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Performance-Based Specifications for Sustainable Pavements: A Lean Engineering Analysis

Yara Hamdar[a], Hussein Kassem[b], Issam Srour[c]*, Ghassan Chehab[d]

[a]Graduate Research Assistant, Civil and Environmental Engineering Department, American University of Beirut, Beirut 1107-2020, Lebanon
[b]Graduate Research Assistant, Civil and Environmental Engineering Department, American University of Beirut, Beirut 1107-2020, Lebanon
[c]Assistant Professor, Engineering Management Program, American University of Beirut, Beirut 1107-2020, Lebanon
[d]Associate Professor, Civil and Environmental Engineering Department, American University of Beirut, Beirut 1107-2020, Lebanon

Abstract

Lean concepts, though born in the manufacturing industry, have since made their way to the construction industry. In a broad sense, lean concepts aim at minimizing waste and maximizing value which can be related to cost, quality, and time. These aims are in-line with sustainable construction processes which target reducing the waste (e.g. resource consumption and emissions) in construction activities. As such, lean should not be viewed as a set of tools and techniques, but rather an approach and conceptual framework that can be catered to suit the needs of the process under study. Implementing lean concepts in the building construction sector has been proven challenging due to the uniqueness of each project. In infrastructure projects, such as pavements and bridges, the application of lean concepts is at its infancy stages and thus is still not well assessed and researched. The focus of this study is to investigate the implementation of lean concepts in pavement construction, specifically in the quality assurance/quality control (QA/QC) process. The ultimate objective is to come up with conclusions on how to maximize the value of pavements as dictated by their performance, while minimizing wastes due to inefficient QA/QC.

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Keywords: Pavement, Asphalt, Rutting, Performance-Based Specifications, Lean Concepts, Dynamic Modulus, Total Quality Management, QA/QC

* Corresponding author. Tel.: +961-1-350000 ext. 3491.
E-mail address: is04@aub.edu.lb

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1. Introduction

Lean concepts, though born in the manufacturing industry, have since made their way to the construction industry. Although the general approach towards lean construction tends towards making construction more like manufacturing through standardization, practitioners and researchers soon realized the dynamic nature of construction project management and attempted to implement lean concepts accordingly throughout the various phases of the project [1]. In a broad sense, lean concepts aim at minimizing waste and maximizing value which can be related to cost, quality, and time. Therefore, lean is not a set of tools and techniques, but a way of thinking that can be catered to suit the needs of the application under study. Typical categories of waste in construction include completing activities ahead or behind schedule, unnecessary transport (double hanging), material stocks, and waste of untapped human potential among others [2].

Implementing lean concepts in the construction sector has proven challenging due to the uniqueness of each project. In construction, the owner/user determines the end product, and the same design is rarely recurrent. Nonetheless, some basic conclusions can be drawn concerning the implementation of lean concepts in similar project types. As a result, lean design and construction are increasingly being adopted in construction projects to derive benefits similar to those established in the manufacturing industry, particularly lower costs, fewer delays, less uncertainty, less waste, more efficient buildings and facilities, and higher user satisfaction [3].

Several attempts have taken place to simulate roadway construction projects whereby different operations have been modelled and the performance of each has been analysed in terms of process flow and resources utilization in order to optimally schedule activities and manage resources [4, 5, and 6]. These attempts are usually carried out either using general-purpose simulation tools or construction-specific simulations. The aim is to simulate the interaction among different resources, activities, and the flow of information in the roadway construction process. The end result is a clear flow of value to the final product which helps the management team in identifying the required activities, decisions, queues and resources required, and in clarifying process sequences and logic, resulting in identifying opportunities for improvements [5].

González et al. studied the use of buffering strategies for roadway construction projects in order to reduce the impact of variability on these projects through models that can be utilized by decision makers [6]. Forbes et al. discussed the safety management of roadways from a lean perspective and proposed methods to avoid accidents and their corresponding wastes [3]. Others ventured into applying lean engineering concepts to roadway construction activities [7].

