Validity of Functional Criteria Related to Structural Parameters Used for Contract and Extended Warranties

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ABSTRACT: Mechanistic-empirical pavement design methods have been practiced for a number of years. The classical approach is employing two different strain criteria. One is fatigue failure for bound materials; as such employing a robust engineering theory. The other is a regression between surface distress and the strain on top of the subgrade. Typically, future rutting is related to the strain by a forth-power rule. Surprisingly, as a single parameter criterion the relation is proven to be fair to good when put to a test. However, the exact amount of rutting is very hard to predict. The initial rutting which is depending on the compaction effort seems to vary much. Further, a pavement consists of several different materials with different mechanical properties. Finally, the properties change with temperature and moisture. Thus, for a three layer structure, there is initial deformation governed by at least two processes in each layer. There is also volumetric change and shear deformation in each material and there is wear at the surface. The rutting equation needs 13 input parameters plus the stochastic influence of weather and uncertainties about traffic. Thus, a contractor must carefully judge the risks involved with long time warranties on rutting. The present paper presents a case where an extra effort was made to minimize the deformation of unbound layers. However, this might have contributed to higher shear deformation of the asphalt layers. In addition to the technical implications, a brief discussion on the economical and contract issues is reported.

KEY WORDS: Functional criteria, rutting, roughness, warranties

1 INTRODUCTION

In many countries, efficient use of mechanistic-empirical (ME) methods in pavement design is hampered by rigorous construction control. Little effort is given to the performance of the road as a whole. Some of the tests used are outdated and incorrectly tailored to pavement performance prediction. This seems to work in a conservative way as more and hard to get material is needed for the construction. Many current design codes do not always account for the benefit of a strong subgrade support. If this situation persists, thousands of tons of materials are being wasted each year due to conservative design parameters. Thus, functional user criteria and contractors taking an extended responsibility for roads including maintenance bodes well for sustainable road construction alternatives. The environmental impact from road construction could also be reduced considerably by taking a few simple steps and disregard some old outdated criteria. There are some important aspects of ME design that makes it attractive for functionally driven criteria.

- New materials are easier to incorporate once their properties are determined
- Better and more accurate models could be introduced, the benefit being reduced uncertainties about the construction
- Cruder models, requiring less testing could still be used, but with the drawback of an increased uncertainty resulting in a thicker design

2 DESIGN CRITERIA

The “bottom of the bound layer horizontal strain” and the “top of subgrade vertical strain” are the two criteria that have been most frequently used for pavement ME design up to now. They emanate from the AASHO Road Test and describe road deterioration as a function of load and number of repetitions. As far as regarding the former criterion, which relates to fatigue cracking, specimens can be tested in the laboratory. However, the geometry of the specimen, various apparatus, and the accelerated nature of the test makes it necessary to apply shift factors when determining the pavement life in the field from such tests. Still, tests are valuable in that reasonable large changes of the mix design can be evaluated. It is relatively easy to determine equations for new materials in the laboratory.

The “top of subgrade vertical strain” criterion is much more difficult to reproduce in practical tests. It was originally determined as a regressed parameter from a full scale accelerated test related to rutting. Over the years many studies have been made to confirm or adjust the relationship. Results vary due to materials used in the construction and subgrade soil as well. Despite all these limitations it is difficult to come up with any better single-parameter based criterion. The strain on the top of the subgrade is also easy to assess in a model with Odemark’s equations of equivalent layer thickness, which were commonly used when the relationship was originally suggested!

Sometimes, the criterion is confused with subgrade strength. It is important to point out that it is not directly correlated to subgrade properties. After an overlay is done, there is no used or residual life left to consider, and the rutting is now progressing from near zero.

