonly referred to as granular base) could be compacted better than on a conventional subbase. As a result, the granular base now has a much higher stiffness/structural strength (~ 450 Mpa) than its counterpart in a conventional pavement structure (200 -250 MPa). As a result of this and the presence of the stiff CTB layer, a relatively thin asphalt mix layer could be utilized on the surface. Studies have shown that when the surface course is properly maintained, such pavements can last indefinitely (***8, 9, 10, 11, 12***). However, the question is, can the benefit of such pavements be translated into environmental benefits as well?

A comprehensive evaluation of the changes in environmental factors (as well as cost) was conducted with the standard and their corresponding alternative structures. Each alternative structure was designed so as to provide a surface deflection that is identical to that of a standard pavement structure. The analysis was carried out with a layered elastic analysis software (WinJulea). The standard and the alternative designs, as well as the surface deflections are shown in Table 1. Note that in this analysis, an increased modulus of the granular base is not considered. The justification is as follows – over time, because of ingress of water, the modulus of the CTB could decrease, and as a result, the increased stress on the granular base (that provides the higher modulus) will also decrease. Therefore, to be on the conservative side, a modulus 250 Mpa is considered – it could be on the lower side initially, but in the long term it is probably more appropriate. Deterioration of cement treated base materials have been identified and demented in Reference ***13***.

It can be seen that the use of cement treated base can significantly reduce the thickness of the other layers. However, the initial cost could increase, because of the use of cement, as shown in Figure 1. The increases are in the range of 3-5%.

Table 1. Standard and alternative IRC structures;Standard-1; CBR = 2; Cumulative standard axle = 10 msa

Layer Material	Layer	Thickness, mm	Modulus, E, MPa	Surface deflection (mm)
Bituminous concrete, BC	1	40	1695	0.46
Bituminous Macadam, BM	2	100	700	
Granular Base, GB	3	250	250	
Granular Subbase, GSB	4	460	100	
Subgrade, SUB		0		

Alternative Standard 1;

BC	1	50	1695	0.46
GB	2	150	450	
Cement Treated Base, CTB	3	175	1200	
SUB		0		

Standard 2; CBR = 2; Cumulative standard axle = 150 msa

BC	1	50	1695	0.31
Dense Bituminous Macadam (DBM)	2	215	1695	
GB	3	250	250	
GSB	4	460	100	
SUB		0		

Alternative Standard 2;

BC	1	87.5	1695	0.32
GB	3	200	450	
CTB	4	300	1200	
SUB		0		

Standard 3; CBR = 6; Cumulative standard axle = 150 msa

BC	1	50	1695	0.26
DBM	2	160	1695	
GB	3	250	250	
GSB	4	260	100	
SUB		0		

Alternative Standard 3;

BC	1	62.5	1695	0.25
GB	2	200	450	
CTB	3	300	1200	
SUB		0		

Standard 4; CBR = 10; Cumulative standard axle = 150 msa

BC	1	50	1695	0.24
DBM	2	150	1695	
GB	3	250	250	
GSB	4	200	100	
SUB		0		

Table 1. Standard and alternative IRC structures (continued)

Alternative Standard 4;