It can be observed from literature that applications of the lean philosophy in construction focus on the buildings sector. Although road construction projects are typically of larger scale than buildings, they have not been as well studied in the context of lean practices. The focus of this paper is to investigate the implementation of lean concepts in pavement QA/QC methods and specifications and link these concepts with sustainable engineering practices. To date, little has been investigated in this area. By relying on a road construction case study, the aim is to come up with conclusions on how to maximize the value of pavements as dictated by their performance, while minimizing wastes due to inefficient QA/QC. The paper begins by introducing background information on asphalt materials, pavement distresses, pavement QA/QC and the application of lean concepts in pavement design and construction (Section 2). Section 3 presents the analysis of pavement QA/QC methods in relation to lean concepts and sustainability based on a selected case study.

2. Background on asphalt pavements

2.1. Asphalt concrete material properties and testing

Asphalt concrete (AC) consists of three main constituents: asphalt (bitumen), aggregates, and air voids. The materials selection and volumetric design (i.e. percentage of binder, aggregates and air voids) of an AC mix mainly depend on the climatic and traffic conditions. Asphalt is a bituminous material that exhibits viscoelastic behaviour, meaning that its material properties vary depending on temperature and duration of loading and are thus difficult to quantify and report. One of the most significant indicators of the quality and behaviour of an AC mix is its stiffness as indicated by its dynamic modulus ($|E^*|$). The same AC mix has different values of stiffness for different combinations of temperature and loading frequency. Unlike concrete whose compressive strength can be accurately acquired from a simple, quick and cheap test for the purposes of QA/QC, measuring the stiffness of asphalt at different temperature and frequency combinations is an intricate, costly and time-consuming process that requires skilled workmanship. The dynamic modulus (|E*|) is measured by conducting a test called simple performance test (SPT) [8]. The test mainly consists of subjecting a cylindrical asphalt specimen to a certain load at different combinations of loading frequency and temperature. On average, testing one asphalt concrete specimen requires at least one day.

2.2. Pavement distresses and pavement performance

The value of an asphalt pavement is dictated by its performance, which is related to the level of distresses in the pavement. The two main pavement distresses are rutting and fatigue cracking. Rutting is a phenomenon that is exhibited through surface depression under the wheel path (Figure 1a). There are two types of rutting: asphalt rutting and subgrade rutting. Subgrade rutting is a structural problem and is not of interest in this paper. Asphalt rutting is directly related to material properties of the asphalt mixture at the surface of the pavement and typically results from poor materials selection, deficient compaction, sub-optimal mix design, among other constructability problems. Rutting typically occurs at high temperatures and low loading frequency (slow vehicle speed). On the other hand, fatigue cracking consists is manifested through the formation of a series of interconnected cracks caused by failure of the asphalt pavement at moderate temperatures under repetitive traffic loading (Figure 1b).

Figure 1a. Rutting [9]

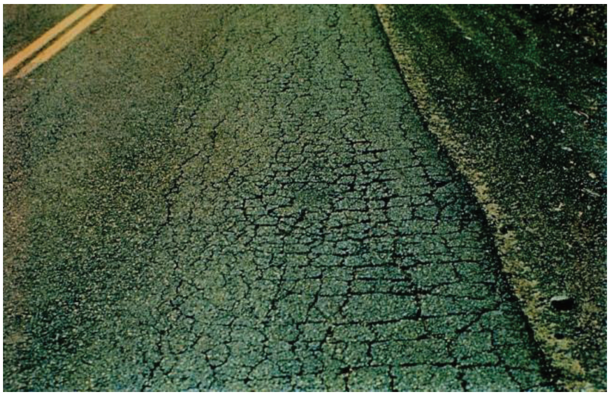


Figure 1b. Fatigue cracking [9]

To avoid rutting, the AC should be very stiff (i.e. with a high |E*| value) at high temperatures, whereas to avoid fatigue, the AC should be soft (i.e. with a low |E*|) at moderate temperatures. From a lean engineering perspective, the higher the level of distresses, the lower the value of the pavement, and the higher the waste due to premature maintenance and/or rehabilitation. On the other hand, over-designing the pavement such that no distresses are present over its service life generates waste in terms of excessive use of natural resources (aggregates and bitumen). The optimal lean pavement is one that exhibits adequate performance over its service life (i.e. limited distresses) with just enough resource consumption.

