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Relating N_{design} to Field Compaction: A Case Study in Minnesota

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Abstract

High field density helps in increasing the durability of asphalt pavements. In a current research effort, the University of Minnesota and the Minnesota Department of Transportation (MnDOT) have been working on designing asphalt mixtures with higher field densities. One critical issue is the determination of the N_{design} values for these mixtures. The physical meaning of N_{design} is discussed first. Instead of the traditional approach, in which N_{design} represents a measure of rutting resistance, N_{design} is interpreted as an indication of the compactability of mixtures. The field density data from some recent Minnesota pavement projects are analyzed. A clear negative correlation between N_{design} and field density level is identified, which confirms the significant effect of N_{design} on the compactability and consequently on the field density of mixtures. To achieve consistency between the laboratory and field compaction, it is proposed that N_{design} should be determined to reflect the real field compaction effort. A parameter called the equivalent number of gyrations to field compaction effort (N_{equ}) is proposed to quantify the field compaction effort, and the N_{equ} values for some recent Minnesota pavement projects are calculated. The results indicate that the field compaction effort for the current Minnesota projects evaluated corresponds to about 30 gyrations of gyratory compaction. The computed N_{equ} is then used as the N_{design} for a Superpave 5 mixture placed in a paving project, for which field density data and laboratory performance test results are obtained. The data analysis shows that both the field density and pavement performance of the Superpave 5 mixture are significantly improved compared with the traditional mixtures. The results indicate that N_{equ} provides a reasonable estimation of field compaction effort, and that N_{equ} can be used as the N_{design} for achieving higher field densities.

Keywords

N_{design}, field density, asphalt mix design, gyratory compaction, field compaction effort

Compaction represents a critical component of the construction process of asphalt pavements. It controls the field density and thus has a significant influence on the durability of asphalt pavements. Numerous studies have emphasized the importance of compaction on pavement performance (*1*, *2*). Inadequate compaction can cause many durability-related pavement distresses to occur at early ages, such as cracking, moisture damage, raveling, and so forth. (*3*, *4*).

Despite the importance of compaction, inadequate compaction is still a common problem in practice. Relatively low field densities have been reported in many states, for example, Georgia (*5*) and Colorado (*6*), and in a nationwide study (*4*). These studies show that although mixtures are designed to 4% air voids in the Superpave mix design method (*7*), they can only be compacted to about 7%–8% air voids in the field, and, for most projects, the 4% air voids was never reached during their service lives. Many authors (*4–6*) have attributed the low field densities to the choice of relatively high N_{design} levels in the Superpave mix design method (*7*). These values were selected to ensure the rutting resistance of mixtures (*8*). They led inevitably to less compactable mixtures and, therefore, to low field densities. It has been well recognized that, after the implementation of the

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Superpave mix design method in the late 1990s, rutting occurrence was reduced. However, durability-related issues, caused by low field densities, became increasingly prevalent (*9*). Consequently, the Federal Highway Administration (FHWA) recommended that state DOTs performed independent evaluations on the proper choice of N_{design} levels (*10*).

N_{design} represents the design compaction effort, expressed as the number of gyrations applied using the Superpave Gyratory Compactor (SGC) to achieve the target air-void ratio of 4% in laboratory conditions. Physically, N_{design} indicates mixtures' resistance to compaction. A higher N_{design} requires more compaction effort to reach the design air-void ratio, and therefore indicates that the mixture is more resistant to compaction, or less compactable. However, when first proposed, N_{design} was introduced to characterize rutting resistance (*8*). It was argued that rutting could be viewed as "compaction" that occurs as a result of traffic loading and that rutting resistance could, therefore, also be characterized by gyratory compaction (N_{design}); a higher N_{design} was believed to indicate higher rutting resistance. In this argument, rutting is equated with compaction: mixtures that are hard to compact are also resistant to rutting. However, compaction and rutting are essentially different. Compaction is mainly a densification process resulting from volume reduction, while rutting in the asphalt mixture layers is typically a result of plastic shear flow. Except for the case of excessive air voids (>10%), the amount of rutting caused by densification is very limited compared with that caused by plastic flow (*11*). Also, compaction is performed at construction temperatures (around 130°C–150°C), while rutting occurs at high temperatures during pavement service life, usually less than 80°C. As a result of the temperature difference, the viscosity of binder differs significantly, which leads to different mechanisms for the two processes (*12–15*). Some experimental studies have shown that mixtures can be designed at lower N_{design} levels and be more compactable, and still have high rutting resistance (*16*, *17*). These results show that rutting and compaction cannot be equated, and the requirement of N_{design} needs to be further investigated.

In this study, N_{design} is interpreted as an indicator of the compactability of mixtures, based on its physical meaning, instead of relating it to rutting resistance. By relating N_{design} to compactability, it becomes possible to adjust it, in the mix design phase, to design more compactable mixtures and improve field density and reduce durability issues.

