Quantitative Assessment of Workability for Hot Mix Asphalt: Inclusive Study on Mix Variables

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Abstract. The workability of Hot Mix Asphalt (HMA) plays an integral role in the successful construction of flexible pavement. Workability not only refers to the ease of handling and paving of the mixture but also to the superior compaction characteristics. In practice, an optimum compaction effort ensures that the laid mixtures attain the desired set of mix variables post-construction. As the HMA exemplifies temperature-dependent viscoelastic properties, several mix variables in HMA offer a complex interaction that in effect contributes to the ease of compaction of HMA. With this background, this study will investigate the workability of HMA and quantify the impact of mix variables on workability of HMA. The scope of this study will include a comprehensive characterization of aggregate gradations, rheological investigation of asphalt binders, an experimental investigation on the compaction behaviour of HMA, and quantitative assessment of variables that potentially contribute to the compaction energy of HMA. In this study, Superpave Mix Design method will be adopted to measure the compaction mechanism of HMA that comprises mix variables such as types of asphalt binders, viscosity at compaction temperatures, the activation energy of HMA, aggregate structures, etc. Furthermore, a predictive model will be developed using the fundamental mix variables which will help predict the optimum compaction energy in terms of gyrations. It is envisaged that the research findings will provide important insights to the compaction mechanism of HMA, and thus advancing the state-of-the-art pertinent to the superior quality of construction for flexible pavements.

Keywords: Flexible Pavement, Asphalt Pavement, Workability, Waste Engine Oil, Compaction Energy

1. Introduction

Hot Asphalt mixture (HMA) is a blend of aggregate and asphalt binder which forms a strong and durable structure used in wearing course of flexible pavement. Since this layer remains in direct contact with wheel loading and is subjected to environmental impacts, the performance of flexible pavement system is governed by the quality and durability of HMA. Though there existed several steps that ensures superior performance of HMA, the construction and design stages constitute the major stages that plays the crucial role in pavement performance. Hence, it is essential to investigate the construction and design process of HMA to improve the performance of flexible pavement system.

In practice, HMA is prepared at Hot Mix Plant, and then transported to the site and compacted at high temperature. In all these stages, the workability of HMA plays a critical role, which measures easy of handling and energy consumption during the compaction. Over the last few decades, several research studies [1-9] explored a host of variables in the design process of HMA that govern the workability. For instance, a study led by Caputo et al. [9] investigated the compaction process with a view to reducing the energy consumption which can lead to more economic construction. The study quantified the activation energies for various types of asphalt mixtures and developed a master curve that integrates compaction characteristics and rheological properties of HMA. Similar research studies [3,5,10] can be found that identified various factors that can potentially contributes to the workability of HMA through pivoting compaction characteristics and activation energy. For example, a study carried out by Kyoungchul and Myungook [10] assessed the impact of compaction temperatures on the volumetric properties using compaction energies of polymer modified asphalt mixture. This study crafted two key indices, namely Compaction Energy Index (CEI) and Compaction Force Index (CFI) which depict the influence of compaction temperature on volumetric of HMA. In addition to the laboratory investigation, research studies employed prototype devices that can simulate different plant scenarios associated with the blending of mixtures. For instance, Ali et al. [11] designed a prototype device to examine the factors that can lead to superior workability of mix. The prototype devise successfully differentiated between Warm Mix Asphalt (WMA) and HMA based on the workability. The study highlighted that the factors such as grade of asphalt binder, aggregate type, and aggregate size showed the most significant impacts than the other design variables. Similarly, several other studies [13-16] can be found that highlighted the importance of aforementioned factors using laboratory investigation to improve the workability of HMA.