BC	1	50	1695	0.23
GB	2	150	450	
CTB	3	300	1200	
SUB		0		

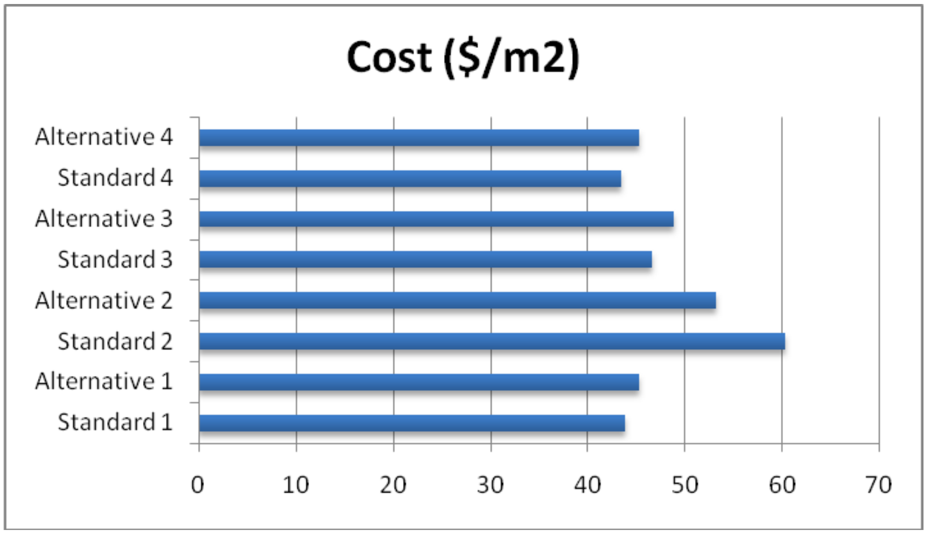


Figure 1. Cost comparisons

Environmental Impact

Next, the four sets were analyzed for their respective environmental impacts with the help of PaLATE software. PaLATE (Pavement Life-cycle Assessment Tool for Environmental and Economic Effects) (***14***) is a worksheet-based software that allows the user to evaluate the environmental and economic impacts of different designs. The primary input elements are materials and equipment (for transportation and processing/construction), and the outputs are environmental impacts (energy, water and emissions). Default values for different inputs are provided in the software, but the user can replace these also. PaLATE derives its parameters for analysis from a host of references, such as ***15***. These references are listed in the PaLate software.

The PaLATE program performs all calculations using volumetric methods. For every one of the eight alternatives, the input values used in PaLATE were based on a 100 cu. yd. (76 cu m) top layer batch. The batch sizes for the lower layers were adjusted based on the thickness of the road. For example, given an alternative with a 50 mm top layer of BC and a 100 mm second layer of granular base, values were entered into PaLATE for a 100 cu. yd. (76 cu m) batch of BC and a 200 cu. yd. (152 cu m) batch of GB. Using this method, PaLATE could evaluate the environmental impact for a correctly proportioned area of road. Unfortunately, the output is then based on a set volume. Because the layers of the different alternatives vary in thickness, the unaltered PaLATE environmental impact is not an accurate reflection of the true environmental impact of each alternative. To utilize the tool effectively, the thicknesses of the layers were used to calculate the area of roadway that each of the 8 alternatives would build. Using these areas, the PaLATE outputs were converted into environmental impacts per 1,000 m^2 of roadway. Note that the same environmental impact could possibly result from two different structures. Specifically, PaLATE is probably not refined enough to show the effect of the varying base layer thicknesses in its results and the effect of the asphalt layer overshadows the effects of the other layers. The comparisons of environmental impacts are shown in Table 2.

Table 2. Environmental impacts (per 1,000 m^2 of roadway)

CASE	Energy [MJ]	Water Consumption [kg]	CO2 [Mg] = GWP	NOx [kg]	PM10 [kg]	SO2 [kg]	CO [kg]	Hg [g]	Pb [g]	RCRA Hazardous Waste Generated [kg]	Human Toxicity Potential (Cancer) Kg benzene air equivalent	Human Toxicity Potential (Non-cancer) Kg toluene air equivalent
1	259,508	70	13	98	69	3829	41	0.3	13	2695	46224	71,742,449
1, alt	92,683	25	4	35	25	1367	14	0.1	4	962	16509	25,623,682
2	491,096	133	24	185	130	7247	78	0.5	25	5101	87479	135,758,373
2, alt	162,196	43	8	61	43	2393	25	0.2	8	1684	28890	4,4841,298
3	389,050	105	19	146	103	5744	62	0.4	20	4040	69278	107,618,797
3, alt	115,854	31	5	43	31	1709	18	0.1	6	1203	20636	32,029,551
4	370,195	100	18	139	98	5471	58	0.4	19	3841	65887	102,502,476
4, alt	92,683	25	4	35	25	1367	14	0.1	4	962	16509	25,623,682