Previous studies have reported on the effect of N_{design} on the compactability of mixtures, and the authors suggested that N_{design} values be adjusted to improve field densities. The best example is the "Superpave 5" mix design method developed by Purdue University, Heritage Research Group, and Indiana DOT (*16*, *17*). The N_{design} levels in Superpave 5 were set at 30 and 50 for traffic levels below and above 3 million equivalent single axel loads (ESAL), respectively, values substantially lower compared with the values in the traditional Superpave design method (*7*). The lower N_{design} values were determined to achieve consistency between the mix design laboratory density and field compaction density. The Superpave 5 mixtures could be compacted in the field to 5% air voids, similar to the compaction in laboratory conditions. However, limited efforts have been devoted to rationally explain why this consistency is achieved.

Inspired by these research efforts, the Minnesota DOT and the University of Minnesota have been working on developing a high-density mix design method based on the use of locally available materials. One important goal of this research is to determine the N_{design} levels for the high-density mixture design method. This paper presents the work performed to achieve this goal and it is structured as follows. First, a statistical analysis of field density data from recent projects is conducted, to determine if N_{design} has a significant effect on field densities. Then, a parameter called the equivalent number of gyrations to field compaction (N_{equ}) is proposed to quantify the field compaction effort. The calculated N_{equ} is then used as the N_{design} for a Superpave 5 project, for which field densities are measured and performance tests (flow number [FN], E*, and semi-circular bending [SCB] test) are performed. The results confirm the ability of N_{equ} to quantify the field compaction effort and provide support to the idea of using N_{equ} as N_{design}.

Effect of N_{design} on Field Densities

Field core density data were collected from 15 projects constructed from 2018 to 2020 in Minnesota during the quality control and quality assurance (QA/QC) phase. The projects cover three different traffic levels. Five of them belong to traffic level 3 (1–3 million ESALs) projects; eight belong to traffic level 4 (3–10 million ESALs) projects; and two belong to level 5 (>10 million ESALs) projects. The N_{design} levels are 60, 90, or 100 for traffic levels 3, 4, or 5 respectively (*18*). All projects are wearing courses and were designed to 4% of air voids at N_{design} by the traditional Superpave mix design method. A statistical analysis of the field density data is conducted, which reveals the effect of N_{design} on field density.

Field Density Distribution

A total of 1,354 data points were collected from 15 projects: 463 data points from traffic level 3 ($N_{design\,=}$ 60); 683 from traffic level 4 (N_{design} = 90); and 208 from

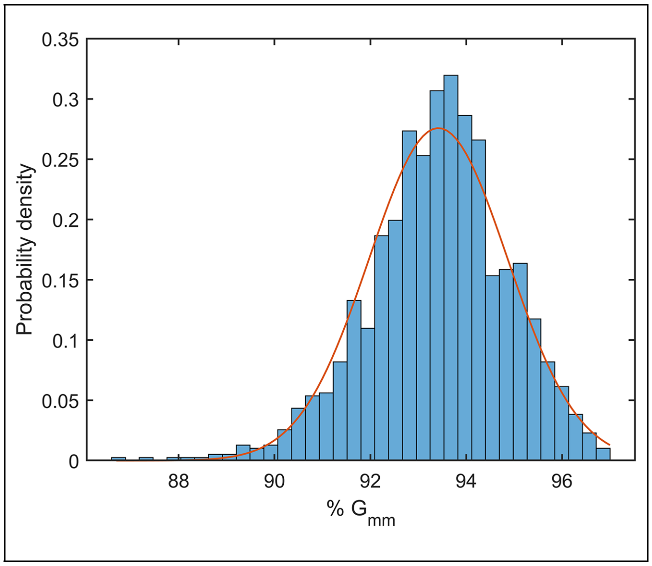

Figure 1. Field density distribution of all field density data obtained (the red curve is a normal distribution regression of the data).

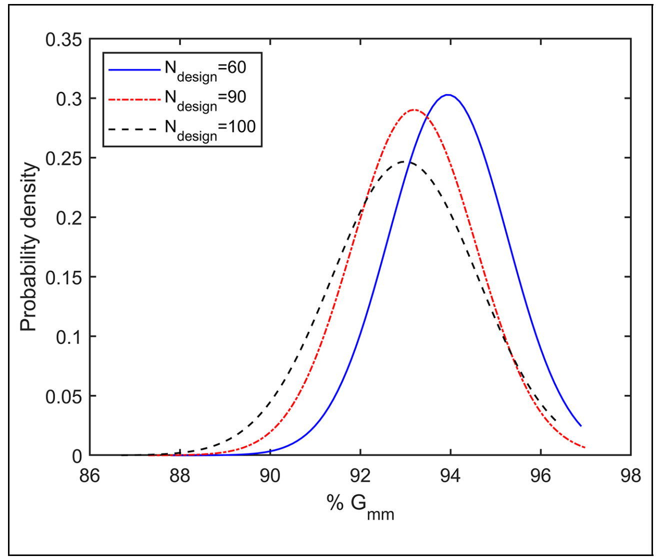

Figure 2. Field density distributions of mixtures designed at different N_{design} levels.

