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COMBINING LCC AND ENERGY CONSUMPTION FOR REAL DECISION MAKING REGARDING REHABILITATION OPTIONS

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Abstract

Life cycle costing (LCC) of rehabilitation options (i.e. the costs incurred over the full life of different pavement structures) is a widely accepted concept. The tools to calculate the energy consumed in the provision of such pavements are readily available. In order to place these decision making tools in context, four different solutions for rehabilitating a specific distressed heavy-duty pavement are considered in this paper:

- Patch the distressed areas of the existing pavement and apply a relatively thick asphalt overlay.
- Mill off and remove the existing distressed asphalt layers, repair defects in the underlying granular layer and replace the asphalt pavement.
- Recycle the upper portion of the existing pavement with a cement stabilising agent, construct a new base layer (using either asphalt or crushed stone) and surfaced with an asphalt wearing course
- Recycle the upper portion of the existing pavement with a bitumen stabilising agent and apply an asphalt wearing course.

Using appropriate pavements models, layer thicknesses are selected to provide a comparable structural capacity for each solution. In addition, the distress mechanism / deterioration time-line for a 20-year service life defined.

The different construction requirements for each solution are quantified and costed, based on average unit rates applicable to the South African contracting industry in the first quarter of 2010. A similar exercise is carried out on interventions required for each option to maintain the same level of serviceability over the life of the pavement.

The salvage value of each solution is then considered in terms of the cost of rehabilitating the type of failure that was assumed to define the end of the service life. Present day costs are used throughout allowing the full life-cycle costs of each solution to be compared without discount rate speculation.

In this paper, environmental consequences are measured through energy consumption. The energy consumed in each of the relevant construction activities is calculated using applicable rates for each material type~~,~~ and used to evaluate the total impact of each solution.

The key concern is LCC and environmental considerations (i.e. the total cost of construction combined with energy consumption) to produce an index for decision making. Various approaches to evaluate both cost and energy factors have been considered in this paper for alternative rehabilitation solutions. Comparisons are made between the different methods and recommendations are made.

1. INTRODUCTION

1.1 Background

In order to investigate different approaches to life cycle costing (LCC), an appropriate pavement structure needs to be selected upon which rehabilitation needs to be carried out. Bearing in mind the distinct continental differences in approaches to pavement structures, it is not possible to select a universal structure that is globally representative. Nevertheless, the pavement structure of southern Africa, with a high bearing capacity, that has been selected for analysis would not be atypical for the majority of continents. Such a pavement is ideally suited to show the implications of the advancements in rehabilitation design technologies, for evaluating the costs and energy considerations for such options, and for carrying out a holistic LCC analysis.

1.2 Rehabilitation Example: Existing Pavement

The pavement structure that has been selected is typical for a heavily trafficked road, see Figure 1. Full-depth cracking in the asphalt layers indicates that has reached the end of its service life. The various pavement layers are 150mm of thick asphalt concrete overlying 350mm of granular material consisting of two layers; a 150mm layer of good quality graded crushed stone (CBR > 80%) above a 200mm thick layer of natural gravel (CBR > 45%). The total cover to the underlying subgrade is therefore 500mm. The subgrade is assumed to have an in situ resilient modulus of 100MPa.

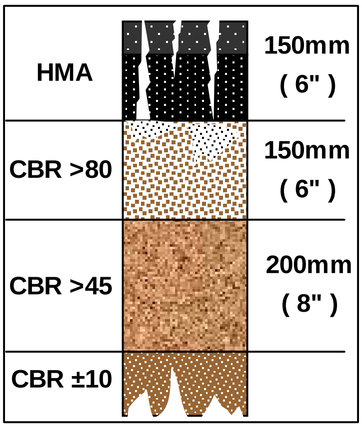

Figure 1. Existing pavement

Distress symptoms are typical for such a pavement structure at the end of the service life. The asphalt material has suffered fatigue cracking with cracks propagating thorough the full thickness to the surface. Such cracks allow water to enter the underlying crushed stone material causing saturation and leading to the hydraulic displacement of fines (pumping) when subjected to heavy traffic loads. The consequence of pumping is degradation of the layer and pothole development. This pavement has reached its terminal state and requires major rehabilitation.