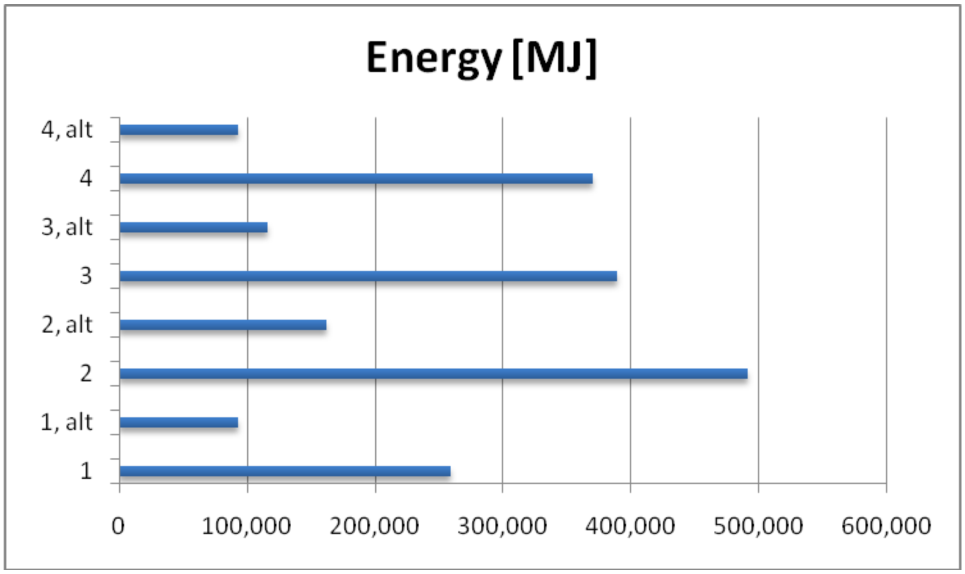
Figures 2 through 4 show the environmental impacts of the different structures for energy and water consumption, emissions and for hazardous waste and toxicity potential. Of the emissions, two gases are selected – CO_2 and NOx on the basis of their importance on greenhouse gas effect as well as health effects. Figure 4 includes hazardous waste, and the toxicity that is cancerous.

A comparison of the costs and the environmental impacts show that because of the use of less amount of stiffer materials, there is a slight increase in cost in three out of four cases (4% increase) – however, the reductions in environmental impacts are very high in comparison, ranging from 64 to 75 % approximately. It is apparent that the selection of a stiffer base layer can significantly reduce the total thickness of asphalt layer that needs to be utilized, and hence the harmful effects of using asphalt are significantly lowered. The reader's attention is drawn particularly to two aspects – the reduction in the CO_2 generation and the human toxicity (cancer) potential. While the CO_2 generation is directly related to global warming (and its harmful consequences), the toxicity part alone is very significant in terms of global health. This fact should be viewed in conjunction of the fact that millions of workers are exposed to fumes that are produced during the construction of roadways in the world, and hence the impact is significant. It must also be stated that while eye and upper respiratory irritation have been reportedly reported by workers who are exposed to asphalt fumes (***16***), significant differences have been found between fumes that are generated in laboratory studies (on which the numbers are based) and those that are produced in actual field conditions, and also carcinogenic materials have not been detected in asphalt fumes collected from field in one study (***17***). However, it is advisable to keep prevent dermal exposure to asphalt fumes and use appropriate respiratory protection (***16***).

In the cases illustrated in this paper, it is seen that an alternative design with CTB can provide response (and hence performance) that is as good as that of a conventional structure, and at the same time does not cost significantly more. These facts, along with the reduced need for natural materials, make this design a suitable one for achieving sustainability in pavement design and construction. Cost comparison of such pavements must be made on a life cycle basis. One important thing to note is that by providing a stronger base, in a CTB pavement, the distresses are limited to the surface layers. Such distresses are relatively easy and less costly to address – therefore maintenance would be less costly for the alternative structures, and hence the life cycle cost is most likely lower than conventional pavements (***11***). In this analysis, the effects of maintenance have been considered to be the same for all of the pavements – in reality, because the maintenance of the alternative structures would be limited to those of the surface layers only, the environmental impact would most likely be even lower than that shown here. Although it is debatable whether an agency would want to bear the *initial* extra cost, if any, or whether the materials that are required for the alternative designs are available or not, a comparison of the benefits versus extra cost is most likely convincing enough for designers to realize that a change in the approach of design of pavement structure is needed in order to address, at least, the very obvious negative impacts on the environment – use of energy and water.

Conclusions and Recommendations

An exploration of alternative designs for four specific pavement cases have been presented in this paper in order to illustrate the importance of consideration of environmental factors. It is shown that technology exists to provide equivalent designs and at the same time reduce the harmful effects of pavement construction and maintenance significantly. The results of analysis and design show that the use of composite pavements with cement treated base can significantly reduce the thickness of asphalt mix layer that is needed, and that this leads to a significant reduction of the quantity of asphalt binder that is needed, and hence the environmental impacts of the use of asphalt, especially in terms of energy-water use, emissions and human toxicity potential. It is recommended that the use of such environmental impact be made routine during the design of structural design of pavements, through its introduction in regulatory body/government publications on pavement design, and that alternative designs such as those mentioned here be evaluated with field projects.