After the major deciding variables were identified, further studies [11-16] can be found that explored the main and interaction effects these design variables. For example, limestone aggregate resulted in reduction in workability than crushed gravel when all the other design variables were kept identical [11]. With regard to the grade of asphalt binder, virgin asphalt binder exhibited a higher workability than the short-term aged ones [9]. In simple words, this finding indicated that the asphalt binder with higher viscosity or with higher PG upper temperature offers lower workability than that of lower viscosity, especially when the other mix constituents remain identical. Furthermore, the research studies [10-20] also explored the sensitivity in mix workability in presence of modifiers and/or new materials. For example, when Reclaimed Asphalt Pavement (RAP) was included in the mix, the workability of mix can be improved by using a softer grade of asphalt binder [16]. The research study [17] concluded that if any external materials, other than aggregate and asphalt binder are used in the mix, the compaction characteristics and workability show noticeable changes, especially during the compaction. A waste material, Electric Arc Furnace Slag (EAFS) was also introduced in the aggregate gradation and the impact were quantified using compaction characteristics [15]. It was concluded that surface roughness and texture of external material and its density, in this case, EAFS lead to the change in workability. Higher is the surface roughness, lower will be the density if the other variables remain same.

With the current needs for developing sustainable pavement infrastructure, several waste materials are frequently used as additives in HMA. Although numerous research studies offered important insights to the fundamental characteristics of workability of HMA and its associated factors, limited research can be found that focused on the mechanism of workability in presence of additives. It is important to understand the compaction mechanism for the asphalt mixtures with additives major because of two reasons: (a) it helps to mitigate the disposal issues of waste materials, and (b) ensure development of terminal blend without any compromise in performance. With this background, this objective of this study was to investigate the impact of Waste Engine Oil (WEO) in the compaction process and explore the compaction mechanism of HMA. The scope of the work included (Figure 1):

- Characterize rheological properties of short-term aged binder and the modified mixers with WEO;
- Prepare asphalt mixtures at various mix composition and analyse the compaction characteristics;
- Estimate the activation energy of each binder and evaluate the resistive efforts against compaction;
- Identify the locking points for different mixtures and then estimate the Compaction Force Index (CFI);
- Differentiate the asphalt mixtures based on their workability and identify the compaction patterns.

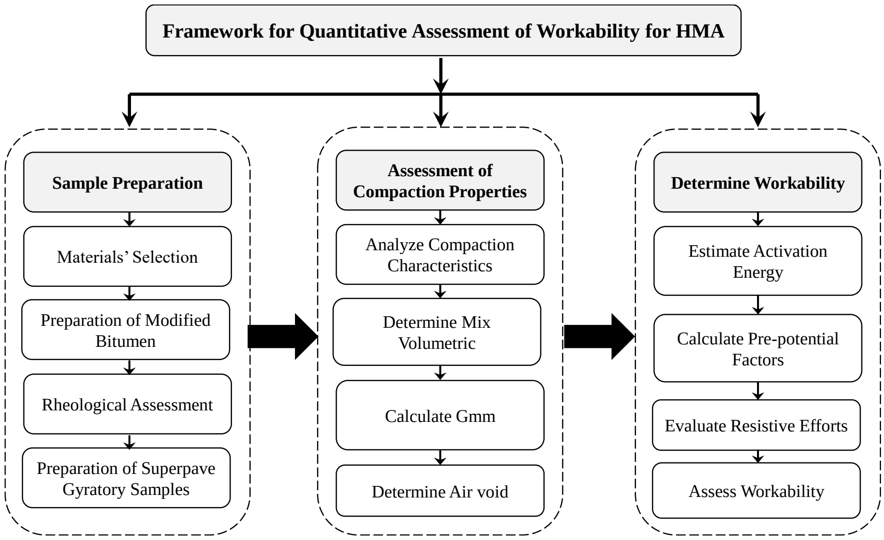

Figure 1. Research Framework

2. Materials and methods

2.1. *Aggregate gradation*

Aggregate plays a main role in the asphalt mix. A well graded mix with fine and course aggregate improve the performance of the asphalt mix. It ensure the durable stable high performance asphalt mix and it useful in many factors. A well graded aggregate mix help to carry rutting and rut resistance, durability of the pavement, stability, strength and also it play a major roll to improve the workability qualities of the asphalt binder. Good workability of the binder easier to handle, place, mixing and compacting. Aggregate gradation mainly effect in mixing and compaction temperatures of the mix. In this study DBM grading 2 was followed. As the first step aggregate were selected and aggregates were sieved as per the specific grading. Then the property tests were conducted for the aggregate. The aggregate gradation is summarized in Table 1.