1.3 Rehabilitation Requirements

Rehabilitation objectives call for a 20 year service life. Anticipated traffic over this period indicates a structural capacity requirement of 30 million ESALs. To meet the normal requirements for ride quality and skid resistance, an ultra-thin friction course (UTFC) surfacing is required. Such a surfacing is expected to provide a service life of between six and eight years (Mallick *et al.*, 2002). At the end of the 20 year service life, rehabilitation will be required to restore structural capacity.

1.4 Rehabilitation Options

Four recognised options for rehabilitation have been considered below. All have a similar structural capacity of 30 million equivalent standard (80kN) axle loads.

1.4.1 Option 1: Patch and Overlay

This option is popular in many first-world countries, primarily due to the speed and simplicity of construction. Severely cracked sections that generally falling within the wheel paths are milled out and replaced with fresh asphalt before an overlay is applied. Known in California as “dig outs”, a milling machine with a 1m cut width is normally utilised to cut a 75mm deep strip following the wheel path. Continuously graded hot mixed asphalt (HMA) is used as backfilled material, placed by paver and compacted. The conceptual rehabilitation in shown in Figure 2.

To minimise the thickness of asphalt overlay, a phased construction approach is adopted. A 60mm thick asphalt base surfaced with a 30mm thick UTFC surfacing is estimated to provide a 7 year life before cracks reflecting from the underlying fatigued structure demand intervention. This is timed to coincide with the requirement to replace the UTFC surfacing as it would reach the end of its functional life after 7 years. It is optimistically estimated that milling off and replacing the UTFC layer together with 35mm of underlying asphalt will carry the design traffic for a further 7 years when the same treatment will be required to achieve the overall 20 year service life. At that stage, advanced distress (in the form of bitumen stripping) can be expected in the body of the asphalt, requiring deep milling to address the problem. Rehabilitation requirements are expected to be the same as those described under Option 2 below.

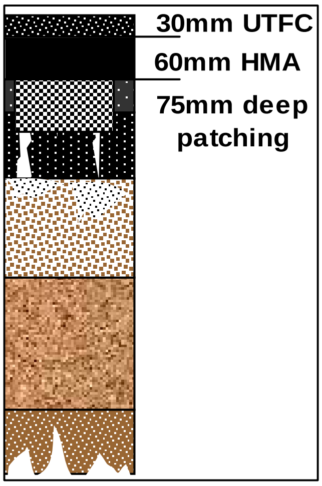

Figure 2. Patch / overlay

1.4.2 Option 2: Mill and Replace

This rehabilitation method calls for the entire thickness of distressed asphalt affected by full-depth cracking to be milled off and removed from site. The underlying crushed stone base will then require repairing by in situ reworking (to a nominal depth of 125mm) before paving a 120mm thick asphalt concrete base, followed by the 30mm UTFC surfacing.

Figure 3 illustrates the operations required. Reworking the crushed stone base implies that traffic will have to be diverted for sufficient time to allow the base material to dry back before the asphalt base can be paved, followed by the UTFC surfacing.

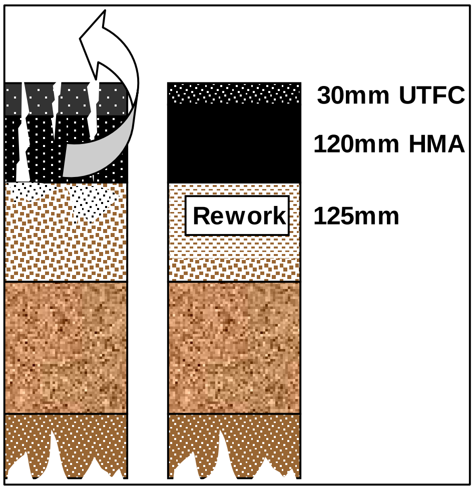

Figure 3. Mill, rework, replace

The critical layer in this pavement is the combined asphalt base and surfacing layers that will suffer fatigue cracking due to a tensile strain level of 162με developing at bottom of the asphalt concrete (a shift fact of 7.2 is assumed for crack propagation to the surface), see (Collings and Jenkins, 2010). Two maintenance interventions are envisaged to coincide with the anticipated life of the UTFC surfacing. After 7 and 14 year intervals, only the UTFC will need replacing. At the end of the service life, cracks would have reached the surface, allowing water to ingress through to the underlying granular layers, causing the same distress and failure mechanism that the pre-rehabilitated pavement has suffered. At that stage, rehabilitation requirements are expected to be the same as those described under Option 1 above.