traffic level 5 (N_{design} = 100). For each project, there are at least 60 data points. The distribution of all field density data is shown in Figure 1. It can be observed that the field density data approximately follows a normal distribution, with the basic statistics listed in Table 1. As shown, the overall mean field density is 93.4% G_{mm}, and the standard deviation is 1.45%. To better characterize the shape of the probability distribution, the skewness and kurtosis were also calculated and are shown in Table 1 (*19*). The skewness value indicates that the distribution is a bit left-skewed (skewness < 0), which means that the distribution is denser in the right side (higher density side) or has a longer tail in the left side (low density side). The kurtosis value indicates that the distribution is slightly leptokurtic (kurtosis > 3), which means that the peak of distribution is slightly taller than the normal distribution. These characteristics can also be noticed from the overall shape of the histogram in Figure 1.

The field density distributions are also obtained for different N_{design} levels (traffic levels), as shown in Figure 2. Both Figure 2 and Table 1 show a clear trend that as N_{design} increases the mean field density decreases, and the standard deviation increases. In other words, as N_{design} increases, mixtures become less compactable in the field, and the field density data become more variable.

Analysis of Variance (ANOVA)

To further check the effect of N_{design} on field densities, an ANOVA was conducted to test the null hypothesis that the mean densities are equal for mixtures with different N_{design} levels. Results of the ANOVA are shown in Table 2. The p-value 3.23×10^{-22} is much lower than the significance level 0.001. The null hypothesis can, therefore, be rejected and it can be concluded that N_{design} does have a significant effect on the field density.

A Tukey method multiple pairwise comparison was also conducted (*20*) to further explore where the significant difference comes from. The results are shown in Figure 3, where the circles represent the mean density

Table 1. Basic Statistics of Field Density Data

Data sets	Mean, %	Median, %	Standard deviation, %	Skewness	Kurtosis
All	93.40	93.5	1.45	-0.44	3.68
$N_{design} = 60$	93.94	94.0	1.32	-0.59	3.84
$N_{design} = 90$	93.20	93.3	1.37	-0.14	3.47
$N_{design} = 100$	92.99	93.2	1.62	-0.77	3.90

Table 2. Analysis of Variance Table

Source of variation	SS	df	MS	F ratio	p-Value
N_{design}	199.98	2	99.99	51.34	3.23×10^{-22}
Error	2,631.10	1,351	1.95	na	na
Total	2,831.07	1,353	na	na	na

Note: SS = sum of squares; df = degrees of freedom; MS = mean square; na = not applicable.

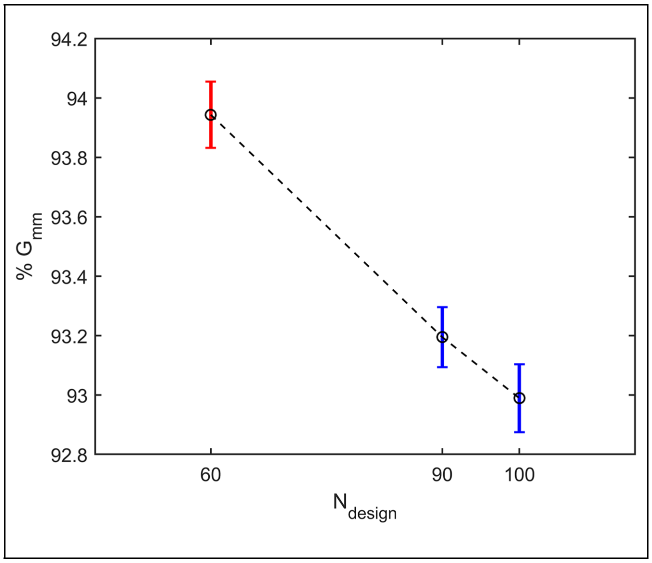

Figure 3. Effect of N_{design} on field density.

values of different N_{design} level groups; the error bars represent the 95% confidence interval of the means. The colors of error bars indicate the classification of groups. Groups in different classes (colors) are significantly different from each other with respect to their field density levels.

The Tukey pairwise comparison shows that the mixtures designed at $N_{design} = 60$ (traffic level 3) have significantly higher field densities than those designed at $N_{design} = 90$ or 100 (traffic level 4 or 5), while the difference of field density between the mixtures designed at $N_{design} = 90$ and 100 is not significant. Generally, Figure 3 illustrates a downward trend of field density with the increase in N_{design}. This result confirms the recommendation of previous studies (*4–6*) to reduce N_{design} to improve field density and durability.

It is important to note that the observed differences in compactability between different N_{design} levels are most likely a result of the differences in the mesoscopic material properties, such as effective binder content, aggregate gradation, angularity, and so forth. The same data were used in a different study (*21*) to investigate correlations between the compactability and material properties. Significant correlations were identified between the compactability of the mixture and the fine aggregate angularity and the fine aggregate gradation characterized using the Bailey method.