Table 1. Aggregate gradation used in this study

Sieve size	% Passing			Cumulative % Retained on each sieve	% Retained on each sieve	Total weight of Aggregate	Cumulative weight of aggregate retained on each sieve	Weight of aggregate retained on each sieve	Total aggregate weight
	Max	*Min*	*Mid*						
19	100	100	100	0	0	1100	0	0	0
13.2	100	90	95	5	5	1100	55	55	660
9.5	88	70	79	21	16	1100	231	176	2112
4.75	71	53	62	38	17	1100	418	187	2244
2.36	58	42	50	50	12	1100	550	132	1584
1.18	48	34	41	59	9	1100	649	99	1188
0.6	38	26	32	68	9	1100	748	99	1188
0.3	28	18	23	77	9	1100	847	99	1188
0.15	20	12	16	84	7	1100	924	77	924
0.075	10	4	7	93	9	1100	1023	99	1188
Pan	-	-	-	100	7	1100	1100	77	924
									13200

2.2. *Bitumen Properties and Modified Bitumen*

Bitumen is the primary binder in asphalt mixers and it is used as the binder to hold aggregate each other in the mixers. Bitumen having different properties including viscosity, adhesion, cohesion and different rheological properties. Viscosity is a main rheological property of the asphalt. The viscosity changes under different shear rates and the different temperatures. The mixing and compaction temperatures are different for every type of the bitumen. EVT is depend on types of bitumen and it is used in evaluating the performance of the bitumen in deferent climate conditions.

Modified bitumen is the bitumen that enhanced or modified with different additives to improve the performance of the asphalt mixture. The modified bitumen having better workability and the better EVT than the normal bitumen. Improving the properties by using waste materials is now famous in the world due to cheap cost and the improvement of the mixes without any high wastage. Normally different waste materials are used to prepare modified bitumen. Polymer modified bitumen, fibre modified bitumen and crumb rubber modified bitumen are famous in modified bitumen. In this study we focused to modify the bitumen by using WEO and Lime. VG 30 (A5) bitumen is selected and conducted the property tests for the bitumen. Two types of modified bitumen were prepared. VG 30 5% mixed with 2% WEO (A5/2W) and another modified bitumen type is VG 30 5% mixed with 2% WEO and 20% Lime (A5/2W/20 L). Property tests were conducted for the modified asphalt samples and found out the penetration values. The viscosity measurements were conducted and measured the variation of viscosity versus shear rates. In order to determine the asphalt binder's viscosity, a Brookfield rotational viscometer test was conducted. Three binders are tested at temperatures from 125ºC to 165ºC, and the resulting viscosity data is combined with penetration and softening point data to plot an A_i-VTS_i curve (Figure 2). And it was observed that the all samples have Newtonian rheological behaviours because the viscosity is independent of shear rates.

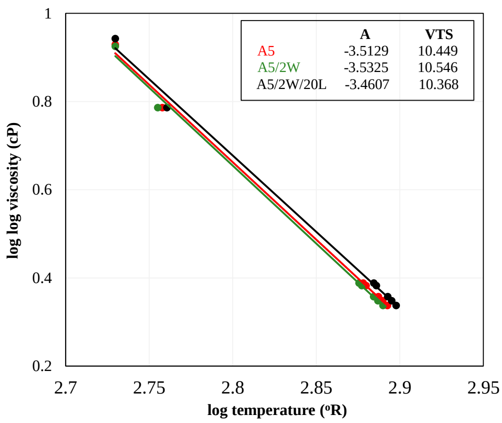

Figure 2. A_i-VTS_i relationship for different asphalt binders

2.3. *Assessment of Compaction Properties*

Superpave gyratory samples were prepared by mixing the bitumen that mentioned in section 2.2 and the aggregate that mentioned in section 2.1 and four types of gyratory samples were prepared by using VG30 5% (A5), VG 30 5.5% (A5.5), VG 30 5% mixed with 2% WEO (A/2W) and VG 30 5% mixed with 2% WEO and 20% Lime (A5/2W/20 L) (Figure 3). Each sample was given 300 gyrations and compaction was done by using the gyratory compactor in different compaction temperatures. The volumetric properties of the samples were measured as a function of time during the compaction. From studying the volumetric properties of samples we can get the variation of density (G_{mm} %), air voids (Va), voids in mineral aggregate (VMA) and the voids filled with asphalt (VFA) throughout the time of compaction. And also the other indicators that mention in Appendix A (CDI, TDI, CFI, TFI). These indicators depend on the three characteristic points during the compaction effort and they are initial (N_{ini}), design (N_{des}), and maximum (N_{max}) number of gyrations.