Hence, if a new road design is based on the subgrade strain criterion there is an uncertainty of the soil and its variations and in addition to that, the variability of the unbound and bound layers in the structure as well. Further, initial rutting and sequential rutting are not discernable from one another. Surface wear is not included but shows up as rutting when measured with surface monitoring devices. An assumption is made that elastic and plastic strains are related in a predictable way, but they are not if the load range vary much. Clearly, this criterion must be handled with lots of precaution. So the questions arise whether rutting should be used as a contractual parameter at all.

3 DESIGN CODE BACKGROUND

Design code of highways emanates from the experience of building roads dating back to historic times. Usually, a layer thickness design based on traffic and climate is employed. As more experience with new materials is gathered there are also restrictions established on the materials that may be used concerning the gradation of aggregate, crushed area, angularity of the particles et cetera.

For functional design criteria some of these restrictions may be obsolete. An example regarding restrictions deals with gradation curves. (Kahndahl & Cooley) reported that hot mixed asphalt concretes may perform well in spite of having gradation curves through a restricted zone. Likely, some failures in the past led to a specification change with the forbidden zone. Maybe, the wrong conclusions were made about the curve, but the forbidden zone remained for many years. The amount of material that had to be wasted over this time remains unknown.

For subgrade strength a rather coarse classification based on the materials is used. After preparation of the surface a static plate bearing test is often used for construction control. It decides if the surface is adequately compacted. If the surface is too soft, it may be difficult to compact the subbase and base layers appropriately, so a poor foundation may easily deteriorate the whole structure.

It has been suggested that the contractor should get a benefit for better than needed values from the test. The present authors agree that strong and well-compacted subgrades may not need as thick subbase and base courses as the average structure, and that a conservative design is just as bad as under design as it does capitalize on limited resources. However, we doubt that the static plate bearing test is the right method to rely on predicting future pavement performance. First, the load is only repeated once, but the testing of materials that relates to bearing capacity deformation, i.e. type II rutting requires conditioning involving several hundreds of repetitions in a tri-axial apparatus. (Type I rutting occurs as post-construction compaction by traffic). Secondly, the test is rather shallow. Instead, it is better to use a test that is able to mimic stress and strain relationships caused by traffic on the finished construction, i.e. the design strain. Further, it must be possible to distinguish between types I and II rutting.

4 USING IRI AS A BIDDING AND WARRANTY CRITERION

The International Roughness Index (IRI) is a true functional parameter. It can be directly related to user costs. As such it is a very good index for the road holder and Pavement Management Systems as it could be used for optimizing maintenance and rehabilitation. The IRI has been criticized as the quarter-car simulation is being outdated. However, the benefits of altering, the constants in the model would be mitigated when historic data are not comparable. As data storage is not a problem any longer the entire profile (of which the IRI is based) can be stored so that any vehicle movement can be reconstructed for the model.

For a structural evaluation, the IRI is of less value as there is no direct relationship between elastic strain and IRI. The IRI has two peaks within the frequency spectrum, relating to a speed of 80 km/h. A Power Spectrum Density (PSD) of the profile is much more informative for this purpose. The road type is often discernable, e.g. PCC roads with evenly spaced joints. Frost heave and settlements at certain depths seem to be detectable as well as surface deficiencies, [Lenngren, 1999].

From the contractor’s view the IRI is a less than ideal parameter for long time warranties as it is hard to predict future development. A contractor could diligently try to avoid the peaks in the spectrum causing high values, like joint spacing. At times it is not possible to reduce the IRI due to geometrical restrictions. This is common for overlay and widening projects. Thus, from the entrepreneurial viewpoint there is some scepticism about using IRI as a warranty parameter, even if there is an understanding for its relation to the end user costs. The conclusion is that IRI could be used as to regulate bonuses and penalties for work carried out, but it should not be a primary parameter for this purpose.

5 USING RUTTING AS A BIDDING AND WARRANTY CRITERION

Rutting is a distress type that can be mutually regarded as a functional and a structural parameter as well. Structural due to its relation to repeated loading by traffic and strain at the top of the subgrade. Developed ruts (larger than 13 mm) do affect traffic. In addition, rutting affects drainage and makes snow and ice removal more difficult. Is it as such an ideal parameter for contracting incentives?