The observed negative correlation between N_{design} and field density is not surprising, since it indicates that mixtures more difficult to compact in the laboratory (designed by higher N_{design}) are also more likely more difficult to compact in the field. More importantly, it also indicates that the achievable compaction effort in the field does not match the compaction effort required by N_{design} (or traffic level) which results in low field density values. One obvious, but technically very challenging solution, is to increase the compaction effort in the field to match the design compaction effort required by N_{design}. A much simpler approach is to design more compactable mixtures by choosing an N_{design} value that corresponds to a compaction effort that matches the real compaction effort in the field, as suggested in the Superpave 5 mixture design (*16*, *17*). Based on this argument, a method is proposed next to quantify the field compaction effort.

Quantification of Field Compaction Effort in Minnesota

To quantify the field compaction effort, a new parameter is proposed and named "N_{equ}." This represents the equivalent laboratory compaction effort, expressed as number of gyrations, to field compaction effort. A schematic diagram for computing N_{equ} is shown in Figure 4. The first step, as shown in Figure 4*a*, consists of obtaining the mean field density ($\bar{\rho}$) from the field density distribution of the project. Then, as shown in Figure 4*b*, the number of gyrations at which the mean field density ($\bar{\rho}$) is reached during the gyratory compaction is determined. The identified number of gyrations represents the N_{equ} for the project. N_{equ} represents the laboratory compaction effort that is equivalent to the field compaction effort used in the project. Therefore, by using N_{equ} as the N_{design}, it becomes possible to design mixtures that can be compacted in the field at the targeted air voids selected in the mix design phase.

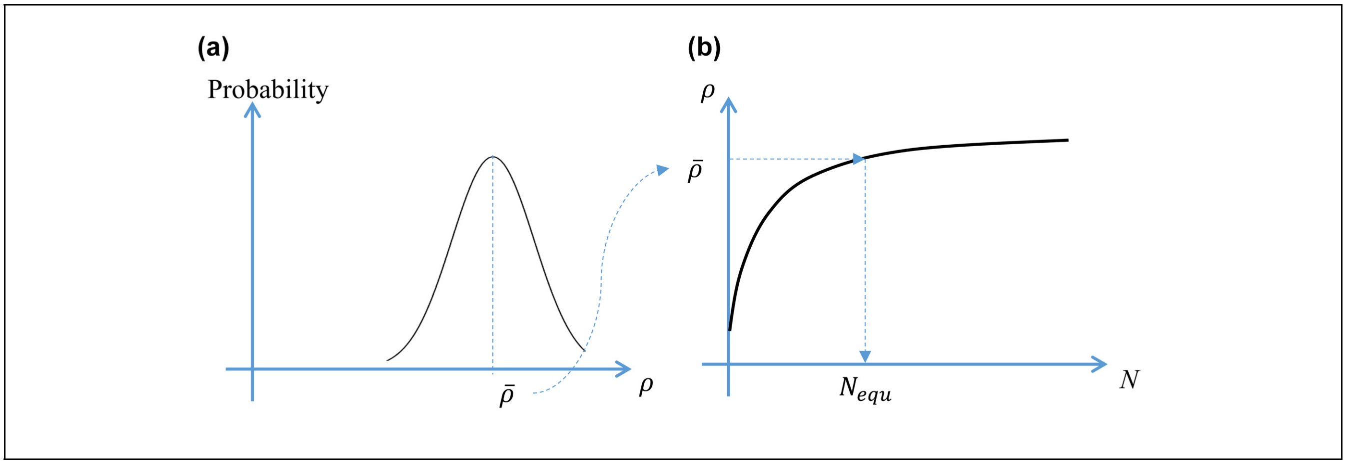

Figure 4. Schematic diagram for computing N_{equ} (ρ represents field density): (*a*) field density distribution; and (*b*) compaction curve.

Table 3. N_{equ} Values of the Five Recent Minnesota Projects

Traffic level	NMAS level	N_{design}	Project ID	Mean field density	N_{equ}	Mean N_{equ}
3	A	60	P1	94.29	29	29
	B		P2	93.34	29	
	B		P3	94.72	28	
4	B	90	P4	93.10	26	27
	A		P5	93.28	27	

Note: NMAS = nominal maximum aggregate size; A = 9.5 mm; B = 12.5 mm.

This approach is demonstrated using field data and loose mixtures from five of the projects previously discussed. Three of them are traffic level 3, and the other two are traffic level 4. The mean field densities of the projects are listed in Table 3. Gyratory compaction was performed on the loose mixture of each project. Two replicates were compacted for each project and the average of the two compaction curves was used to determine N_{equ} following the approach shown in Figure 4. The computed N_{equ} values for all five projects are listed in Table 3. An example is shown in Figure 5 for project P1.