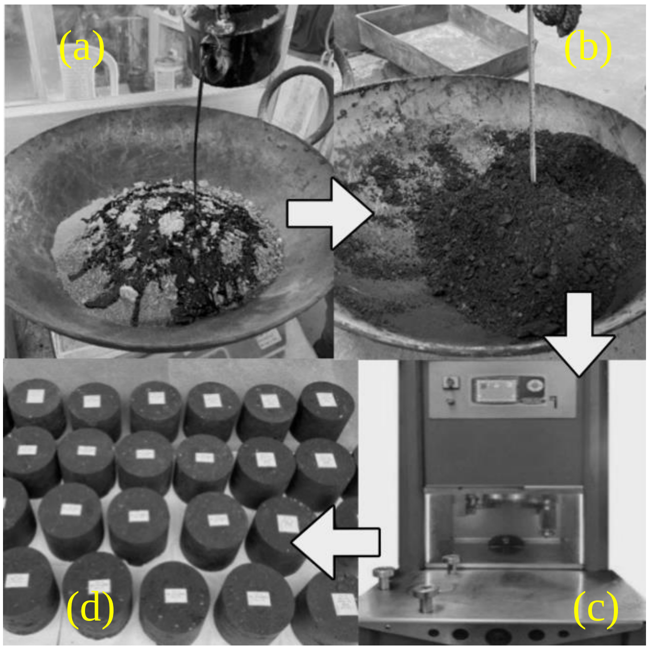

Figure 3. Sequential steps of Gyratory Compaction.

3. Results and Discussion

To understand the rheological properties of bitumen that are used in the study viscosity used as a function of temperature for all bitumen types including the modified bitumen. In this study the first attempt is to understand the molecule based microscopic behaviour of the bitumen and to show that the viscosity is an important indicator of the total energy that absorbed under shear condition.

In Figure 4 it shows that the viscosity depends on the temperature here ln ɳ and the 1000/T. This plot is an Arrhenius plot but the Arrhenius plots not follow to show the temperature dependence of a dynamical property. But in this study is based on the molecular interpretation of the macroscopic properties. The linear trend in the Arrhenius plot suggests that the two-well potential model is effective at least within the temperature range considered. This allows for the safe extraction of both the activation energy (Ea) and the pre-exponential factor (ln As) by fitting experimental data through the plot of ln ɳ and 1000/T using Equation 1.

$$\ln \eta\,(T) = \ln As + \frac{Ea}{R} \cdot \frac{1000}{T}$$

Here, ɳ is viscosity and R is gas constant (R = 8.314 J K−1 mol^{-1})

Figure 5 Shows how E_a vary with the *lnAs* for each different sample. And the plot line shows the co-relationship between two quantities. In the framework of the Arrhenius model, *Ea* and *As* have physical meanings. In fact, although the Arrhenius model was derived from the reaction kinetics in the gas phase, the application of the transition-state-theory (TST) of Arrhenius chemical kinetics to transport phenomena has provided a preferred theoretical basis for the interpretation of viscosity. TST describes the reaction rates of fundamental chemical reactions under the assumption of a chemical quasi-equilibrium between reactants and an activated transition state complex.

