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Review

THE FUTURE OF PERFORMANCE-RELATED BINDER SPECIFICATIONS

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Abstract. *This paper outlines a conceptual groundwork for the next generation of comprehensive performance-related binder specifications. A system is proposed that captures a binder's relative contribution to the performance of the hot-mix asphalt (HMA) based on averaged damage-weighted functions rather than current practice using single-point properties. The damage weighting is based on the environment, traffic conditions and the pavement structure. In the new concept the bulk material properties (e.g. viscosity, expansion coefficient, etc.) as well as failure properties (e.g. failure stress, failure strain, etc.) are incorporated into the specification and/or performance predictions.*

A binder specification cannot predict pavement performance because ultimately it is a purchase specification that assist in the selection of the binder with the best cost-performance-ratio for given design condition. The performance depends on the actual quality of the other mix components (aggregate, fillers, etc.) as well as construction quality (in-place air voids, aggregate, fillers, etc.) and the interactions. Thus, ideally the owner (or highway agency) would specify certain guaranteed pavement performance criteria and the producer (i.e., the maker of the HMA) would use component specifications (e.g., binder, aggregate, filler, etc.) for selecting the superposition principal and therefore the interactions between the various components, which would require the development of much more sophisticated models, are not considered.

In the proposed new scheme, the classification and certification of a binder are each separated into three different levels:

- *Binder Grading*
- *Binder Certification*
- *Binder Verification*

The grading part does not enter the purchase process and, thus, is only a guide to assist binder producers in properly evaluating their systems. Prior to its shipment, a binder must be pre-qualified and certified to meet the specification. This certificate of compliance is based on a performance-related specification. Once a binder has passed this "checkpoint" it is subjected to verification testing during actual production. This means that the testing can be reduced to certain descriptive tests, which guarantee the purchaser that the supplied binder can be regarded (within reasonable tolerances) as the "same" binder that was supplied during pre-qualification. Failure to meet the binder verification does not mean the binder will not perform adequately, it only means that the binder has changed and needs to be re-certified before production can be proceed. A sound engineering approach for determining the tolerance thresholds is also discussed herein.

In addition, the Superpave binder specification is evaluated with regard to the conclusions presented in this paper and a next-generation "SHRP-2" specification proposal is introduced that captures the concepts presented in this paper. Its possible implementation and implications are also discussed.

Key words: *performance-related binder specifications, averaged damage weighted functions, single point properties, bulk material properties, fracture properties, cost-performance-ration, component specifications, binder certification, binder verification, SHRP-2*

1 Purpose of Binder Specifications

The primary purpose of any specification is to facilitate the purchase of superior quality product. Thus, for a potential seller it defines the product that the buyer expects. A binder specification should not only define the product but it should also ensure that the binder performs adequately and does not cause premature pavement failure. Hence, an ideal specification should contain those properties that directly affect the pavement performance when all other mix components meet their respective specifications and where the binder significantly influences the in-place performance. If the binder's influence on a certain distress is only minor then it should be a part of the binder specification. In that case it would be more effective to improve specifications that substantially improve the resulting in-situ performance.

Generally, binder specification requirements (excluding those parameters pertaining to health, safety and environment) should always be economically justified. This means the true cost for adding a parameter (extra testing and analysis, extra storage capacity cost because of delays in testing, ...) should be significantly less then average expected benefit (reduced annual per lane mile cost because of increased pavement life, reduced user cost, ...) as shown in Figure 1.

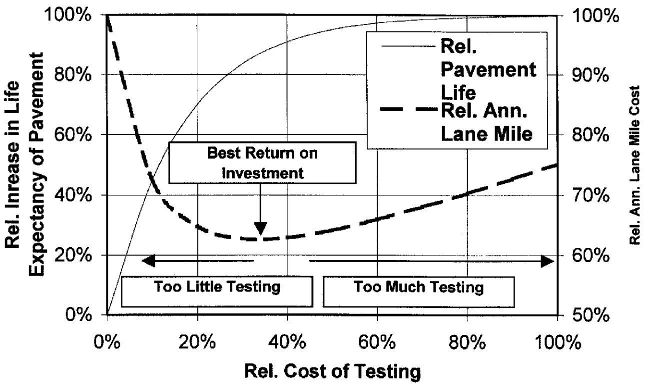

Figure 1. Schematic plot of cost of testing versus relative increase in life expectancy of a pavement and relative annual per lane mile cost.