1.4.3 Option 3: Recycle / Cement Stabilise the Existing Pavement and Overlay

A standard rehabilitation approach that is popular in several parts of the world is shown in Figure 4. This method is essentially a South African "catalogue design" calling for the upper 300mm of existing pavement to be recycled in situ, stabilised with cement. Such a blend of recovered asphalt pavement material and crushed stone would normally require the addition of some 2.5% (by mass) of cement to achieve an unconfined compressive strength (UCS) of 2MPa.

After a curing period of 7 days, a new 150mm thick highly densified graded crushed stone base is constructed from on top of the new subbase. Achieving high levels of density requires the layer to be "slushed" that, in turn, calls for a drying out period before the asphalt binder layer and UTFC surfacing can be applied.

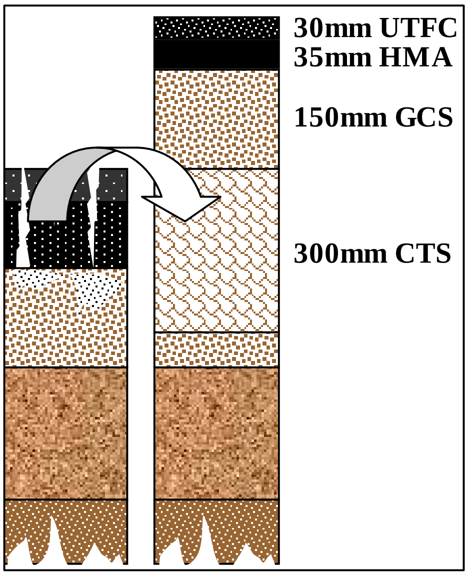

Figure 4. Recycle with OPC, overlay

Since a cohesionless crushed stone base cannot tolerate the action of traffic without ravelling, this method of rehabilitation calls for all traffic to be diverted away from the works until the asphalt has been applied.

The critical layer in this pavement is the crushed stone base with a safety factor (stress ratio related) of 1.15 (Collings and Jenkins, 2010). The failure condition assumed is 20mm of permanent deformation followed by degradation due to moisture-activated distress.

Two maintenance interventions are envisaged to coincide with the anticipated life of the UTFC surfacing. After 7 years, only the UTFC will need replacing. After a further 7 years (i.e. 14 years after the initial rehabilitation), both layers of asphalt will need replacing to ensure that the 20 year service life is achieved. At the end of the service life, deformation in the wheel paths can be expected to be in the order of 20mm. At that stage, rehabilitation requirements are expected to be the same as those described under Option 4 below.

1.4.4 Option 4: Recycle / Bitumen Stabilise the Existing Pavement

As illustrated in Figure 5, this rehabilitation method calls for the upper 250mm of the pavement to be recycled in situ with the addition of a bitumen stabilising agent. (Assumed application rates are 2.2% residual bitumen and 1% cement (by mass.)) One of the reasons for this method becoming popular is the increase in cohesion of the stabilised material that allows the completed layer to be opened to traffic soon after it has been compacted (normally to a density in excess of 100% of the modified AASHTO T-180 density) and finished off. When a properly-formulated bitumen emulsion is used as the stabilising agent, a delay of between 2 and 4 hours is required to allow the emulsion to break sufficiently. Instant cohesion is, however, achieved on compaction when foamed bitumen is used as the stabilising agent.