It is observed that the mean N_{equ} for traffic levels 3 and 4 are 29 and 27 respectively. Given that N_{equ} is an approximate estimation of the field compaction effort, the N_{equ} values for the two traffic levels can be reasonably rounded up to 30. The consistency of the N_{equ} values for both traffic levels indicates that the compaction effort for the projects of different traffic levels is about the same and is represented in the laboratory by approximately 30 gyrations of gyratory compaction. It can be hypothesized that this gyratory compaction effort represents a typical field compaction effort of the current practice in Minnesota. It is important to note that the small sample size (three projects for traffic level 3 and two for traffic level 4) may affect the accuracy of the estimation of mean N_{equ} for each traffic level. As more data

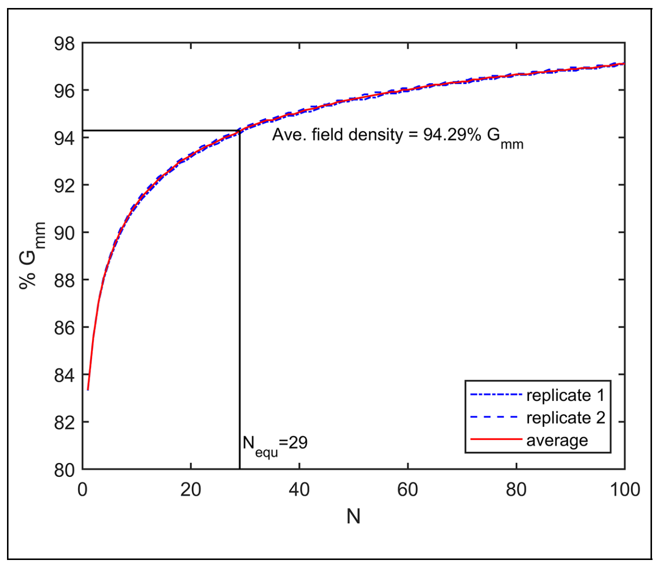

Figure 5. Compaction curves and N_{equ} for project P1.

becomes available, a more accurate estimation of the mean N_{equ} can be obtained.

It is also important to note that the calculated N_{equ} coincides with the N_{design} level used for traffic level 3 in

Table 4. Mix Design Information of the Superpave 5 Project and the Project P2

Mixtures	% Passing of different sieve sizes (mm)										P_{be}, %	PG
	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075		
SP5	100	97	82	61	46	33	23	12	7	4.7	5.0	58H-34
P2	100	94	89	75	61	42	28	15	8	5.7	5.1	58H-34

Note: P_{be} = effective binder content; PG = performance grade of the binder.

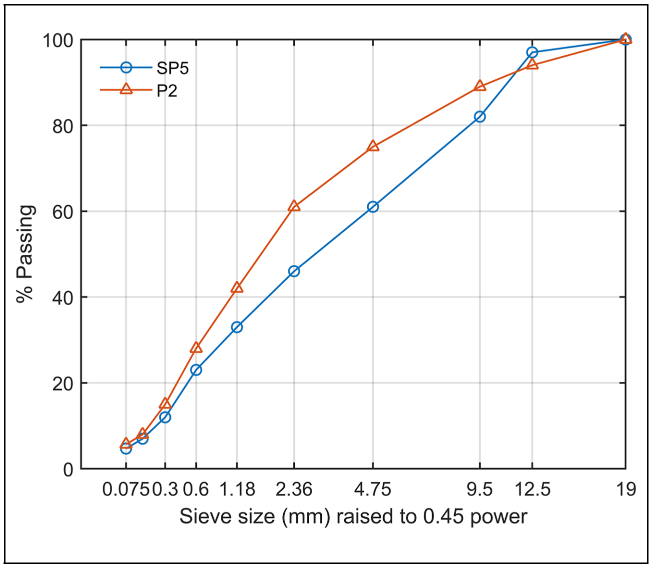

Figure 6. Aggregate gradation of Superpave Project 5 (SP5) and Project 2 (P2).

the Indiana Superpave 5 mix design. The possibility of using $N_{equ} \approx 30$ as the N_{design} for a Minnesota project is investigated below.

Example of Using N_{equ} as N_{design}

The validity of using N_{equ} as N_{design} is investigated next using field data and loose mix from a recently completed Superpave 5 project (denoted as SP5) in Minnesota. The SP5 mixture, with nominal maximum aggregate size (NMAS) = 12.5 mm, was used in the wearing course. The mixture was designed to achieve 5% air voids at a N_{design} = 30 gyrations, the same as N_{equ}. Compared with the traditional Superpave mixtures, the compactability of the mixture was increased by optimizing aggregate gradation with no increase in effective binder content.

The designed aggregate gradation and the effective binder content for the SP5 mixture are shown in Table 4. For comparison, the same information is shown for the traditional Superpave mixture used in project P2, previously discussed. The two mixtures have the same traffic level and NMAS. As shown in Table 4, the effective binder contents are also similar: 5.0% and 5.1%, respectively. The gradation curves of the two mixtures are however different, as shown in Figure 6; SP5 mixture is clearly coarser than P2 mixture.