The other important aspect of the specification is the guarantee of uniformity. If the specification is not uniform then it appears in many different versions according to the experience of the users (highway agencies). Users are often tempted to change specifications so that the products they have satisfactorily used in the past continue to be used. Proliferation of specifications becomes more prevalent if the specification parameters do not correlate with observed pavement performance, or are unusual in that they were designed to test a particular composition or formulation of the binder. Specifications can also proliferate because of the constrains of the local economy and specifications adopted by surrounding territories. The state of Oregon in the United States of America at one time accepted asphalt binders specified by three different grading methods [1]. As early as 1929 Julius Adler [2] has discussed the need for standardization and discontinuation of unnecessary and unusual tests.

2 Specification Types

There are in principal three different types of specifications.

- Descriptive Specifications
- Performance-Related Specifications
- Performance-Based Specifications

Our definition of each specification type is given in the following.

2.1 Descriptive Specifications

Descriptive specifications have been widely used for modified asphalt systems. In this case the test that are performed and their parametric values are selected to ensure that a certain type of material is provided. The specification is not design to target a performance level via the tests. The correlation with performance is emprical and is, generally, based on field observation. Typical examples for descriptive specs are the ASTM polymer modified (PMA) specifications (ASTM D 5976, D 5841, and D 5892) for EVA, SBR and SBS, respectively.

2.2 Performance-Related and Performance-Based Specifications

Performance-related and performance-based specifications are often not properly distinguished. However, they are conceptually very different specifications. In this paper specifications are defined as performance-related where the test parameters are selected to correlate with pavement performance. The specification is intended to be blind, i.e., the specification tests and their critical thresholds have not been selected to be descriptive of a certain material (e.g., Trinidad Lake modified asphalt or a blend of 3% SBS in an AC-5, etc.). However, a performance-related specification parameter(s) covers only the binder component. Obviously, the in-place performance is also influenced by the aggregate, fines, AC content, air void content, etc. Thus, the main difference between performance-related and performance-based specification is that the latter is based on the performance of the complete system.

Example: Let us assume, for the sake of discussion, that the current Supersave high temperature specification parameter, $G^* / \sin\delta$*, of a binder correlates with the rut resistance of the mix. If a binder A has a higher value of* $G^* / \sin\delta$ *at a temperature T than another binder B then we can assume that binder A is more resistant at this temperature. We may also be able to predict how large the performance is using fundamental or semi-empirical models where we assume certain mix properties. However, it would be a fallacy to assume that A will outperform B in a different mix, i.e. a certain value of* $G^* / \sin\delta$ *for the binder only means that the binder will probably not be the cause for the premature failure in rutting if the mix meets certain minimum quality standards. In a truly performance-based specification the* $G^* / \sin\delta$ *of the mix would have been specified.*

Generally, component specifications such as a binder specification are always, at best, performance-related. The only real exception to this rule is when a component (e.g., the binder) totally controls the performance. Our observation has been that in the case of all major distresses in asphalt pavements (i.e. rutting, fatigue, thermal cracking and stripping) the performance is never controlled by just one component.

Performance-related specifications can be further subdivided into two groups.

- Empirical Specifications
- Fundamental Specifications

The empirical specifications are based on empirical tests and, thus, generally use empirically derived relationship to establish the link to pavement performance. Fundamental specifications, on the other hand, use fundamental engineering material properties, such as stress and strain for specifying the binder, which can be used in theoretically well founded mechanistic models (cf., section 4) to predict pavement performance.

3 Binder Testing

The specification parameters should be measured using relatively easy, fast and affordable test methods. This however does not preclude the use of sophisticated tests when warranted by the importance of the measured property on the overall pavement performance. As previously mentioned the average expected long-term savings, as shown schematically in Figure 1, should outweigh the real compounded cost of testing.