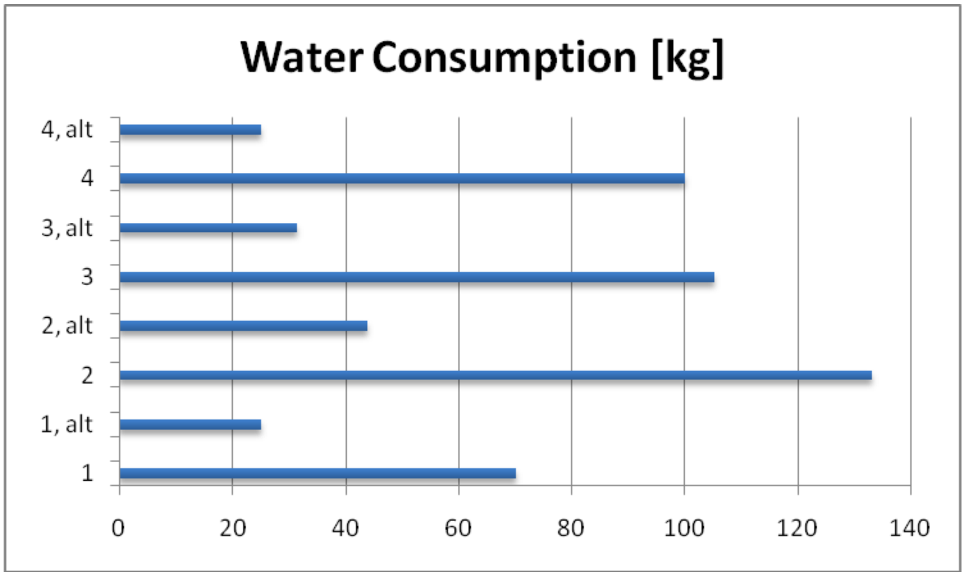
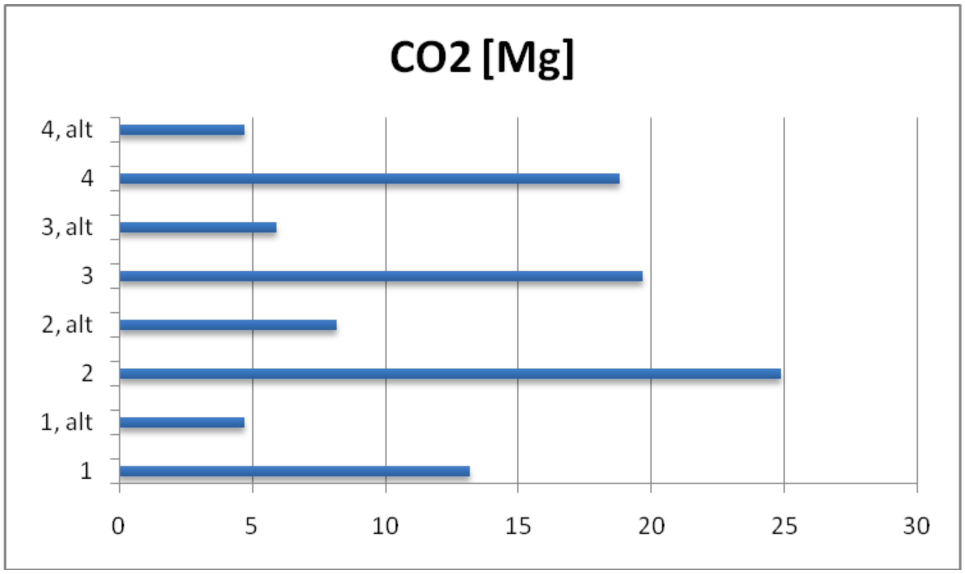


Figure 2. Comparison of environmental effects: energy and water (basis of 1,000 m^3);
Note: 1 – Standard 1; 1, alt – Alternative 1 (structure)



