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# Quantitative Assessment of Aggregate Shape Parameters on Mechanical Properties and Performance of Bituminous Mixtures in Flexible Pavement Applications

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***Abstract: The geometric characteristics of coarse aggregates significantly influence the mechanical properties and long-term performance of bituminous mixtures used in flexible pavement construction. This study investigates the comprehensive relationship between aggregate shape factors and key performance parameters of bituminous mixes through systematic analysis. The research examines three primary shape indicators - flakiness index, elongation index, and angularity index - and their effects on critical performance measures including Marshall stability, flow value, air voids content, indirect tensile strength, and rutting resistance.***

***A synthetic dataset was generated to analyze performance variations across different aggregate types including crushed stone, natural gravel, and recycled aggregate materials. Statistical analysis techniques including correlation analysis, regression modeling, and comparative studies were employed to establish quantitative relationships between shape characteristics and mix performance.***

***The study utilized advanced visualization methods to present comprehensive data analysis through correlation matrices, multi-panel scatter plots, three-dimensional surface plots, and performance dashboards.***

***Keywords: Flexible Pavement; Quantitative Assessment ; Machine Learning***

## I. INTRODUCTION

The design of flexible pavements holds paramount importance in the development and sustainability of transportation infrastructure, directly influencing the functionality, durability, and cost-effectiveness of road networks. Flexible pavements are layered systems that distribute traffic loads from the surface to the subgrade, relying on the strength and deformation characteristics of each underlying layer to ensure long-term performance. Unlike rigid pavements, which are constructed with concrete slabs, flexible pavements predominantly use bituminous materials and gain their load-bearing capacity through layer interaction and material flexibility. This type of pavement is widely adopted across the globe due to its comparatively lower initial construction cost, ease of maintenance, faster construction time, and adaptability to a wide range of climatic and traffic conditions [1-3]. The significance of flexible pavement design lies in its ability to accommodate varying levels of traffic volume, axle load repetitions, and environmental stresses while minimizing the occurrence of distresses such as rutting, cracking, and surface disintegration. An efficiently designed flexible pavement not only ensures user comfort and safety but also reduces lifecycle costs through minimized maintenance interventions.

The background of flexible pavement design is rooted in mechanistic-empirical principles, where materials are selected and structured based on empirical performance data and mechanistic understanding of stress-strain behavior under vehicular loads. With increasing urbanization, industrial development, and vehicular density, the demand for high-performing pavement systems has intensified, prompting researchers and engineers to explore advanced materials, design methodologies, and performance indicators. In this context, understanding the material properties and their influence on the pavement's response to loads becomes critical. Among all constituents of a flexible pavement, aggregates represent a major portion—typically 90 to 95% of the total mix by weight—and play a crucial role in defining the structural integrity and mechanical performance of the pavement layers [3-4].

Their geometric characteristics, particularly shape, size, texture, and angularity, significantly affect the interlocking behavior, compaction characteristics, and load distribution capacity of the mix.

Hence, the design of flexible pavements is no longer limited to traditional empirical methods but now encompasses a detailed evaluation of material behavior, with particular attention to aggregate morphology, to meet the demands of modern transportation infrastructure and to ensure the long-term sustainability of pavement systems.

Despite the central role that aggregates play in the structural and functional performance of flexible pavements, there remains a significant gap in understanding how their geometric characteristics—namely flakiness, elongation, and angularity—quantitatively affect key performance indicators of bituminous mixtures [5-7]. Traditional pavement design and material selection processes often prioritize parameters such as gradation, specific gravity, and strength, while shape-related attributes are either overlooked or subjected to overly simplistic acceptance criteria. This oversight leads to inconsistent mix behavior in the field, particularly under high traffic loads or in regions with extreme climatic conditions. For instance, two aggregates with identical gradation and strength properties but differing shape profiles may perform vastly differently when subjected to the same service conditions, leading to unanticipated distresses like rutting, reduced stability, and moisture-induced damage. Moreover, with increasing use of non-traditional materials such as recycled aggregates and natural gravels, the variability in geometric properties becomes more pronounced and difficult to control without systematic evaluation. The current lack of standardized, performance-based guidelines for aggregate geometry introduces a level of uncertainty in the mix design process and undermines efforts toward quality assurance and durability optimization [8-9]. Additionally, limited research has focused on developing predictive models that relate aggregate shape parameters to mix performance metrics such as Marshall stability, flow value, air voids, indirect tensile strength, and rutting resistance. This creates a challenge for engineers and practitioners who seek to make data-driven decisions in aggregate selection and mixture design. Therefore, there is an urgent need for a detailed, analytical study that investigates the impact of aggregate shape indices on the mechanical and volumetric behavior of bituminous mixtures, using both statistical modeling and visual analytics. Addressing this problem is essential for advancing pavement engineering practices, particularly in the pursuit of more resilient and cost-effective infrastructure.