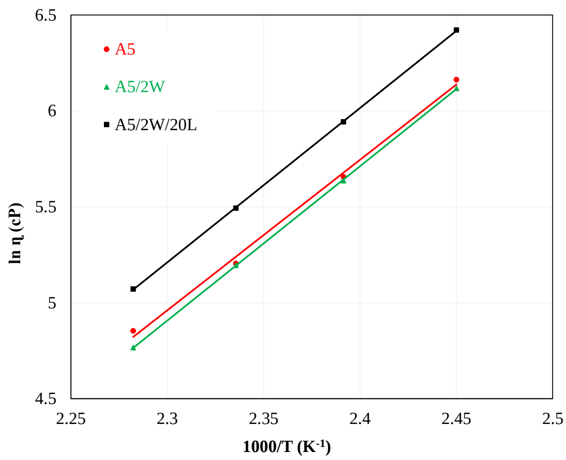

Figure 4. Arrhenius Model parameters for various asphalt binders

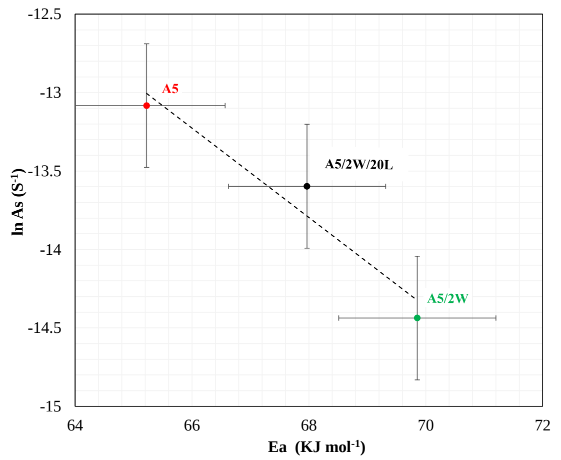

Figure 5. Correlation between the pre-exponential factor (*ln As*) and the activation energy (E_a).

3.1 Activation Energy and Pre-Exponential Factor

In transition-state theory (TST), E_a, the activation energy that must be overcome for flow to occur. The E_a values of the samples are on the order of hundred kJ mol^{-1} and they are comparable to those observed for other bitumen types at room temperature. Due to the high temperature of our samples, the bitumen is completely in the liquid state, resulting in a more disaggregated form than typical bitumen at room temperature. For in this situation from the Figure 4 we can say that the activation energy for flowing is lower than that at room temperature.

- The samples that mixed with lime has higher viscosity than the normal bitumen and the bitumen only mixed with engine oil has less viscosity when it compares with the normal un modified bitumen.
- The bitumen modifying causes of increase of the viscosity.
- The relationship between pre-exponential factor and the activation energy is a linier relationship. In this study the data present a proper view of rheological behaviour at the molecular basis as the plot contain a universal behaviour.

3.2 Volumetric Analysis

By using the gyratory compactor asphalt samples are compacted to reduce the voids. In this process volume of the samples and the shear resistance are continuously measured with the number of gyrations. Number of gyrations is a function of time and the following data measured with the number of gyrations.

- Density variation (%G_{mm})
- Air voids content (%Va)
- Voids in mineral aggregate (%VMA)
- Voids filled with asphalt (%VFA).

The results are reported in table for VG 30 (5%), VG 30 (5.5%) and both modified bitumen (Table 2). The focus of this research is placed between N_{ini} and N_{des}, where the true workability of the mixes is point out and has a significant impact on compaction.

Table 2. Density variation and air voids content at different gyration levels for asphalt mixtures

Asphalt mixes	No of gyrations	$\%G_{mm}$	%VMA	%VFA	%Va	%Va Acceptance Thresholds
A5	N_{ini}=10	91.7	19	55	9	11-15
	N_{lp}=12	92.0	18	56	8	-
	N_{des}=120	96.9	14	78	3	3-6
	N_{max}=210	97.8	13	83	2	≥2
A5.5	N_{ini}=10	91.0	21	57	9	11-15
	N_{lp}=14	92.0	20	60	8	-
	N_{des}=120	97.3	15	82	3	3-6
	N_{max}=210	98.3	14	88	2	≥2
A5 2W	N_{ini}=10	91.3	20	56	9	11-15
	N_{lp}=14	92.0	19	59	8	-
	N_{des}=120	96.6	15	78	3	3-6
	N_{max}=210	97.5	14	83	3	≥2
A5 2W 20L	N_{ini}=10	91.5	21	59	9	11-15
	N_{lp}=13	92.0	21	61	8	-
	N_{des}=120	96.5	17	79	3	3-6
	N_{max}=210	97.4	16	83	3	≥2