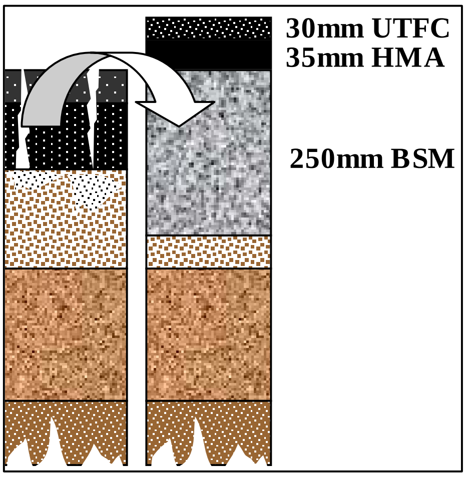

Fig 5. Recycle with bitumen,

Since the asphalt concrete surfacing cannot be applied until the moisture content of the recycled base has reduced (< 50% of the optimum is normally specified), a fog spray of dilute emulsion is usually applied to prevent the finished surface from ravelling under traffic action.

The critical layer in this pavement is the bitumen stabilised base (deviator stress ratio of 0.215), see (Collings and Jenkins, 2010); the failure condition assumed is 20mm of permanent deformation. Two maintenance interventions are envisaged to coincide with the anticipated life of the UTFC surfacing. After 7 and 14 year intervals, only the UTFC will need replacing. At the end of the service life, permanent deformation of 20mm would be evident at the surface, and this can be addressed by milling off and replacing the asphalt layers. This will return the pavement to its original state and restore the structural capacity.

2. MAINTENANCE MEASURES AND LCC COSTS

The requisite maintenance and rehabilitation measures outlined in the previous sections, are summarised in Figure 6.

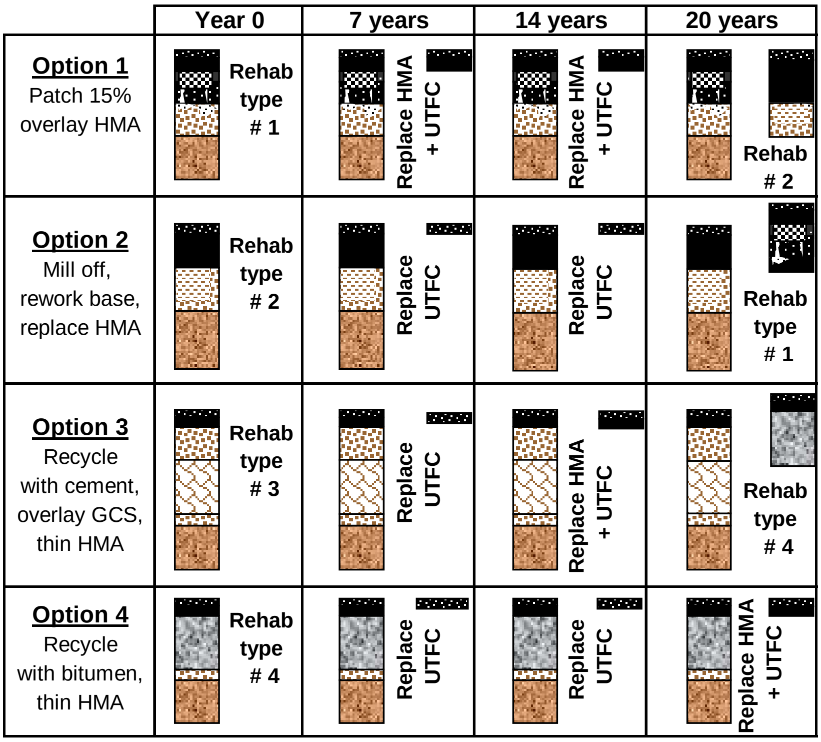

Fig 6. Maintenance intervals and rehabilitation required after 20 years

3. CONSTRUCTION & MAINTENANCE COSTS

The construction and maintenance costs are included in detail in (Collings and Jenkins, 2010). It is not the purpose of this paper to repeat the analyses already carried out, but rather to take the results a step further. The construction and maintenance costs calculated previously, remain applicable. Applying the maintenance measures of Figure 6 and using realistic unit rates, the construction costs and life cycle costs can be determined for the various maintenance and rehabilitation measures. Using a discount rate of 6%, these monetary values are plotted in Figure 7. It is apparent how important the whole-of-life costs are in decision making, rather than just the initial construction costs.