Field Density of SP5

After the SP5 project was constructed, 167 field density data were collected. The mean field density is 94.69% G_{mm}, which is, as expected, close to the design density level of 95% G_{mm}. Figure 7 compares the field density distribution of SP5 and the traditional Superpave projects of traffic level 3 previously discussed. It can be seen that the mean field density level of SP5 is higher than that of the traditional traffic level 3 projects. This result confirms the ability of N_{equ} to reasonably quantify field compaction effort, which indicates that by using N_{equ} as N_{design} consistency can be achieved between field density and design density.

As shown in Figure 7, the variability of the field density values of SP5 is higher than those of the traditional Superpave projects. Possible reasons are the higher variability of field compaction effort, or the higher variability of material composition during the construction phase, or a combination of both. Further investigation is needed to better understand the effects of random sources on the variability of the field density distribution.

Performance Test Results

To better understand the effect of changing the N_{design} on performance of asphalt mixtures, experimental testing was performed to evaluate the rutting resistance, the stiffness, and the low-temperature cracking resistance of the SP5 mixture compared with the traditional mixture, to make sure they are not adversely affected. In this research, the flow number test, the diametral dynamic modulus test, and the semi-circular bending test at low temperature were performed on the SP5 and P2 mixtures. All test specimens were prepared using loose mixtures taken from the two projects during the construction phase. The loose mix was reheated to the compaction temperature and conditioned for two hours before gyratory compaction. Both mixtures were compacted using

Table 5. Air-Void Ratios of Gyratory Compacted Specimens

	Air-void ratio, %						
Mixtures	1	2	3	4	5	6	Average
SP5	4.85	4.80	4.92	4.72	5.11	4.93	4.89
P2	6.87	6.90	7.21	6.74	6.84	7.19	6.96

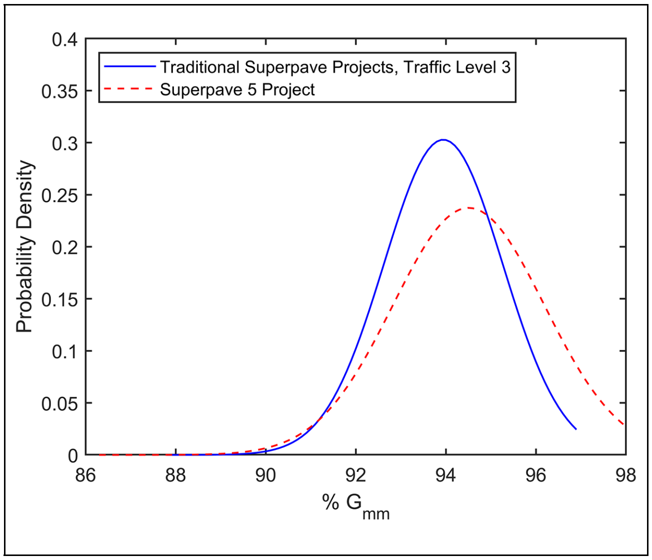

Figure 7. Comparison of the field density distribution between Superpave 5 project and Superpave projects for traffic level 3.

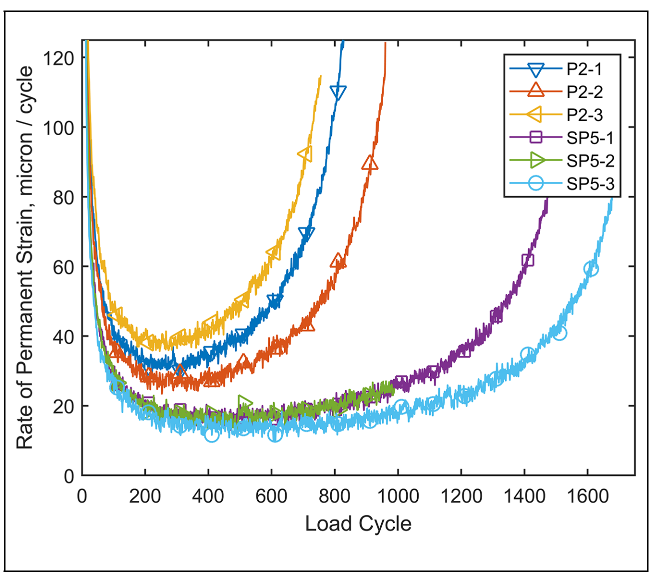

Figure 8. Rate of permanent strain.

30 gyrations to simulate the field compaction effort. For each mixture, six gyratory samples were prepared. The air-void ratios of the compacted samples at 30 gyrations

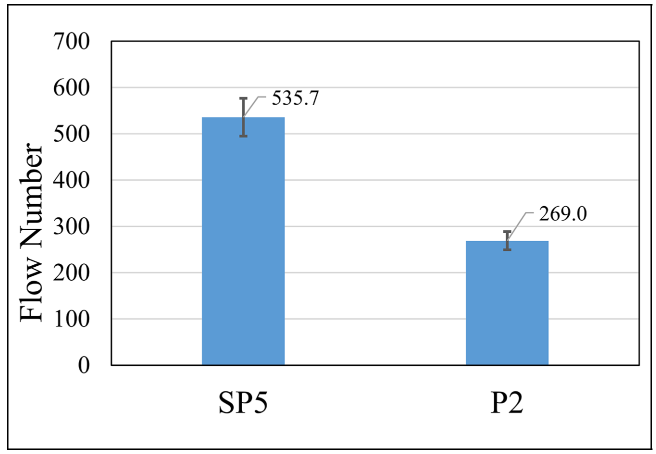

Figure 9. Flow number test results.

are listed in Table 5. It is seen that the air-void ratios are about 5% for the SP5 samples, and are about 7% for the P2 samples, which are values consistent with the field density levels of the two projects (94.69% and 93.34% G_{mm} for SP5 and P2, respectively). The compacted samples were then sawed and cored to obtain specimens of the required shape and dimensions corresponding to each test.