Traditionally, ruts were measured by a short straight-edge placed transversally over either rut on the road surface. As automated road surface characteristics equipment started to appear in the 1980: ies there was a need to define rutting with a new approach. One common method was to place an imaginary string across the end points of the transverse profile and register the largest deviation between the surface and the string. Other distress than actual rutting would be recorded like “bird baths”, but a convex surface would pass without rutting. Some road engineers would rather use the term “transverse unevenness” but for all practical purposes most of the parameter could be regarded as rutting indeed.

The relationship established between rutting and top of the subgrade strain was established in the AASHO Road Test and numerous subsequent field studies. In general, the equations derived are similar but they also differ depending on the location. Usually, the coefficient of determination is much less than for the fatigue relationships found for bound materials. An example is shown in Figure 1 from a study on reconstructed roads. Even if the regression is fair, there is still an outlier with almost twice as high stress that gets the same rut depth (2mm) as a group of other data points.

Rutting occurs due to volumetric change, shearing and abrasion. Dilation also occurs in unbound layers, but should not happen if the design is right. Further, stresses in cohesive subgrade material should also be so low by design to not occur. Extreme climate situations and/or overloads may trigger these however. So if we look at the mechanism causing ruts as measured on the surface we can divide them into categories as in Table 1 below.

The surface wear is only occurring where friction enhancers are used to a high degree. If that is the case there are usually some required properties of the wearing course. Provided that the hardness of the aggregate is known with the mix properties and the traffic with studs, precipitation et cetera, the rutting is computable. Very little of the other causes of rutting can be seen in the wearing course as this layer is usually confined by the passing load in all directions. Anyway, from the standpoint of contracting, the rutting caused by wear is relatively easy to determine and thus one should be able to settle disputes about it. The ruts are also distinguishable if they are caused by passenger cars as they are narrow and closer to each other than those caused by larger trucks.

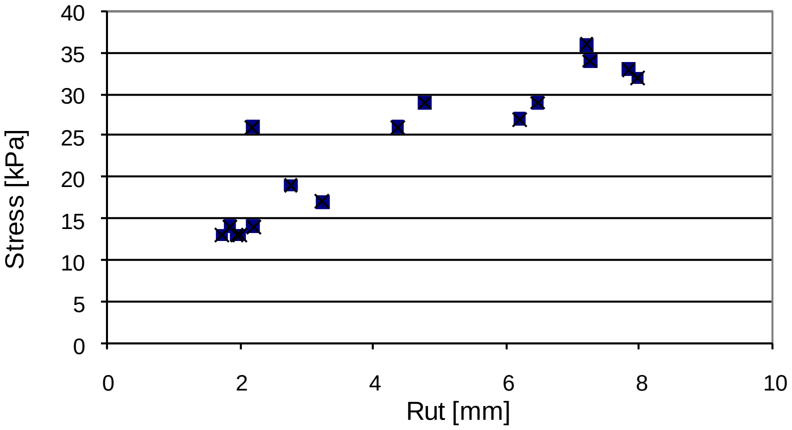

Figure 1: Relation of subgrade stress and permanent deformation determined in the field.

The rutting in asphalt bound layers is very much depending on the ambient temperature. It can be estimated from laboratory tests. A field study from California with predominantly thick bond layers recommended using shear test data, [Monismith et al 2006]

Table 1: Categorized rut mechanisms

Cause	**Predictable**	**Comment**
Surface wear	Yes	Mix and aggregate properties must be known
Initial rutting in asphalt layers	Difficult	Due to poor compaction.
Rutting in asphalt layers	Yes	Can be determined with mix design parameters
Initial rutting in granular layers	Difficult	Related to compaction
Rutting in granular layers	Difficult	Hard to distinguish from initial rutting
Rutting in cohesive layers	Very difficult	Should not occur as designed!