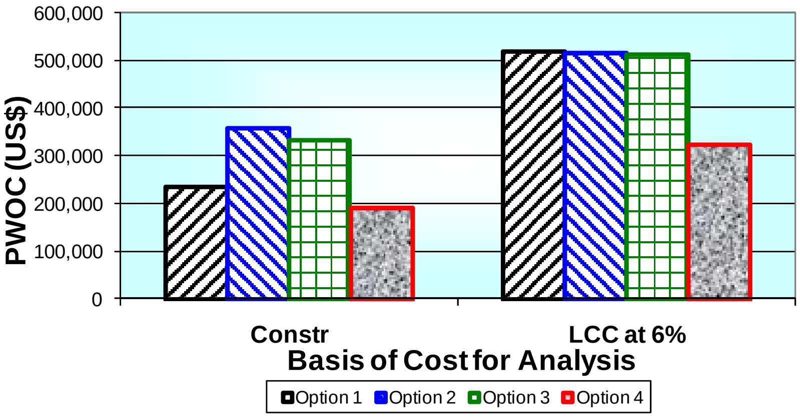

Figure 7. Construction Costs and Life Cycle Costs per km, for Maintenance Options 1 to 4

4. ENERGY CONSUMPTION

An increasing awareness of global warming is making society focus more on energy consumption. The construction industry is not exempt and several studies have been undertaken to estimate the amount of energy being consumed, particularly in the construction of roads where large machinery is employed and the quantities of material either consumed or moved is high.

Studies have been carried out to evaluate how energy consumed in the production of construction materials (e.g. bitumen, cement, aggregates, etc.), as well as various construction activities (e.g. excavating, transporting, asphalt paving, etc.) Several authors have published papers highlighting the savings that can be anticipated from adopting different construction techniques (e.g. recycling material from an existing pavement compared to conventional construction processes). A detailed exercise carried out in New Zealand (Patrick *et al.*, 2008) reported on the energy consumption data shown in Table 1.

Table 1. Energy consumed in procuring materials and in executing primary construction activities

Material procurement / Construction activity	Unit	Energy consumed (MJ)
Material procurement		
Graded crushed stone (GCS)	MJ / t	50
HMA manufacture	MJ / t	30
Cement	MJ / t	7000
Bitumen	MJ / t	6000
Material haulage	MJ / t km	1
Construction activity		
Milling [1]	MJ / t	5
In situ recycling / stabilising	MJ / t	10
Processing aggregate layer	MJ / t	66
Ditto per m^2 for 150mm thick laye	MJ / m^2	10
Compacting and finishing layer [2]	MJ / m^2	10
HMA paving and compaction	MJ / t	20

Since they were not covered by Patrick's study, the following two energy consumption rates were derived:

- Milling. Half the energy consumed under Patrick's heading "In situ recycling / stabilising" has been adopted as being both realistic and conservative.
- Compacting and finishing off a new pavement layer, required for estimating energy consumed in compacting, levelling and finishing off the material mixed by a recycler. Half the energy Patrick estimated is consumed for "processing aggregate layer" (expressed in terms of kj/m^2) was considered realistic (thereby allowing 50% for mixing).

(It should be appreciated that no allowance has been made for diverting public traffic away from the site where newly constructed layers of graded crushed stone cannot be trafficked (Options 2 and 3), nor for any increase in the road-user costs due to increasing travel times / delays caused by such diversions. Similarly, no allowances have been made for the additional shoulder work required to match the increase in final surface levels resulting from pavement rehabilitation requirements. The inclusion of additional granular or asphalt layers will result in an elevation increase of 90mm in Option 1, 215mm in Option 3 and 65mm in Option 4.)

Table 2. Cumulative Energy consumed per kilometre (in GJ)

Rehabilitation Option	Initial rehabilitation	7 year intervention	14 year intervention	Rehabilitation after 20 years
Option 1	1793	2996	4199	7046
Option 2	2847	3426	4005	5798
Option 3	2692	3271	4474	6855
Option 4	2381	2960	3539	4742

The quantities determined of each construction activity were then used with the unit consumption rates in Table 1 to estimate the total energy consumed by each of the four different rehabilitation options. Table 2 summarises the energy consumed in Giga-Joules by all construction activities required for each option (whole-of-life energy consumption). As with the cost estimates, a one kilometre length of two-lane road is assumed with a surfaced width of 10m (i.e. 10,000m²).