The measured properties should be fundamental material properties and not be empirical, surrogate measures, which cannot be used in comprehensive performance prediction models. Ideally, there should be for any given distress mechanism a theoretically sound performance models for which the specification parameters are direct input variables.

$$\tilde{P} = f\,(a,b,c)_{\alpha,\beta,\gamma} \qquad (1)$$

where $\tilde{p}$ = normalized performance (e.g., rel. rut rate)
a,b,c = binder specification parameters
α,β,γ = other components variants which are held constant

Example. The penetration test is a classic example of an empirical test because the state-of-stress imposed by the penetration needle is ill-defined. Fundamental properties such as engineering stress and strain are not obtained and, hence, the penetration values cannot be used in mechanistic models. In the low temperature tensile test, for example, the stress state is "simple" and well-defined which produces fundamental material properties such as failure stress and strain at failure. These properties in turn are used in the most recent proposed modification to the provisional AASHTO Binder Specification to predict pavement performance /5/ at low temperatures.

It is not sufficient to measure the correct property but also to measure this property at conditions that match the field conditions as closely as possible. If service temperatures are not practical to use in a laboratory, alternative rates and temperatures can be determined using time-temperature superposition. This is done in the Supersave binder specification at low temperatures both for the Bending Beam Rheometer (BBR) and the Direct Tension Tester (DTT). Because of the difficulties in measuring at very low temperatures (generally -22 to -36 °C) and to reduce testing time (the BBR would be a eight hour test instead of a 240 second test) the tests are performed at the lower spec limit plus 10 °C ($T_{test} = T_{spec,\,min} + 10$ °C) and a high extension rate (e.g., $\varepsilon'_{DTT} = 3\%/\mathrm{min}$).

In section 4 it will be shown that it often does not suffice to take a single-point measurement because the conditions and ranges modelled are not singularities. Thus, for certain distress forms the binder properties should be measured over a range of conditions to obtain a property spectrum (e.g., the BBR where the stiffness is measured at 8, 15, 30, 60, 120 and 240 seconds[3]). In these cases the specifications does not contain a threshold for the binder property (e.g., the binder viscosity shall be greater than ...). The threshold in the specification pertain to the computed performance indicator (e.g., the critical cracking temperature shall be lower than ...).

To-date certification and production testing are generally conducted using the same specification and tests. However, we would like to advocate an approach where two separate sets of testing are utilised. Initially the binder should meet all the specification has been judiciously designed this certified binder should perform adequately. This testing we define as Certification Testing. The certified binder is then used to prepare the mix. Inherently, the mix properties and mix formulation (e.g., AC content and design air void level, etc.) assume that the binder properties remaining do not only meet the specification but also remain constant within certain tolerances levels.

Example: Let us assume a binder was certified to meet the 70 °C G/sinδ requirement of 2.2KPa. The actual G*/sinδ may have been 2.45KPa. Now let us assume that during production the producer increases the modifier concentration and in this process raises the G*/sinδ value to 3.12KPa. From the seller's point of view this may represent a better product because the G*/sinδ has actually increased (i.e., it should be more rut resistant). From the purchaser's point of view they are receiving a different product, and in fact, the pavement performance may suffer (e.g., the in-place air void levels may increase, etc.).*

During actual production the binder should be subjected to what we defines verification testing. This means that the testing can be reduced to certain descriptive tests, which guarantee the purchaser that the supplier binder can be regarded (within reasonable tolerances) as the "same" binder that was certified to comply with the specific. The requirements for these tests are, thus, very different to the beforementioned specification tests. In this case the prime objective from the purchasers point of view is to capture binder changes whilst the producer will want a set of fast and easy to run tests. To reduce cost of testing and to increase the frequency of such quality control testing is also beneficial to the user and can be effectively used to establish pay factors. An example is discussed below.

Example. Bouldin et al. /4/ have proposed the following approach for the new low temperature specification currently under consideration by AASHTO. The two BBR tests and one DTT, which constitute the certification tests, are substituted for verification testing by one DTT test. In this case the DTT's sensitivity to material quality changes is utilized. Formulation changes invariably have a significant impact on the materials strength and extendibility. In this case, the BBR and DTT data are used to calculate a critical cracking temperature, T_{cr} *and the strength* ($\sigma_f \geq \sigma_f^{Tol}$; σ_f *is the strength, is the minimum allowed strength) and stiffness* ($E_f \leq E_f^{Tol}$, E_f *is the actual secant modulus*