In colder climates and regions having plenty of aggregate sources much of the bearing capacity is accomplished by relatively thick unbound layers. In recent years there has been much research spent on their behaviour in tri-axial testing equipment. The rutting proneness can thus be determined as long as one is below the so called shake down limit. This is normally not a problem, but during certain conditions like spring thaw situations this can occur in combination with high axle loads. The tri-axial testing is also conditioned so initial rutting is almost impossible to predict from material properties tests. From a study with a Heavy Vehicle Simulator (HVS), the stress sensitivity analysis from FWD tests showed strong relationships between load and E-modulus when the material was compacted. The relationship was very low or nil before compaction. The reason being, that more energy was dissipated at the higher load levels, [Hansson & Lenngren, 2006].

So, even if there are some sound and validated relationships about rutting, there are still too many parameters that are very hard to predict. From the contractor's view it seems that warranties about future rutting ten years ahead is a too high risk that must not be taken lightly. If the warranties are too strict or the penalties are high, the result would be a need for a larger margin and hence a higher price.

6 USING OTHER DISTRESS AS WARRANTY CRITERIA

Unless there are settlements, the cross slope does not change much during the warranty time. The texture is more related to the maintenance and that may be under a different contract then the actual construction.

Cracking is usually included even if it can not be regarded as a functional parameter. Fatigue cracking in the wheel paths is a true indicator that the end of life of the pavement is reached, thus the salvage value of the bound materials is zero. This phenomenon could also be backcalculated from FWD testing data.

7 E4 MOTORWAY AT SKÅNES FAGERHULT

In recent years the present authors have come across construction projects where the as-built design was distrusted by some authorities. The examples lend themselves to suggest a comprehensive test program using the FWD during construction.

One unconventional design example is from a motorway construction in southern Sweden. It is located in a moderately undulating forested area. The subgrade is mostly consisting of a moraine formed during the latest glacial period of the area. The unbound material was compacted to a high degree so that the bound layer thickness design could be somewhat reduced. Prior to the construction, some full scale tests were done with a HVS and a larger stone subbase aggregate grading was tried. The early FWD tests showed that the bearing capacity was adequate for the alternative thinner bound layer design.

The road building code for these circumstances stipulated a traditional gravel-bitumen base layer type. It consisted of 420mm of subbase material and 80mm of unbound base material. Two alternative designs were tried in an accelerated load test facility. A heavy vehicle simulator was positioned in the roadway prior to placing the asphalt layers. A 45mm asphalt bound capping layer was placed for the purpose of creating a smooth surface for the test. Sections were instrumented with pressure cells and strain gauges. FWD testing was done prior to and after the test as well. More FWD testing has been done on an annual basis since the road opened for traffic in October 2004. The final design is shown in Table 2 below.

Table 2: Motorway Design thickness in mm.

	Code [mm]	Alternative Slow lane [mm]	Alternative Passing Lane [mm]
Asphalt concrete bound layers	210	180	95
Unbound base and subbase	500	500	585

It is outside the objective of the present paper to report about this particular test in detail but the coarser material used in the subbase exhibited significantly lower stresses and strains. Thus, the design ought to be less prone to rutting as the top of the subgrade strain was also reduced. In addition, the strain at the bottom of the asphalt layer was also reduced meaning an improved fatigue life. These findings and an extensive laboratory testing of the bituminous layers are published in a note from the Swedish Transportation Research Institute, (Hakim & Said 2000). The report also presents a pavement design for the remaining part of the project based on 30 million equivalent 10 ton standard axle loads. The design is based on the National Swedish Road Administration (NSRA) design tool program PMS Object literally translated as Pavement Management Systems Project Level. It is available as software from the NSRA website, (NSRA). As indicated above, the material elastic properties are based on generic, tabulated values resulting in a bound layer total thickness of 210 mm of which 20 mm is included accounting for studded tire wear. The contractor being confident of the results from the HVS accelerated test decided to use a somewhat thinner design, of 175 mm of bound layers. At the time of the design a change in the code was introduced. The stud wear could be based on the actual property values of aggregates. Thus 7 mm instead of the generic 20 was accounted for stud wear. Further the number of standard axle loads could be interpolated between classes, permitting an additional reduction of 17 mm. As can be seen in Table 2, the passing lane was reduced another 85 mm according to actual traffic prediction on this type of rural freeway. The question at the time of opening in October 2004 was of course if the proposed design would suffice?