2.3. Importance of reliable pavement QA/QC

Proper pavement QA/QC is essential to limit pavement distresses over its service life. Pavement distresses have the following main consequences:

- Deteriorated pavement conditions leading to increased user costs (e.g. vehicle maintenance costs, traffic delay, accidents), and
- Premature rehabilitation and/or reconstruction leading to waste of resources (materials, money, time,

workmanship) and closure of roadway which causes traffic stoppage (vehicle or aircraft) and/or imposes work-zone user costs (e.g. work-zone traffic delay, work-zone accidents, work-zone vehicle maintenance).

2.4. Common reasons for pavement distresses and importance of TQM

Based on a literature review focusing on case studies targeting pavement distresses, a summary of factors contributing to improved pavement performance are depicted in the fishbone diagram in Figure 2. These case studies constitute a basis for a qualitative analysis of pavement distresses and failures (rutting, cracking, ravelling etc.) resulting from errors during design, mix production and construction. The fishbone diagram suggests lean solutions to avoid errors that may lead to pavement distresses pavement distresses and failures. The diagram highlights the importance of total quality management (TQM) which is achieved through ensuring that designer and contractor aim at providing pavements with acceptable long-term performance instead of concentrating only on the short-term consequences.

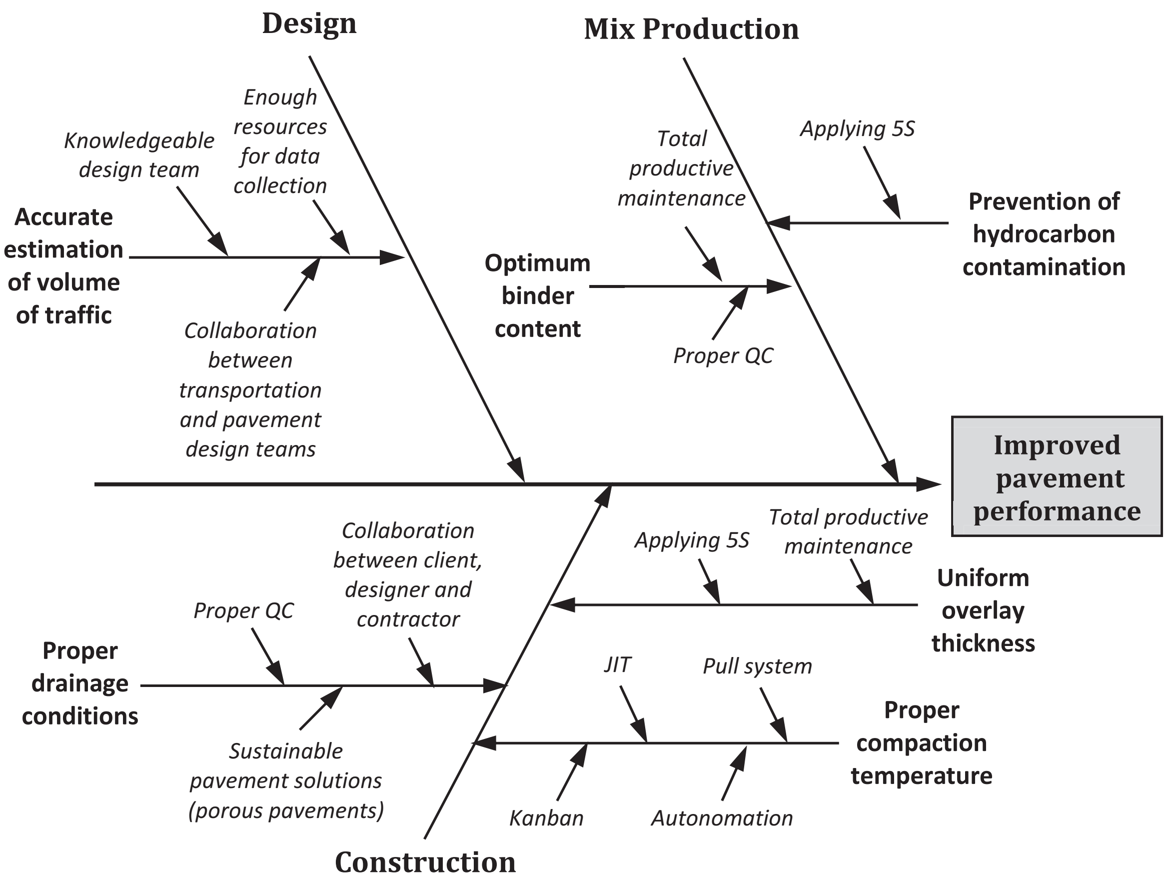


Figure 2. Suggested application of lean concepts for improved pavement performance

3. Analysis of pavement QA/QC methods and specifications in relation to lean concepts and sustainability – case study

As highlighted in Section 2, asphalt is a complex material and its proper characterization requires an intricate process. The pavement QA/QC process may rely on simple volumetric parameters or thorough material characterization. A case study is used to analyse three main criteria for pavement QA/QC from a lean engineering and sustainability perspective:

1. Volumetric specifications, particularly binder content:
   These pertain to QA/QC specifications that rely solely on the composition of the mix, i.e. percentage of binder, aggregates and air voids in the mix.
2. The stiffness or |E*| at a single temperature and frequency combination:
   This refers to QA/QC specifications that are based on |E*| values corresponding to a single temperature and frequency combination based on the prevailing traffic and climatic conditions.