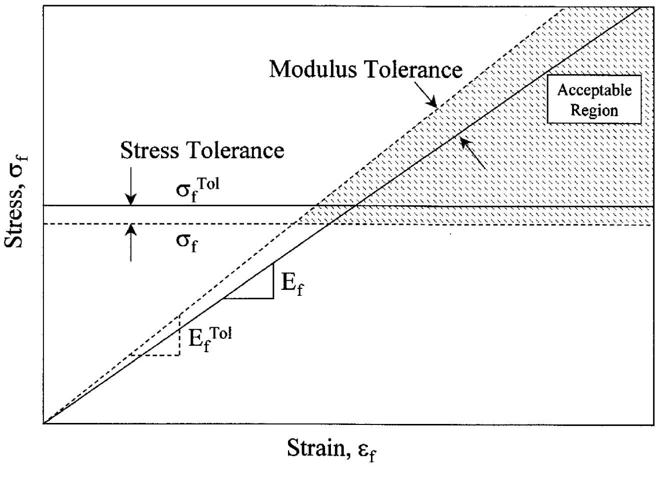

Figure 2. Schematic plot of failure stress and failure modulus tolerances.

at the failure point; E_f^{Tol} *is the maximum allowed stiffness) limits are selected to disallow binders, which would reduce* T_{cr} *by more than 1 °C. An acceptable area or region is obtained (cf., Figure 2). Ideally there would be for both* E_f *and* σ_f *an upper and lower tolerances, which would reduce the allowed region into a trapezoid.*

4 Performances Models

As previously mentioned specification parameters should have a direct correlation to pavement performance. The models that link the performance with the specification parameter(s) can be empirical or semi-empirical. Truly non-empirical models do not exist because at some point it becomes necessary to link mix/pavement performance via a damage transfer function to the measured properties. Two examples that have been extensively discussed in the literature are fatigue testing and single event thermal cracking at low temperatures [5]. However, there should be a strong bias towards developing sound theoretical models which assist the engineer and producer in understanding what kind of binders will perform well in a given environment. They also decrease the probability that binders can be formulated to "fool" the specification without providing adequate performance.

The models and performance predictions should, whenever possible, be validated using mix testing and filed performance data is not a simple task. In most cases the results are confounded by a large number of variables so that it is difficult from the WestTrack. Thus, it is often advantageous to use so-called torture tests top validate the selected models and parameters. Typical examples are widely used wheel trackers [6,7] (e.g., Hamburg wheel tracker or Georgia wheel tracker) or accelerated loading facilities (ALF) [8].

4.1 Averaged Weighted Damage Functions versus Single-Point Properties

Basically all binders specifications are currently sold using single-point properties as a specification limit. In some cases ranges are employed (e.g., penetration grad 80/100). However, to properly model a binder's response to distress it is important to understand that the distress will manifest itself over a range of conditions. This is especially true for many load-associated distresses where the damage progression is cumulative versus a single event [9]. In this case the performance can only be understood by averaging the sum of the damages. A generalized form for determining the damage is as follows [10].

$$\bar{D} = \frac{}{(x'-x_0).(y'-y_0).(z'-z_0)} \int\int\int_{x_0y_0z_0}^{x'y'z'} \varphi(x,y,z)dxdydz \qquad (2)$$

x, y and z are the variables that the damage function φ is dependent on. (The number of variables is obviously not limited to 3 but can be any number from 1 to n). Some examples, which illustrate the application of Equation 2, will be discussed below.

4.1.1 Averaged Weighted Damage Functions in Rutting.

For rutting Kern and Carperter [11] have shown that the concept of a singular temperature to determine the rut resistance of a binder does not work. They compared locations with equal "average weekly pavement highs", which is currently used in the Supersave binder specification for the determining the resistance of a binder, in locations with significantly different average temperature distributions. They concluded that the sites, which had the same 7-day average high but had on average higher temperature, were much more prone to rutting. This can be easily explained using Equation 2 to determine the average relative rut damage. This can be implemented to determine the damage weighted effective inverse shear loss compliance, $(G^*(\omega_R)/\sin\,\delta(\omega_R))_R$, and the damage weighted effective temperature, T_R for a particular binder and location. The $(G^*(\omega_R)/\sin\,\delta(\omega_R))$ of the binder must then, at this damage weighted temperature and the frequency, that corresponds to the traffic velocity in the field (fast-medium-slow/standing), be equal or greater than the critical threshold value, $(G^*(\omega_R)/\sin\,\delta(\omega_R))$ is equal to the specification limit is the "reserve" that a material has. The process would have the outcome that the materials high temperature properties would be site specific. However, it would not require additional testing because the results are obtained numerically. This approach minimizes performance give-away and the risk of catastrophic failure. At the same time most locations with comparable high temperature in a certain region should exhibit very similar damage weighted temperatures. The system easily adapts to varying average traffic loading (i.e., ADT), Θ. To adjust for higher loads, $(G^*(\omega_R)/\sin\,\delta(\omega_R))_{spec}$ would either be a function of or would have ranges.