Flow Number. Flow number (FN) tests (*22*) were performed to characterize the rutting (permanent deformation) resistance of the mixtures. The tests were performed at 49°C, and three replicates were tested for each mixture. The rates of permanent strain are shown in Figure 8. It can be seen that the P2 replicates have higher rates of permanent strain than the SP5 replicates. More specifically, the average lowest rates of permanent strain are 35 and 18 micron/cycle for P2 and SP5, respectively. This difference is most likely a result of the difference in air-void ratios of the two mixtures.

FN values for the two mixtures are shown Figure 9. Each value represents an average of three replicates, and the error bars indicate the standard error of the mean values. It is seen that the FN value of SP5 is about twice the value of P2, which shows that the rutting resistance of SP5 is significantly higher than that of P2. The results also indicate that a lower N_{design} level does not

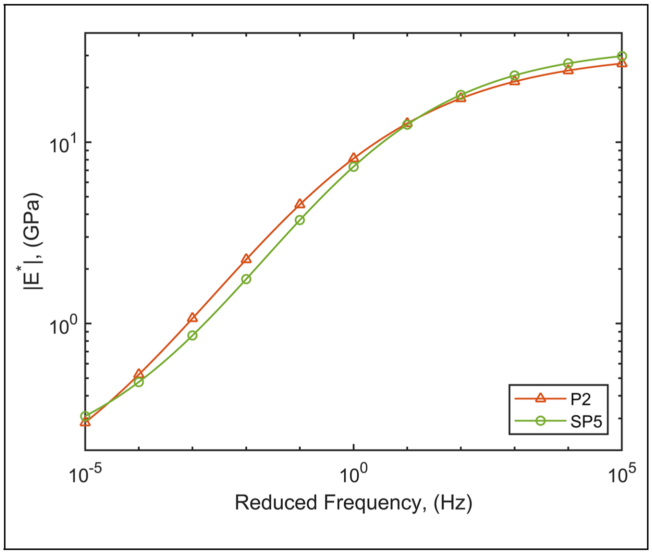

Figure 10. Master curves at the reference temperature 12°C.

necessarily lead to poorer rutting resistance. In this case, rutting resistance increased even though the N_{design} was lower. The properly designed aggregate gradation of SP_5 resulted in a denser aggregate packing, which led to its higher compactability and rutting resistance compared with P2.

Dynamic Modulus. Diametral dynamic modulus (E*) tests (*23*) were conducted to characterize the stiffness of the mixtures. Frequency sweeps ranging from 0.01 Hz to 25 Hz were performed at three temperatures: −12°C, 12°C, and 36°C. Dynamic modulus |E*| for each mixture, at each temperature, was computed as the average of three replicates. The computed |E*| values at different temperatures were then used to construct master curves, according to AASHTO R62 (*24*). The reference temperature was chosen as 12°C. Figure 10 shows the |E*| master curves for the two mixtures.

It can be observed that the differences in |E*| between the two mixtures are insignificant. For instance, |E*| values at the high frequency end (10^5 Hz) are 29.8 and 27.1 GPa for SP5 and P2, respectively. The SP5 mixture has higher |E*| values at both low and high frequencies, while in the intermediate frequency range (from 0.0001 to 10 Hz), the SP5 mixture has lower |E*| values compared with the P2 mixture. The higher |E*| values for the SP5 mixture at low frequencies (corresponding to higher temperatures) confirm the better rutting resistance indicated by the result of the FN test. The higher |E*| values for the SP5 mixture at high frequencies (corresponding to low temperature), may indicate a lower cracking resistance at low temperatures. However, low-temperature cracking resistance is better captured by the fracture energy of the mixture.

Semi-Circular Bending Test. The semi-circular bending (SCB) fracture tests were performed according to AASHTO TP105 (*25*) to characterize the low temperature cracking performance of the two mixtures. Two temperature levels were investigated: −20°C and −12°C. The results for fracture toughness and fracture energy are shown Figure 11, *a* and *b*, respectively. The error bars indicate the standard error of the mean values.

Both the fracture energy (G_f) and fracture toughness (K_{Ic}) of the SP5 mixture are higher than the corresponding values of the P2 mixture at the two test temperatures, indicating a better low-temperature cracking resistance for the SP5 mixture. This result is not surprising, given that the SP5 mixture has lower air voids than the P2 mixture. Similar results have been shown by Marasteanu et al. (*26*) in a previous research effort.