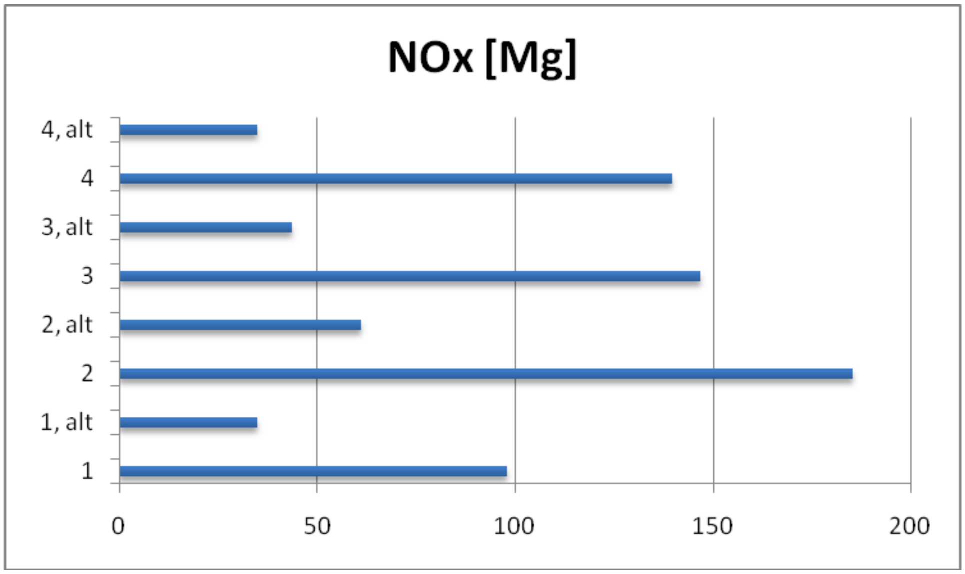


Figure 3. Comparison of environmental effects: CO_2 and NO_x (basis of 1,000 m^3)
Note: 1 – Standard 1; 1, alt – Alternative 1 (structure)