$$(G^* \;/\; \sin\,\delta)_{spec} = f(\Theta) \qquad (3)$$

$$(G^* \;/\; \sin\,\delta)_{spec} = x_1 \;\; for\;\; \Theta \le \Theta_{spec1} \qquad (4)$$

$$(G^* \;/\; \sin\,\delta)_{spec} = x_2 \;\; for\;\; \Theta_{spec1} < \Theta \le \Theta_{spec2} \;\; etc. \qquad (5)$$

The example below illustrates the possible implications of such a damage-weighted specification.

Example: Let us examine for a location, which within the current system has an average 7-day high temperature (50% reliability) of 52.9 °C the possible implications for two hypothetical binders. The current Supersave binder specification would call for PG58-YY, and both binders are thus assumed to have exactly 2.2KPa at 58 °C. Let us also assume that the binder A is very low temperature susceptible whilst binder B has a very low temperature susceptibility. The current models predict both binders to perform equally well for a given mixture. In reality, however, the difference in temperature susceptibility means that binder A would be stiffer at lower temperatuers and softer at higher temperatuers. Hence, the tempearture susceptible asphalt would be on average less prone to rutting because the damage weighting always reduces the effective temperature compared to the $T_{7d\text{-}max}$*. The damage weighted (50% reliability) effective modulus for binder A is consequently significantly higher than that of the apparenetly equivalent binder B. The same holds true for a 98% reliability with average standard deviation of the air temperature of 3 or 6 °C, respectively (cf. Table 1).*

Table 1. Damage Weighted Temperatures (T_{7dmax} = Supresave seven Day Average Maximum, T_{avrg} = Average High Pavement Temperature At 12.5 mm Depth, T_R = Traffic and Damage weighted Effective Rut Temperature), Moduli (@T_R) and Predicted Relative Propensity to Accumulate Permanent Deformation (D_{avrg}) for Two Hypothetical PG58-XXs.

(Temp. Suscep-tibility	T_{avrg}	T_{7dmax}	T_R	$(G^*/\sin d)_{eff}$	D_{avrg}	StdDev
High	43.7	52.9	48.6	7.56	0.0882	0
High	44.8	54.2	49.8	6.42	0.1073	3
High	46.5	56.1	51.7	5.03	0.1439	6
Low	43.7	52.9	48.4	3.77	0.2035	0
Low	44.8	54.2	49.5	3.53	0.2198	3
Low	46.5	56.1	51.4	3.18	0.2491	6

The example discussed here illustrates the need for moving a performance-related specification towards damage-weighted temperatures, which take material propertias and simple temperature distributions into account. Similar cases can be made for intermediate and low temperature cracking.

5 The Supersave Binder Specification

5.1 Historic Development of the Supersave Binder Specification

The Provisional AASHTO Binder Specification MP-1 AASHTO-TP1-9812 which is generally better known as the SHRP or Supersave binder specification represents historically a logical steppingstone on the path to develop a truly performance-related specification for binders.

In the 40´s and 50´s the penetration grading system was primarily used in the USA and Canada. The penetration grading system (ASTM D 946) requires that an asphalt binder is graded using a maximum and minimum penetration values or criteria at a temperature of 25 °C (77 °F). This temperature was chosen as an approximate mid-point of the service temperature range. Because the penetration value is not fundamental measure it cannot be rationally included in any mechanistic model for a particular distress mechanism. However, it did attempt to control the binder stiffness (via min and max pen value) and temperature susceptibility (by tests at multiple temperatures).