7.1 Early Results

Ever since FWD testing emerged in the 1980: ies it has been suggested that the method should be used for construction control. Even though the method should be suited for this purpose the industry was not overly enthused. The problem being that the virgin road does not exhibit particularly stiff layer moduli. It seems that the bearing capacity increases with time as unbound materials are compacted by traffic over time. In recent studies it has been suggested that type I and type II rutting may be perceptible in a single, but more elaborated FWD test. Thus, better predictions can be made about future rutting and specific criteria can be postulated for the two different rutting mechanisms, (Hansson & Lenngren 2004).

FWD testing was done on a yearly basis from the opening in 2004 until 2008. The first year there was some gain in the unbound layer E-modulus, some of it likely due to post-compaction. Further testing in the years 2006 and 2007 did not show much further growth of strength in the upper layers, meaning that type I rutting had ceased to occur, which would be expected. In May of 2007 the unbound base and subbase actually lost stiffness, of which some may be attributed to the seasonal variation. On the other hand the embankment continued to grow in strength. The stiffening of the unbound layers seems to propagate downward with the number of loads, which was also seen in a previous study, (Hansson & Lenngren 2006).

The asphalt strain increased from the target 150 to 160 microstrain, which still is near the adjusted target for the remaining design traffic.

The top of subgrade vertical strain was reduced from 148 to 122 microstrain in the two years between 2005 and 2007. The target value is 240 microstrain so the criterion is met by a large margin.

For the upper unbound layers the change is attributed to the post-compaction of traffic. The apparent softening of the subbase is more likely an effect of different stress condition with less bulk stress when the upper layers spread the load better. This layer could also be wetter after the spring thaw. The subgrade consisting of cohesive soils also appear stiffer if the deviator stress goes down. The FWD testing at different load levels indicated that this may be the case. However, no further study was done in this particular case, but the assumption that the upper layers did gain strength was indeed verified. An overlay design based on a test in the spring (and adjusted for seasonal change) now suggested an overlay of 0 – 30 mm for the various test sections and actually very close to the target design if traffic lateral wander is considered.

7.2 Results after Four Years in Traffic

In spite of the relatively low critical strain values, the rutting performance of the road showed nothing but mediocre results after four years of traffic as the average rut depth as measured on the surface in the northbound direction was approximately 8 mm. Allowing for an initial rut depth of 3 mm, something like 5 mm is more likely to be expected by the model. A rut measured on the surface is the result of many processes though. Studded tires are allowed during the winter season contributing to the effect. The shape, distribution and distance between ruts all point to different layers and mechanisms behind the ruts, (Lenngren 1988). In this case it seemed as the surface was heaving somewhat besides the ruts, see Figure 2. Some other interesting observations were made:

- The deepest ruts were found on bridge decks
- The least rutting was found under overpasses