Figure 7 illustrates the cumulative energy that is consumed by the various construction activities (including maintenance interventions and rehabilitation at the end of the service life) for all four options.

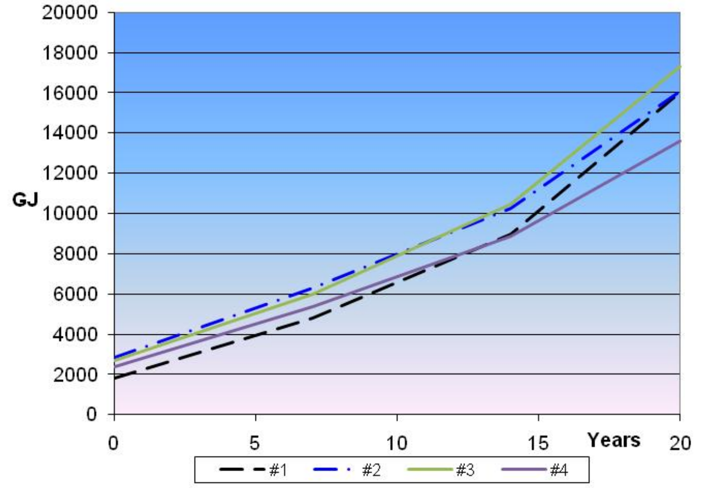

Figure 7. Cumulative Energy Consumtion per kilometre

Similar to the trend shown in the construction costs, this graph emphasises the true benefit of adopting a technology that provides improved performance over the full service life with the picture changing from that painted by the energy consumed during the initial construction.

5. COMBINING COST AND ENERGY CONSUMPTION

Various approaches have been identified for combining costs (life cycle or other) and energy considerations. Numerous energy consumption and emissions calculators have been developed in different countries. The construction practices, consumption rates as well as energy costs are country specific, so detailed information is required to cover all of the input parameters accurately. Each individual type of energy consumed needs to be evaluated separately, as their costs per kW e.g. fossil fuel versus electricity, differs. The question is: Can a simpler and sufficiently reliable alternative method of energy and emission evaluation, be found?

Collings and Jenkins (2010) proposed a method to take account of energy in the economic evaluations, using a "Relative Importance Ratio" of environmental versus cost considerations. Ultimately, a Cumulative Impact ratio is used to evaluate the maintenance and rehabilitation options. The outcomes of this approach can be seen in Figure 8, showing how the relative importance of environmental considerations can change the outcomes. Unfortunately the relative importance is highly subjective and that is why a more objective approach is required.