3. The stiffness or |E*| at a range of temperature and frequency combinations coupled with performance prediction models, i.e. performance-based specifications:
   This refers to QA/QC specifications that rely on accurate performance prediction (i.e. rut values (depth) and fatigue percentages) based on thorough SPT results at various combinations of temperatures and frequencies.

The first criterion is a *performance-related specification;* whereas, the second and third ones are *performance-based specifications* [10, 11, and 12]. Performance-related specifications, as indicated by their name, rely on materials and construction quality characteristics that have been found to correlate with fundamental engineering properties that predict performance, such as air void percentage and binder content. Those typically require simple, quick tests, data of which are easy to analyse. Performance-based specifications take pavement QA/QC to a new level by relying on fundamental engineering properties (e.g. full |E*| characterization) to predict the performance of the mix over its service life. These predictions typically include rut values (depths) and fatigue percentages. Because most fundamental engineering properties are associated with timely and costly testing and more complex data analysis, performance-based specifications are not yet widely used in pavement construction. However, as the case study described below shows, adoption of performance-based specifications from a lean engineering perspective is essential and timely.

3.1. Case study description and methodology

The findings of this section are based on data from a pavement construction project that has been recently completed in the Middle East. During construction, samples from a total of 18 batches corresponding to 18 paving days were collected for testing and QA/QC analysis. Each batch is in the order of thousands of m^3/day. Due to the high stakes of this project, and for the interest in more reliable and accurate QA/QC, and hence expected performance, the stakeholders agreed on conducting the SPT test for each batch in addition to the commonly adopted volumetric tests.

Volumetric and SPT test results were compiled and a Microsoft Excel-based tool (NCHRP 09-22) [13] was used to predict the distresses corresponding to the properties of each mix. The distresses were predicted based on two different sets of data for comparison:

1. One |E*| value for each batch selected at a temperature and frequency combination relating to the prevalent traffic and climatic conditions, and
2. Complete |E*| data (mastercurve) from the SPT test.