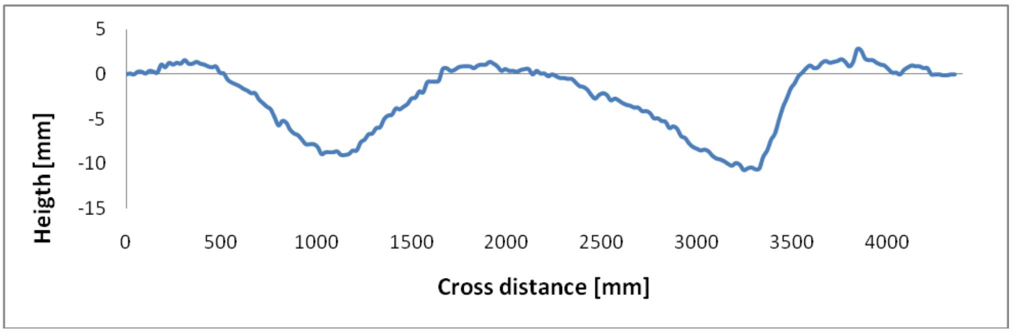

Figure 2: Cross profile showing rutting. Note heaving of material beside the ruts

This led an investigation team to believe that the rutting took place in the asphalt layer as plastic deformation. The road surface is indeed facing southwest being exposed to sunlight in the afternoon. In addition, heavy trucks arriving to seaport Helsingborg seem to agglomerate in the afternoon on their way north. The pavement temperature is considerably lower in the shade of the overpasses and hence the asphalt concrete is stiffer and less prone to deform. The deeper ruts found on the stiff foundation are attributed to the fact that the material is pushed to the side, where some heaving occurs, resulting in deeper ruts as measured. A cross-section beam was sawed through the asphalt layers as to verify which layer was deformed the most, see Figure 3.

Figure 3: A beam was sawed from the slow lane showing significant deformation. (Cracking is from moving the beam and was not caused by traffic).

8 NON DESTRUCTIVE TESTING FOLLOW-UP

An FWD was brought to the site in May 2008. Pavement temperature was recorded at depths of 40 and 80 mm respectively. During the unusually cold but sunny day the pavement temperature rose from 15 to 25°C during the test. In the shade under the overpass the temperature was more or less constant at 15°C. A second test was slated to July when it was much warmer. Then, the pavement temperature was 40°C at a depth of 40 mm and 38°C at 80 mm. In the shade it was only 21°C though. The linear layer elastic backcalculation showed very stiff unbound materials but the asphalt layers were backcalculated low as was expected at high temperatures.

Time histories showed a large difference between shaded and sunny areas for the center deflection. Figures 4 and 5 show the load plotted versus the deformation for seven deflection sensors. Note that the sensor at 1200 mm showed an almost elastic response. This sensor is mostly responding to subgrade deflection, but nevertheless it is unusual to see this response as there is normally some damping in all materials. Anyway, the test confirmed that rutting most likely occurred during hot weather in the asphalt-bound upper layers.