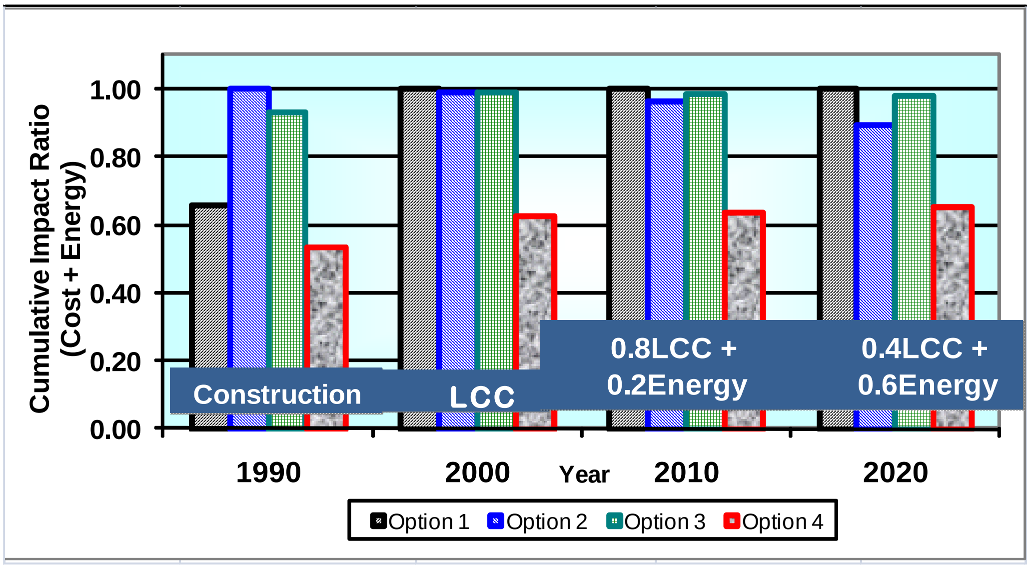

Figure 8. Combining Cost and Energy using a Relative Importance Factor (Collings and Jenkins, 2010)

Alternative approaches such as GreenPave, which is a sustainability rating system for pavement construction and rehabilitation options that is applied in Ontario, uses a points system based on energy consumption and GHG emissions evaluation for decision making (Kazmerowski *et al*., 2010). The points are used to calculate a "Green Discounted LCC" which is ultimately used for decision making. It is a holistic system, but requires a significant amount of input information.

Exploring simpler ways of combining Life Cycle Costs with energy and emission data for decision making in the selection of road rehabilitation alternatives, requires some insight into the factors at play. Consideration needs to be given to some of the following imperatives regarding energy types, consumption and emissions:

- Although a cumulative energy consumption value in Mega Joules (MJ) can be calculated for e.g. a pavement rehabilitation option, it can comprise different fossil fuels as base ingredients. Each fossil fuel has a different calorific value, for example crude oil : coal : natural gas calorific ratios are 12.5 : 8.5 : 15.5;
- The cost of energy production varies depending on the source and country, with non-renewable resources such as fossil fuels usually the cheapest. In South Africa, at approximately R 0.50/kWh electricity is almost half the price of fuel oil. Wind energy is more expensive
- The emissions generated in energy production are proportionate to the energy generated as well as generation method. Coal : Petrol: Gas emissions of kg's of CO_2 per kWh produced compare as follows 0.5 : 0.25 : 0.2. "Clean" energy from hydroelectric power, wind and wave generators do not share the same emissions and are therefore considered to be "green" energy forms.

- The proportional contribution of different energy sources is country dependent. In South Africa, oil as a primary energy source was about 20% of the total up until the 1980's (Country studies, 2011). Currently electricity comprises approximately 75% of SA's energy (BBQonline, 2011) and less than 5% of energy emanates from alternative, clean sources i.e. wind, solar heating etc.
- South Africa's electricity is generated from various sources, namely coal : nuclear : hydro : other in the approximate proportions of 88 : 6.5 : 2.3 : 3.2.

In a nutshell, less than 10% of South Africa's energy is currently clean and green. SA is the 14th highest producer of GHG's in the world. So, 90% of energy consumption for road building is contributing to GHG production, besides the emissions that form part of the construction processes. It would not be equitable nor sustainable to just use a basic energy cost to account for the energy consumption of various rehabilitation alternatives. In order to put a price to the energy for holistic LCC evaluation, it is proposed that the inverse of the green energy fraction is used as a factor to magnify the basic cost of energy to estimate the combined cost of construction, maintenance and energy. It needs to be stressed that the purpose of this calculation is not aimed replacing the methods using detailed emissions evaluation, but rather as a feasibility phase analyser to gauge the potential of each pavement alternative.

Using a value of 1/10% for the magnification factor of the cost of non-renewable energy in South Africa, and US$ 100 per barrel for the basic cost of energy to provide 158 litres, each litre generating 38 MJ of energy, the consumption values can be calculated and combined with the Life Cycle Costs, see Table 3 and Figure 9. It can be seen that decision making just based on cost does not give the entire picture. Construction costs alone provide a different perspective to Life-Cycle Costs. In addition to the Life-Cycle Costs shown in Figure 9, the energy consumption provides deeper insights into the greater impact of road interventions. It highlights the benefits of cold recycling using BSMs (foamed bitumen or emulsion) both from a cost and an energy perspective.