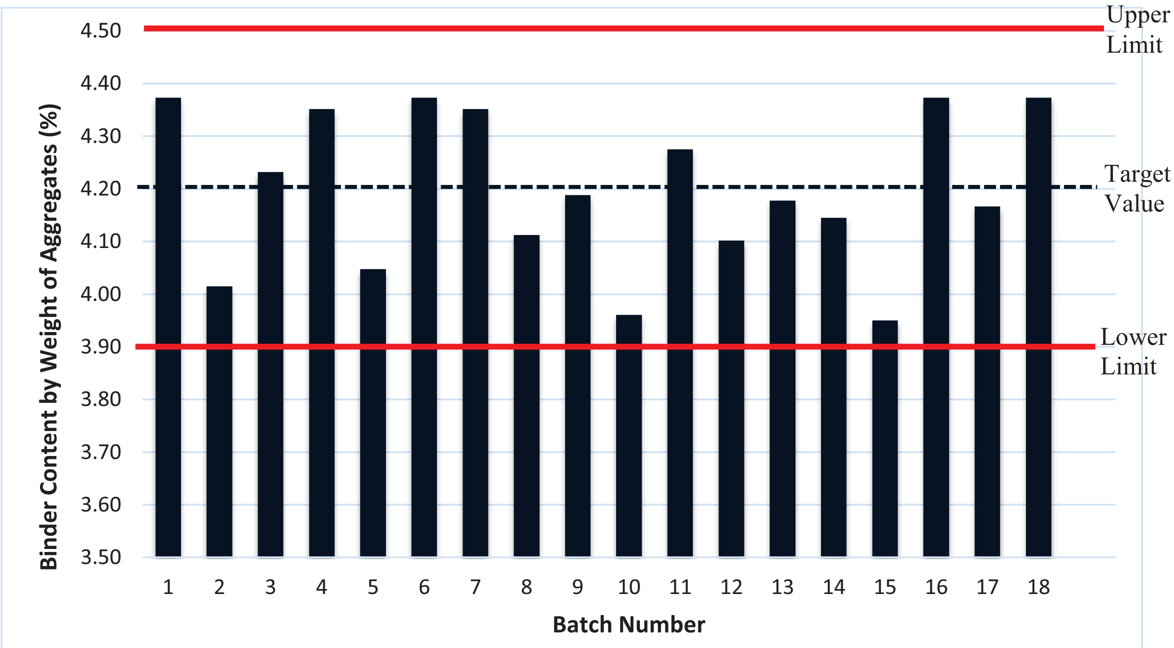
Since hot climatic conditions prevail in that region, the analysis focuses on rutting which is the most critical distress in such a case.

3.2. Analysis of the QA/QC methods and specifications

The following discussion presents the analysis of the three main pavement QA/QC criteria: binder content, single |E*| value, and full |E*| characterization, in light of lean engineering and sustainability concepts.

3.2.1. Binder content (performance-related specifications)

Theoretically, high binder content corresponds to higher susceptibility to rutting. For this reason, binder content is often used as a criterion in QA/QC and pay factor analysis in the context of rutting. The advantage of this test is its relatively low cost. While value of binder content serves as a good indicator of the quality of the mix production, it is not an adequate indicator of the mix's performance over its service life. The quality of the mix's performance is dependent on many variables in mix production, laying and compaction. Relying solely on one volumetric property is simply not enough to forecast the performance of the mix. Typically, specifications set a target binder content and an allowable margin of error. For the case study presented in this paper, the required asphalt content is 4.2% by weight of aggregates with an acceptable error of ±0.3%. Tested samples from each batch indicate that the binder content falls within the acceptable range of 3.9-4.5%, as shown in Figure 3, which theoretically indicates that all mixes will have adequate performance over their service life. To validate or negate this hypothesis, the binder content of each batch was compared to the predicted rut value based on the full SPT (Figure 4). By comparing the two, no correlation was found between rut value and binder content, i.e., it is not always the case that higher binder content leads to higher rut value. Moreover, even though the binder content of all mixes falls within the acceptable range, the rut values of two of the lots fall above the upper limit of 0.5 cm. Therefore, the drawback of relying solely on binder content is the lack of accurate prediction of distresses which may weaken the reliability of the QA/QC. From a lean engineering perspective, this hinders the detection of potential "defects" (distresses) at an early stage (during or shortly after construction) when corrective measures can be taken. This, in turn, results in delayed problem detection which will most likely occur after the distresses appear, leading to premature rehabilitation and/or reconstruction (e.g. waste of resources, money, energy, and workmanship). From a sustainability standpoint, premature rehabilitation and/or reconstruction leads to higher consumption of natural resources (asphalt and aggregates) and increased emissions due to the construction process (asphalt concrete manufacturing and construction machinery). Based on the aforementioned, relying solely on binder content for pay factors (incentives and penalties) is thus not highly accurate.