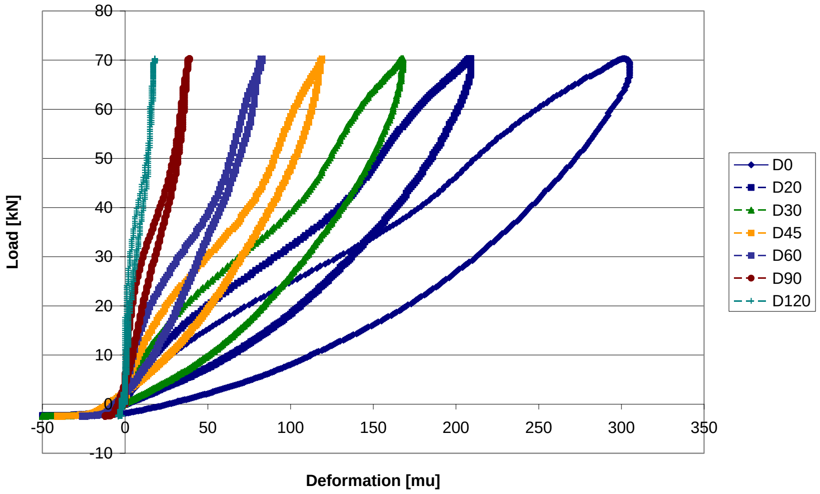

Figure 4: FWD Load-Deformation plot at 40°C

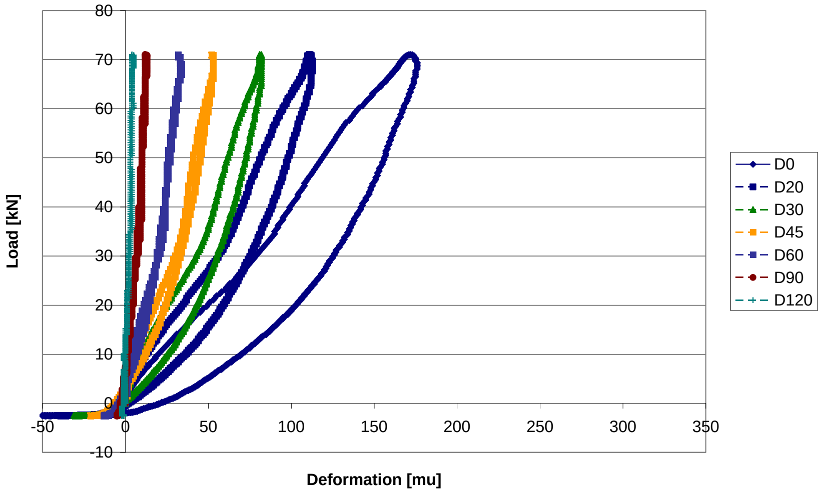

Figure 5: FWD Load-Deformation plot at 21°C

In an attempt to backcalculate the wearing, binding and base courses separately, the latter became notably stiffer than the upper two layers. The temperature gradient was about .005 K/m at the time, so it is not entirely due to the colder state. It is more likely that the deformation and inherent attenuation within the materials is redistributing the load in the time domain in a positive sense. The set up and spacing of the FWD sensors were too crude to confirm this, but the phenomenon is certainly worth studying in further evaluations.

9 SOME CONCLUSIONS ABOUT THE PROJECT

By interpolating actual design traffic between classes and by choosing a stud wear resistant material the bound layer thickness could be reduced by 30 mm or about 14 %.

By treating traffic in the fast lane separately a 125 mm reduction of bound layers was achieved. That is a 60 % reduction.

The seasonal change of layer moduli is tabulated for new roads in Sweden. No particular consideration is taken to unusually stiff subgrade or embankment layers mitigating an opportunity to reduce material spending. The motorway at Skånes Fagerhult shows a 40 mm reduction of the asphalt layer if the ambient condition is considered. This effect was not used, but shows up in the bearing capacity measurements. Nevertheless, rutting has occurred in the binder and wearing courses. This type of rutting becomes more severe if the unbound layers are stiff. This is a reminder that ME criteria may have to be adjusted and recalibrated if substantially better or different materials are being used.

10 DISCUSSION

Working with the ME model it is important to understand the need for data calibration, which is a consequence of the empirical part. For instance, in the Swedish design code, the various layers are attributed a stiffness according to the season. The unbound subbase layer is considered to be rather stiff, even during the summer period. In reality, such high values are rarely backcalculated from field tests. Thus, with one layer systematically overrated other layers or the criterion itself are adjusted to fit the model. Other issues of concern are the global warming and change of vehicles that take place over time. In the assessment of properties one must carefully consider that older laboratory and field testing equipment may not be adequate. As a rule, the test load and derived strains should be near those exerted by traffic.