Table 3. Combined Life Cycle Costs and Energy Costs

	Initial Constr Cost (US$/km)	PWOC (Disc=6%) (US$/km)	Total Energy (GJ/km)	Energy Cost (US$/km)	LCC+Energy Cost (US$/km)
Option 1	233,506	515,142	976	162475	677,617
Option 2	356,500	512,803	809	134793	647,597
Option 3	331,875	509,924	1,048	174534	684,458
Option 4	191,825	323,322	574	95586	418,908

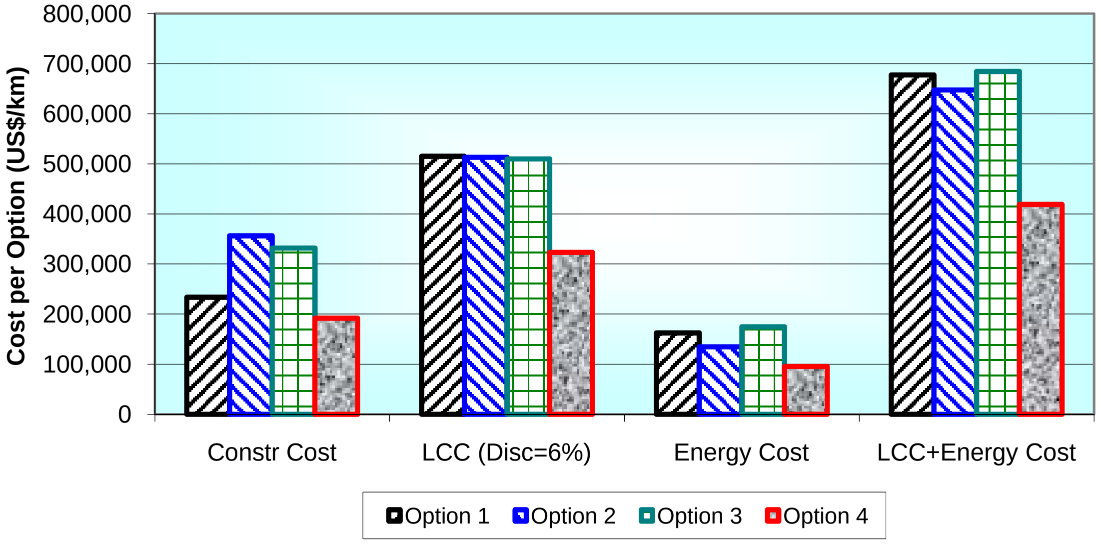

Figure 9. Combined Life-Cycle Cost and Energy Consumption for All Options

10. CONCLUSIONS

Environmental considerations in pavement engineering are no longer mysterious and abstruse. Increasing emphasis on the environmental impact of road construction and rehabilitation, has led to sufficient data becoming available for use in analysis and decision making. In this paper, energy consumption figures have been used in combination with whole-of-life costs for four realistic rehabilitation options currently used globally in road pavements. This provides insight into project selection leading to the following conclusions:

- Initial construction costs alone are inadequate for selection of rehabilitation alternatives. They can provide skewed and unrealistic rehabilitation selection, which will lead to unnecessary wastage of resources. *Cheapest is dearest*.
- Whole-of-life analysis using PWOC provides more realistic financing requirements for pavement upkeep over the entire analysis period. *Better an ounce of prevention than a pound of cure.*
- Environmental considerations in pavement engineering are no longer mysterious and abstruse. Increasing emphasis on the environmental impact of road construction and rehabilitation, has led to sufficient data becoming available for use in analysis and decision making
- Bitumen stabilisation with foam or emulsion as cold recycling technology offers significant benefits both in terms of economic and energy considerations, compared with more conventional pavement rehabilitation methods. Maximising the reuse of existing materials and minimizing the consumption of new materials is the solution.

Combining whole-of-life costs and energy consumption in terms of evaluating pavement rehabilitation options is an aspect that needs attention. Combining these factors optimally by enhancing the recycled materials using bitumen stabilisation for flexibility and durability provides an attractive technology for cost-effective pavements.

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