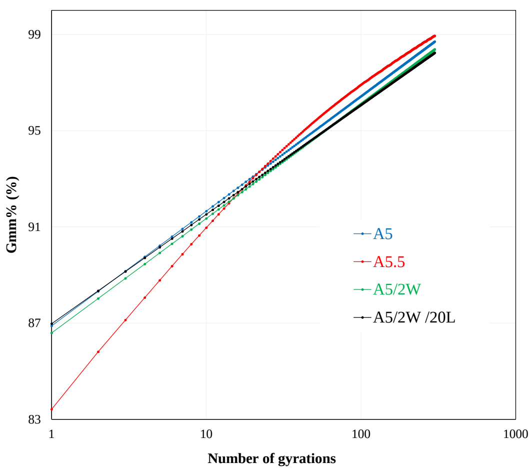

Figure 6. Gmm% as a function of the number of gyrations.

From these plots and the shear resistance values as a function of gyration the important indicators can be derived. In appendix A the indicators are described. In here we observed the locking point which the number of gyrations beyond the state that asphalt mixture compaction and the aggregate structure become stable. Beyond this point compaction not involve that much in density of the mixture and the aggregate structure can be damage beyond this point. In this study, the locking point is assumed to be the number of gyrations necessary to achieve 92% ($\%G_{mm}$) of the "ideal" compaction. With different compaction different asphalt mixes reach to locking point in different number of gyrations as they having different workability.

The lower number of gyrations for the locking point means the sample having better workability because it can reach the LP in lower number of gyrations. When this degree of compaction is attained during press rotation, another parameter is considered as the compaction densification index (CDI), whose derivation and meaning are described in Appendix A. The calculated LP and CDI values are shown in Table 3.

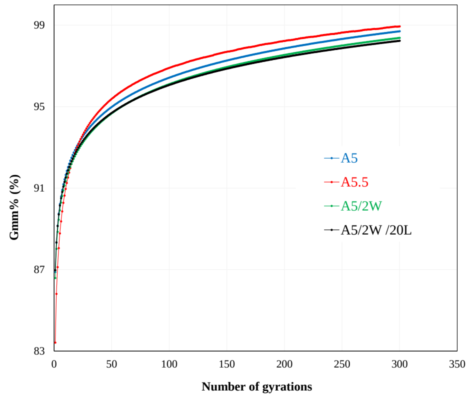

Figure 7. G_{mm}% as a function of the number of gyrations.

Table 1. Compaction Densification and Compaction Force Indexes

Index	A5	A5.5	A5/2W	A5/2W/20L	Ratio (A5 & A5/2W)	Ratio (A5 & A5/2W/20L)
Locking point (LP)	12	14	14	13	0.86	0.92
CDI	0.4	2.2	1.5	0.8	0.26	0.48
TDI	853.2	715.1	1001.6	1092.1	0.85	0.78
CFI (kN m^{-2})	11.0	18.9	22.0	16.2	0.50	0.68
TFI (kN m^{-2})	1157.2	927.4	1361.1	1437.2	0.85	0.81

Here, as it can be understood that the behaviors of two modified asphalt mixes is compared with the un-modified asphalt mix. All the ratio has been calculated according to the values of each mix.

- LP of the A5 is 12 and the LP of A5/2W is 14 so the ratio we can calculate as 12/14 = 0.86
- CDI of the A5 is 0.4 and CDI for A5/2W is 1.5 so the ratio is 0.4/1.5 = 0.26

By studying the figure 6 it can be observed all the curves having same shape when the scaling factor is considered. That means the physical principle behind the process has to be universal. Another significant consequence is the termed traffic density index (TDI). In Appendix A the term is discussed. It is an integral of the curve between LP and a maximum number of revolutions and is therefore as an indicator of the compacted mixture's stability under traffic load. Taking into consideration that the compaction curves can be x-scaled according to the efficacy of compaction to produce a unique curve, the "maximum" number of revolutions must also be scaled if comparisons are to be made.