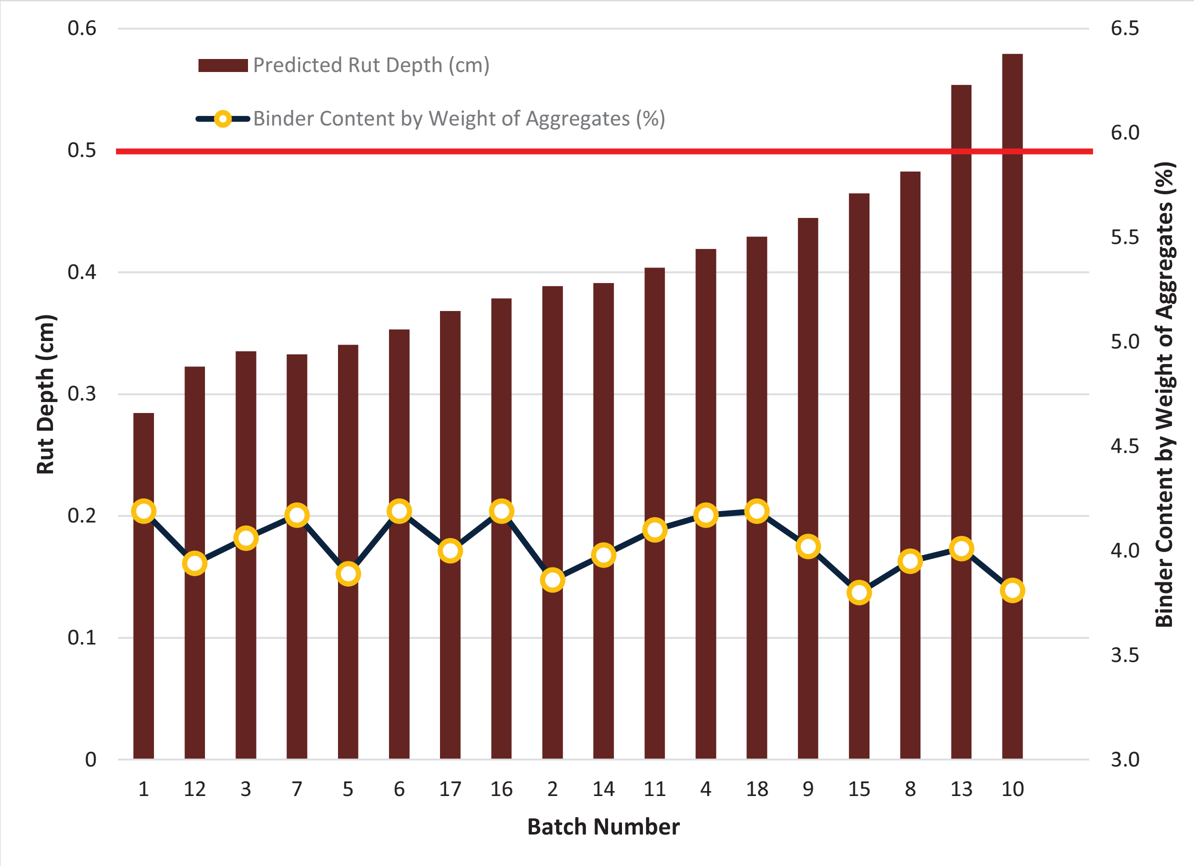


Figure 4. Rut values and binder content

3.2.2. Single |E*| value (performance-based specification)

A common QA/QC method relies on a single |E*| value at a specific temperature and frequency combination that is deemed appropriate by the QA/QC engineer based on the distress type, climatic and traffic conditions. The advantage of this method is that it is more reliable than considering the binder content alone. Moreover, it requires testing the asphalt specimen at one temperature and frequency combination only, which significantly reduces the time required to conduct the SPT test from about a day to about an hour. The corresponding cost and time for data analysis are reduced as well. To assess the effectiveness of this method, the rut value corresponding to each of the lots based on one |E*| was predicted using the NCHRP 09-22 tool [13]. These values were then compared to those acquired based on full SPT data (multiple frequency and temperature combinations). The results showed that the simplified method of considering a single |E*| value underestimates the predicted rut depth by an average of 15%. In other cases, the simplified method might overestimate rut depths.

Here too, from a lean perspective, though relying on a single |E*| value saves money, time and effort in terms of conducting the SPT during the QA/QC process, it hinders the detection of potential “defects” (distresses) at an early stage (during or shortly after construction) when corrective measures can be taken. As a result, detecting any problem most likely occurs after the distresses appear, leading to premature rehabilitation and/or reconstruction and their associated costs. When considering pay factors (incentives and penalties), relying on one |E*| will not result in reliable liability weighting. If relying on one value of |E*| for QA/QC under-predicts distresses, losses resulting from the defected lots (premature rehabilitation) are shifted to the client although the contractor should be held accountable. Whereas, if relying on one value of |E*| leads to an over-prediction of distresses, the contractor is held accountable for an error that is non-existent or less severe than what is predicted.

3.2.3. Performance-based specifications and lean concepts