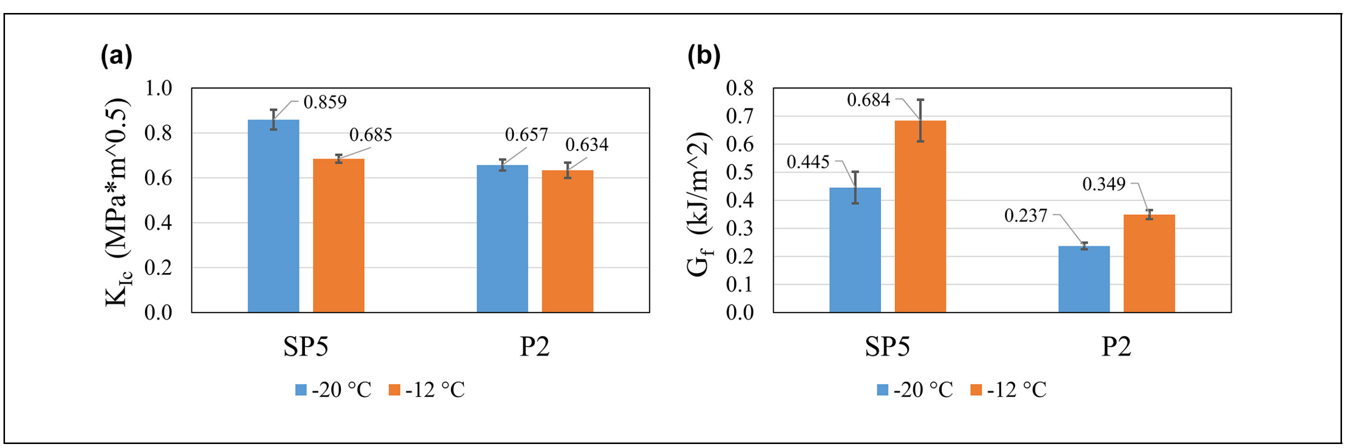

Figure 11. Semi-circular bending (SCB) test results: (*a*) fracture toughness; and (b) fracture energy.

Conclusions

In this research, a simple method to quantify the field compaction effort was proposed. The method provides a rational way to determine the N_{design} values for mixtures for which the target air voids are achieved during the construction process. The following conclusions were drawn at the end of this research.

1. The analysis of field density data, from 15 recent projects in Minnesota, showed a clear negative correlation between N_{design} and field density. This confirms that the N_{design} value has a significant effect on the compactability of mixtures.
2. The low field density values observed in these projects indicate that typical field compaction efforts used during paving operations do not match the compaction effort corresponding to the N_{design} values used in the traditional Superpave mix design method. A simple solution is to select N_{design} values that reasonably represent the real field compaction effort.
3. Consequently, a new parameter, called the equivalent number of gyrations to field compaction, (N_{equ}), was proposed to quantify the field compaction effort. It was found that the N_{equ} values for different traffic levels are similar and around 30 gyrations. This value approximately quantifies the compaction effort in the current paving practice in Minnesota.
4. Field density data and laboratory test results on loose mix from a recently completed Superpave 5 (SP5) project in Minnesota were then used to demonstrate the applicability of this method. The results showed that by using a $N_{design} = N_{equ} = 30$ the densities obtained in the field matched the design densities obtained in the laboratory.
5. The results of experimental testing to evaluate the rutting resistance, the stiffness, and the low-temperature cracking resistance of the SP5 mixture, showed that the SP5 mixture had better mechanical properties than a similar traditional mixture.

While the results demonstrate the clear potential of this approach to design better performing and more durable mixtures, it is also important to discuss the limitations of this study and to suggest future research directions. This study covered a limited number of projects for each traffic level. More projects should be investigated in the future for a more accurate estimation of N_{equ}. The ratio between lift thickness (l) and NMAS, which represents an important factor affecting field compaction, was not considered in this study because of the lack of lift thickness data. Intuitively, N_{equ} should be a function of the ratio l/NMAS. Future studies should focus on determining this relationship as more data become available. Also, this study followed the approach used in the development of Indiana Superpave 5 mix design in which it is assumed that 5% represent the desired as-constructed air-void ratio. More comprehensive studies are needed to investigate what the optimal air-voids ratio (or field density) is to achieve the best overall pavement performance. Lastly, this study mainly focused on the mean value of the field density, while the shape (variability, skewness, and kurtosis) of the field density distribution was not fully investigated. More research is needed to understand the shape of the field density distribution.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: Yan and Marasteanu; data collection: Turos, Bennett, and Garrity; analysis and interpretation of results: Yan, Marasteanu, Turos, Garrity, and Bennett; draft manuscript preparation: Yan, Marasteanu, Turos, Bennett, and Garrity. All authors reviewed the results and approved the final version of the manuscript.

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Data Accessibility Statement

Data used in this study are available from the corresponding author by request

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