ME based pavement design methods are replacing the former empirical ones. Authorities and industry have to work together on this task and come up with good proposals on a number of issues; what software to use, proper testing equipment et cetera. New construction methods and materials must be dealt with and it seems that the process of legitimizing new approaches has become more complex and harder to get through. In spite of the two rather simple strain criteria that govern the design, there are more and more restrictions on materials and more production control is usually required. The present authors recognize that all these measures are important for quality. At the same time they sometimes contribute to the waste of materials and that limited resources thus are being unnecessarily strained. In the present example about 35 mm less asphalt concrete was used compared to the specifications in the right lane and 115 mm in the passing lane. This is an average saving of over 500 metric ton per lane km. Thus, user-defined functional criteria seem to be a plausible solution to forgo some restrictions. In reality it means that the contractor is allowed to experiment, some would say gamble, more with the design. The driving force is of course cheaper solutions and perhaps a more efficient way of building.

Among concerns about foregoing construction control is the time aspect as the service life of a road sometimes outlives the life of a construction company. Sheer functional criteria would likely keep rutting and roughness down, but what about fatigue cracking which does not affect traffic directly? In reality an entrepreneur could use a stiffer binder and limit rutting at the expense of a reduced fatigue life. Warranties over a long time seem to be necessary perhaps combined with a responsibility of maintenance. For contractual purposes it will be necessary to at least roughly calculate a salvage value on which the final responsibilities between builder and buyer will be settled. Since economical values are involved both parties must agree on the method. The key to the relationship between structural status and the remaining functional prediction of service is still “the strain at critical strain points” in the structure. For a start, the two classical critical points can be used. However, deformation in each layer can now be calculated and should be used instead as field validation of new FWD backcalculation techniques continue to improve. To successfully employ mechanistic design concepts the following should be considered:

- Functional criteria are well suited to be accepted by industry and authorities alike
- The predictability of roughness and rutting is questionable. Incentives and penalties must not be exaggerated.
- Measured or backcalculated strain is an excellent parameter for assessing salvage values and remaining life of bound layers
- Deformation of layers should be calculated with concern of initial, type I and long/time type II rutting
- Improved unbound materials may contribute to increased rutting in bound materials, thus criteria may have to be adjusted accordingly.

12 CONCLUSIONS

Thorough full-scale testing of unbound materials prior to the construction proved that better performance could be predicted as regarding permanent deformation. However, the plastic deformation in the bound layers was affected so that rutting as being measured increased somewhat. The example shows how important it is to address the finished product rather than the components and how difficult it is to assess asset valuation at any given point in time. Functional criteria are suited to be accepted by industry and authorities alike. However, from the contractor's point of view there are still many uncertainties about predicting roughness and rutting so for long-time warranties the penalty rates should be reasonable. In calculating capital worth, remaining life and salvage values, the preferred parameters are backcalculated or measured strains in the structure. The reason being that the ME models are based on these strains to predict further performance. The actual performance is also affected by uncertainties about future traffic and stochastic weather and not the least imperfections in the model. From the viewpoint of the builder the uncertainty of future penalties is reduced. From the viewpoint of the public or the administration it is also attractive as a final overlay, yielding good functional data, still could be very poor structural wise. Strain criteria for bound layer fatigue are very useful for this purpose. The top of subgrade strain criterion however, is actually too generic and needs to be revised. Relying solely on the strain at a couple of critical points often calculated indirectly seem to be too outlandish for most highway authorities on the other hand. Therefore, most of the construction control tests remain; needed or not. However, sometimes these prevent better and cheaper methods from being developed. Hence, a careful evaluation is needed for each and every test.

The authors see a great potential for saving resources by the mechanistic approach and functional criteria working together. As mentioned in the paper it is not a trivial task to implement mechanistic design to replace older code built entirely on empirical knowledge. However, with sound field testing and tools to backcalculate mechanical properties, we think there is reason to adopt these ideas. Hopefully, our experience will help people interested in getting started. Advanced models employing FWD time, history evaluation is recommended. A thorough testing with FWD using repeated multi-drop sequences with increasing and decreasing loads is helpful in assessing soil and materials properties other than pure elastic. Thus, deviations from the elastic models could be assessed and properly handled. In later stages the non-elastic behaviour could be included in the model.

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