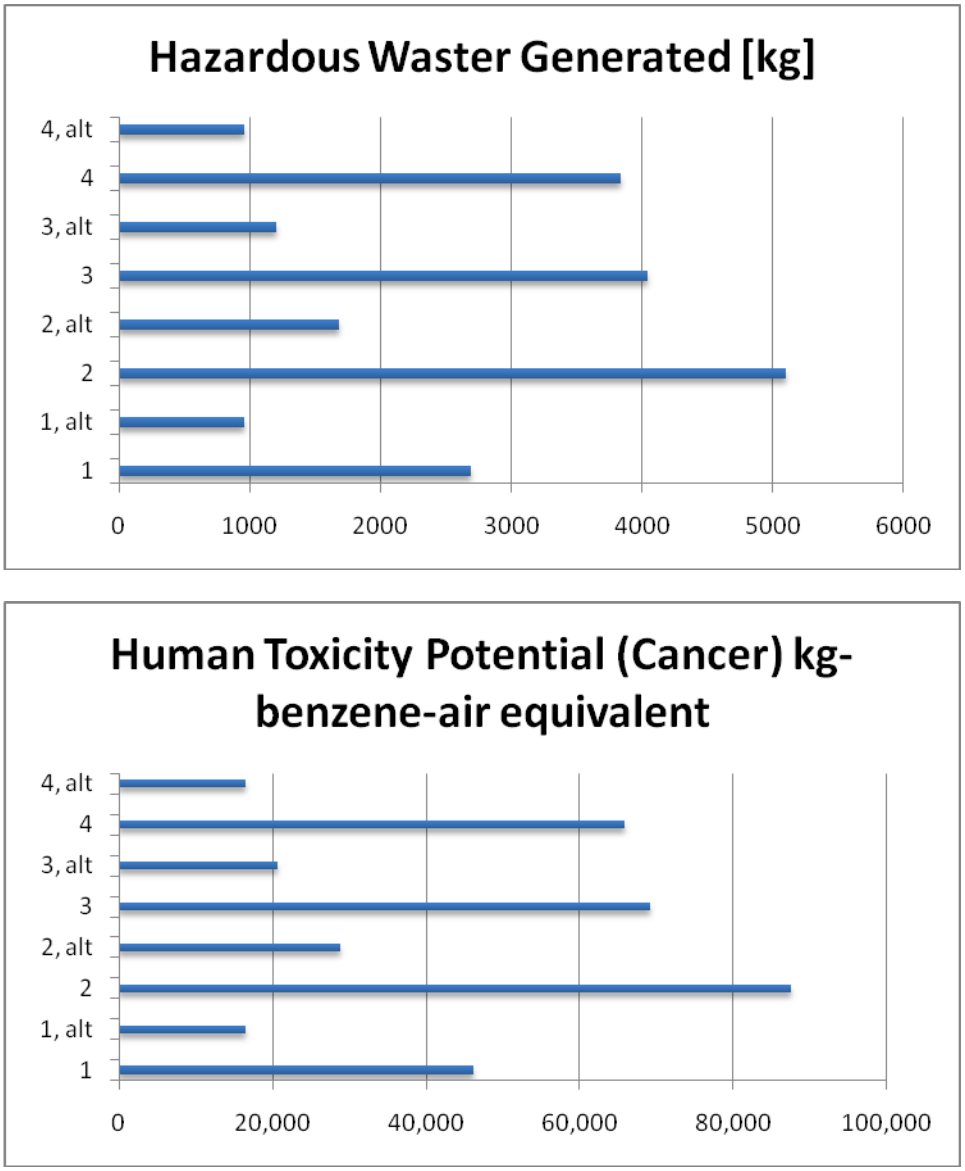


Figure 4. Comparison of environmental effects: hazardous waste and human toxicity potential (basis of 1,000 m^3)
Note: 1 – Standard 1; 1, alt – Alternative 1 (structure)

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References

1. Yoder, E. J. And M. W. Witczak. Principles of Pavement Design , 2nd ed. New York: John Wiley, 1974.
2. Huang, Yang. Pavement Analysis and Design . Englewood Cliffs, NJ: Prentice-Hall, 1993.
3. American Association of State and Highway Transportation Officials. AASHTO Guide for Design of Pavement Structures . Washington, D.C.: AASHTO, 1993.
4. National Cooperative Highway Research Program (NCHRP). 1990. Calibrated Mechanistic Structural Analysis Procedures for Pavements. Vol. 1, Final Report. Washington, DC: National Cooperative Highway Research Program.
5. Ullidtz, Per. Pavement Analysis , New York: Elsevier, 1987.
6. Huang, Y H and Vaswani, N K. Deflection and Curvature as Criteria For Flexible Pavement Design And Evaluation. Highway Research Record, No. 345. Washington DC, 1971.
7. Indian Road Congress. Guidelines For The Design Of Flexible Pavements, New Delhi, April, 2011.
8. Rust, F. C., Mahoney, J. P and Sorenson, J. B. An International View of Pavement Engineering, Bearing Capacity of Roads and Airfield Conference, Trondheim, Norway, 1998.
9. Technical Recommendations for Highways (TRH) 4, Department of Transport, republic of South Africa, Pretoria, South Africa, 1996.
10. Theyse, H. L. , De Beer, M., Rust, F. C. Overview of the South African Mechanistic Pavement Design Analysis Method. Transportation research Record: Flexible Pavement Design and Rehabilitation Issues, No 1539, Transportation Research Board, Washington DC, 1996.
11. High Performance Crushed Stone Base (G1) Used on South African Highways, South African National Roads Agency, Pretoria, South Africa, October 1998.
12. Jooste, F. J., and Sampson, L. The Economic Benefits of HVS Development Work on G1 base Pavements. Gauteng Provincial Government, Department of Public Transport, roads and works, July 2005.
13. Freeme, C.R., Maree, J.H., and Viljoen, A.W. Mechanistic Design of Asphalt Pavements and Verification Using the Heavy Vehicle Simulator. Fifth International Conference on the Structural Design of Asphalt Pavements, The Netherlands, 1982.
14. Pavement Life-cycle Assessment Tool for Environmental and Economic Effects http://www.ce.berkeley.edu/~horvath/palate.html (accessed June 15, 2011)
15. Carnegie Mellon University Green Design Initiative (2003), *Economic Input-Output Life Cycle Assessment (EIO-LCA) model* [Internet], Available from: <http://www.eiolca.net/>
16. Center for Disease Control. Health Effects of Occupational Exposure to Asphalt U.S. Department of Health and Human Services, Public Health Service Centers for Disease Control and Prevention National Institute for Occupational Safety and Health, December, 2000.
17. Asphalt Institute. Comparison between Field versus Laboratory Generated Asphalt Fumes.*Undated.*