The next evolutionary step was the viscosity-grading system (AC grading system ASTM D 3381) which is based on the binder viscosity. The viscosity is by definition a fundamental property. This specification was developed to obtain a new approach based on funadmental material properties and was based upon extensive research [13]. The performance of the pavements built with viscosity graded asphalt binders is thought to be controlled by placing limits on the viscosity-temperature susceptibility. The temperature susceptibility is limited to a range by requiring a minimum viscosity at 135 °C (275 °F), a viscosity window (x ± 20%) at 60 °C and a minimum penetration value at 25 °C (77 °F). The problem is that the tests do not adequately control the rheology of the binder, which can be non-Newtonian (and visco-elastic) requiring further characterization in addition to the viscosity.

The Asphalt Residue or AR grading system developed at Caltrans can be seen as the next logical step. Plant aging was introduced via the Rolling Thin Film Oven (RTFO). In this specification, which very much resembled otherwise the AC grading, the RTFO residue was evaluated.

In the late 80s and early 90s the Pacific Coast User Producer Conference adopted a new sapecification which had been sperheaded by J. Goodrich and R. Reese. This so-called Performance-Based Asphalt Specification (PBA) attemted to include regional climate variations and long-term field aging [14]. Seven binder grades (PBA-1 to PBA-7) were created based on the average high and low air temperature of the hottest and coldest month, respectively. For severe climates (deserts) the California Tilt Oven Aging Test (CTOAT) was utilized to mimic 5 to 7 years of aging [15] in the pavement.

The Supersave binder specification adopted many of the concepts of the PBA specification. The most significant advancement was probably the move from empirical tests to advanced testing where a binder could be characterized at a controlled rate and temperature to obtain the "real" engineering properties of the binder. The Dynamic Shear Rheometer (DSR), BBR and DTT replaced viscosity, penetration and ductility, respectively. With regards to plant aging the RTFO was adopted and the Pressure Aging Vessel (PAV) was introduced for all climatic regions instead of the CTOAT to stimulate 10 to 15 years of aging in the field. Climate, which had first been introduced in the PBA specification, was introduced in a more comprehensive approach by substituting air temperature with predicted pavement temperatures. The so-called Supersave Performance Graded (PG) asphalts are based on the average 7-day highest pavement temperature and the lowest measdured air temperature (the new low temperature and the lowest measured air temperature (the new low temperature proposal would substitute this with the lowest pavement temperature at 12.5mm depth). Thus, a PG64-22 means that the 7-day high in the pavement will with a certain level of probability not exceed 64 °C and that the air temperature will with a certain level of probability not fall below -22 °C.

5.2 Evaluation of the Supersave Binder Specification

As previously mentioned the supersave grading system in its current version is no more than a sophisticated version of the PBA specification. There are no comprehensiove models eitherfor rutting, fatigue or low temperature cracking which the speification parameters are based on. Just like in the viscosity grading system, single-point measurements are made at high and intermediate temperatures to crudely control the temperature susceptibiliy of the binder. Measuring the binder properties at the actual low temperatures constitutes are large step forward but it still lacks a sound theoretical mechanistic model. Recent progress in this area promises to move the current specification from a, de facto controil point specification, to a distress related specification.

In a next generation "SHRP-2" specification every parameter should relate directly to a distress. The variation of the distress and climate will need to be addressed in a much more comperehensive fashion. This can most probably be relatively easily accomplished by measuring a spectrum properties, i.e., instead of a single measurement at 10 rad/sec in the DSR a full frequency sweeps in run. This can be accomplished with the current equipment without creating new prolonged procedures. We foresee that ultimately the next generation of performance-related specifications should require certain damage and climate-weighted limits. These limits will be material dependent and will ultimately need to be determined using sophisticated computer programs such as TSARTM [16]. This should not generate significant extra testing, in fact, it is conceivable that by measuring key properties at certain critical points testing could be reduced. A verification testing specification also need to be developed which will reduce overall testing for the producers and will provide the user with the confidence that the binder has not changed significantly since certification.

6 Conclusions

The Supersave grading system represents a significant step forward in the development truly-performance related specifications. However, the following improvements are still needed to move to a "real" performance-related binder specification.

- Eliminate single-point measurements and capture true property spectrum of binder.
- Eliminate check-point parameters that do not correlate with performance (e.g., G* sin δ).
- Improve pavement temperature prediction capability.
- Develop comprehensive performance models.
- Introduce damage weighting that takes the local environment into consideration.
- Introduce a set of verification tests in place of the standard specification testing for an already certified binder.

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