As highlighted in the sections above, performance-related specifications hold a lot of uncertainty and do not offer an accurate indicator of performance. The added benefit of performance-based specifications, particularly those relying on thorough material characterization (full SPT results), is that they offer a platform for a *pull system*. They allow the stakeholders in general, and the QA/QC engineer in particular, to pull the level of distress predicted to occur at the end of the pavement's service life, and use this information for defect detection and corrective action at early stages in the project. Corrective action or rework at an early stage of the project is less costly than rework at a later stage. Later stage rework incurs higher mobilization and work-zone costs. Thus, performance-based specifications allow for function analysis of the pavement to reduce uncertainty and ensure sustainable practice by reducing waste, mainly, excess resource consumption and emissions due to rework.

Although performance-based specifications theoretically offer more reliable QA/QC and reduce wastes as highlighted in the discussion so far, it is important to note that the choice of specifications is directly related to the type and scale of the project. The quality cost versus the cost of quality should be considered in a benefit/cost analysis to determine the optimal procedure and specification type for the project under consideration. In large-scale and/or high-profile projects such as the case study discussed above, opting for performance-based specifications adds significant value to the QA/QC process and to the project in general. However, in small-scale projects such as construction of rural roads, performance-based specifications may not be viable from a value versus cost perspective.

4. Conclusions and recommendations

Due to the high cost and lengthy time associated with conducting the SPT, it is often the case that pavement project stakeholders opt not to conduct the test for QA/QC. Instead, the QA/QC process is based on volumetric properties such as air void content and binder content. The shortcoming of such method is that volumetric properties are not always reliable indicators of the asphalt concrete's long-term performance. This is also the case for the use of one |E*| value at a specific temperature and frequency combination. For reliable QA/QC and proper total quality management (TQM), the culture of the pavement industry should shift towards performance-based specifications. This is achieved through the use of SPT results with accurate performance prediction models and tools in order to predict level of distresses of the pavement throughout its service life. However, a benefit/cost analysis of QA/QC methods and specifications helps determine the optimal option for the project at hand depending on its type and scale.

5. Acknowledgements

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