In compaction process some samples are more efficient than others. Therefore, a unique maximum number of revolutions for each mixture will result in various levels of compaction at the end of the process. So in this case keeping N_{max} in a same value is doubtful. Here TDI value is different from LP ratio and noted that A5 having lower value when compare to A5/2W and A5/2W/20L.

When modified bitumen use the compaction efficiency is higher than the normal bitumen. The bitumen modified with lime having higher viscosity than the other two types of bitumen also wen the bitumen modified with WEO only the viscosity goes lover than the normal bitumen. Because of that it allows a higher momentum transfer during shear through intermolecular interactions. This means that the sample gets more energy and motion as it is pressed in the gyratory press, making the process more efficient. Because the bonds between molecules in RTFOT-aged samples are stronger, the activation energy is also higher. The activation energy is the energy barrier at the molecular level that the gyratory press has to fulfil. Furthermore, the ratio of the activation energies of the normal bitumen and the modified bitumen is near to the ratio of the LP that calculated previously. Also, the ratios of the CDI, TDI, CFI and TFI also having nearly the same value when it compares to the ratio of the LP.

4. Summary and Conclusion

In this study, asphalt binder with two modifiers were investigated to understand the workability of asphalt mixtures. The study on workability majorly focused about the inter connection between activation energies and the pre-exponential factors and how these connected with the rheological properties of the bitumen liquids. Furthermore, this study also determined the activation energies and studied about the locking points (LP), Compaction Densification Index (CDI), Traffic Densification Index (TDI), Compaction densification index (CDI) and Compaction force index (CFI) for each bitumen sample.

From the findings, it can be concluded that the bitumen that modified with WEO and Lime having better viscosity than the normal bitumen and then it modified with WEO reduce the viscosity. When we study about the activation energies both modified bitumen having greater activation energies when it compares to the normal bitumen. We mainly focused to reduce the energy consumption on mixing and compacting the HMA by different modification on the bitumen by using waste materials. And it can be inferred that using waste materials to modify the bitumen is good in improvement of the binder performance and good in economic and environmental viewpoint.

Appendix

Density variations and shear resistance data are recorded by using Gyratory compacter. From these compaction and resistive effort curves it can be evaluate the mix resistance respectively to densification and to traffic loads calculating specific densification indexes. These curves having two zones and from each zone two different indexes can be calculated. They are Compaction Densification Index (CDI) and Traffic Densification Index (TDI).

Also, by using resistive effort curves two index can be calculated. They are Compaction Force Index (CFI) and the Traffic Force Index (TFI). These indexes are used to evaluate the mix resistance to distortion. And the resistive effort (w) can be calculated by using following equation (Figure 8).

$$w = \frac{4Pe\theta}{Ah}$$

Here, e is the eccentricity of the resultant force, P is the magnitude of the resultant force (kN), θ is the angle of tilting (rad), and A is area (m^2) and h (m) is the height of the specimen. Resistive effort represents the work that done by the compactor per unit volume per gyration. The area between the function of N_{ini} to N_{lp} is call as the construction effort. The area under the curve between N_{lp} and a number of gyrations corresponding to 98% Gmm is representing the TFI. Mixtures with higher CDI/CFI values have poorer workability because they are difficult to compact, whereas asphalts with higher TDI/TFI values are more stable under traffic loads.

In this study different indexes were calculated for VG30 and the modified asphalt mixes for 300 number of gyrations.

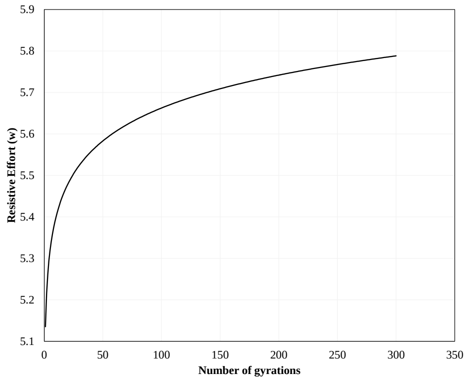

Figure 8. Traffic indexes for mix resistance to distortion.

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