## II. METHODOLOGY

To systematically evaluate the impact of aggregate geometric characteristics on the performance of bituminous mixtures, a synthetic dataset was generated and subjected to an extensive statistical and visual analysis shown in Figure 1. The methodology employed combines principles from materials science, transportation engineering, and data science to simulate real-world variation and derive meaningful patterns that can be generalized for flexible pavement applications. The process begins with the use of Python—an advanced programming language widely adopted for data modeling and scientific computation—along with key libraries such as NumPy, Pandas, Matplotlib, Seaborn, and Scikit-learn. These tools facilitate numerical computation, statistical analysis, data manipulation, and high-quality visualization.

The dataset was designed to replicate realistic variability in coarse aggregate properties and mix performance parameters. First, three primary shape indices were synthesized using normal distributions: flakiness index, elongation index, and angularity index, each clipped within realistic engineering ranges based on empirical data (e.g., flakiness between 5–35%, elongation between 10–40%, and angularity between 0–12). A combined shape factor was also computed as the mean of flakiness and elongation indices to capture the aggregate's overall deviation from ideal geometry.

These geometric descriptors were then used to simulate dependent performance parameters such as Marshall Stability, Flow Value, Air Voids Content, Indirect Tensile Strength (ITS), and Rutting Resistance. Each performance parameter was generated using domain-informed equations that modeled plausible engineering behavior. For example, Marshall stability was inversely related to the combined shape factor and positively influenced by angularity, reflecting the physical role of angular particles in enhancing interlock and stability. Gaussian noise was added to each performance metric to simulate experimental uncertainty, and values were clipped to maintain plausible engineering bounds.

In order to mimic field conditions, a categorical variable—Aggregate_Type—was introduced to represent material sources: Crushed Stone, Natural Gravel, and Recycled Aggregate, with assigned probabilities based on typical construction usage. This allowed for comparative analysis across material types and the isolation of shape-induced variability. The resulting data frame formed a robust foundation for statistical modeling and visualization.

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Figure 1. Implementation of the framework

## III. RESULTS AND DISCUSSION

The correlation matrix titled "Correlation Matrix: Shape Factors vs Performance Parameters" shown in Figure 2. provides an insightful statistical overview of the relationships between aggregate shape characteristics and the key performance parameters of bituminous mixtures. Each cell in the matrix represents the Pearson correlation coefficient (r), which ranges from -1 to +1, quantifying the strength and direction of the linear relationship between two variables. A positive value indicates that as one variable increases, the other tends to increase as well, while a negative value suggests an inverse relationship. A value near zero indicates weak or no linear correlation.

From the matrix, it is evident that the Combined Shape Factor—an average of flakiness and elongation indices—shows a strong positive correlation with Flow Value (r = 0.61) and Air Voids (r = 0.56), but a strong negative correlation with Marshall Stability (r = -0.37). This implies that higher shape irregularities (more flaky and elongated particles) tend to increase the mixture's deformation under load (higher flow) and internal void content, while simultaneously decreasing its resistance to permanent deformation, as reflected in reduced Marshall Stability. Similarly, Combined Shape Factor also shows a moderately negative correlation with Rutting Resistance (r = -0.38), indicating that mixes with higher combined shape irregularities are more prone to rutting, aligning well with expected field behavior.

Looking at individual shape parameters, Flakiness Index shows positive correlation with Flow Value (r = 0.56) and Air Voids (r = 0.39), and negative correlations with Marshall Stability (r = -0.23), ITS (r = -0.59), and Rutting Resistance (r = -0.33). This suggests that flaky particles tend to make the mix more porous and less stable, reducing both strength and resistance to rutting. Likewise, the Elongation Index follows a similar but milder trend, with a notably strong correlation with Combined Shape Factor (r = 0.78), further validating its influence on structural behavior.

In contrast, Angularity Index demonstrates a positive correlation with Marshall Stability (r = 0.74), indicating that angular aggregates significantly improve the load-bearing capacity of the mix. It also correlates positively with ITS (r = 0.45) and Rutting Resistance (r = 0.30), confirming the beneficial role of angular particles in resisting tensile failure and rutting. However, Angularity Index is negatively correlated with Air Voids (r = -0.59), implying that angular particles help achieve denser compaction with fewer voids, which is desirable for long-term durability.

Interestingly, ITS correlates positively with both Angularity Index and Marshall Stability (r = 0.42), and negatively with Flakiness Index and Air Voids, reinforcing the idea that mixes with well-shaped, angular aggregates provide stronger tensile resistance. On the other hand, Flow Value correlates positively with Flakiness Index, Combined Shape Factor, and Elongation Index but negatively with stability and strength indicators, signifying that poor aggregate shape leads to more flexible and potentially unstable mixes.

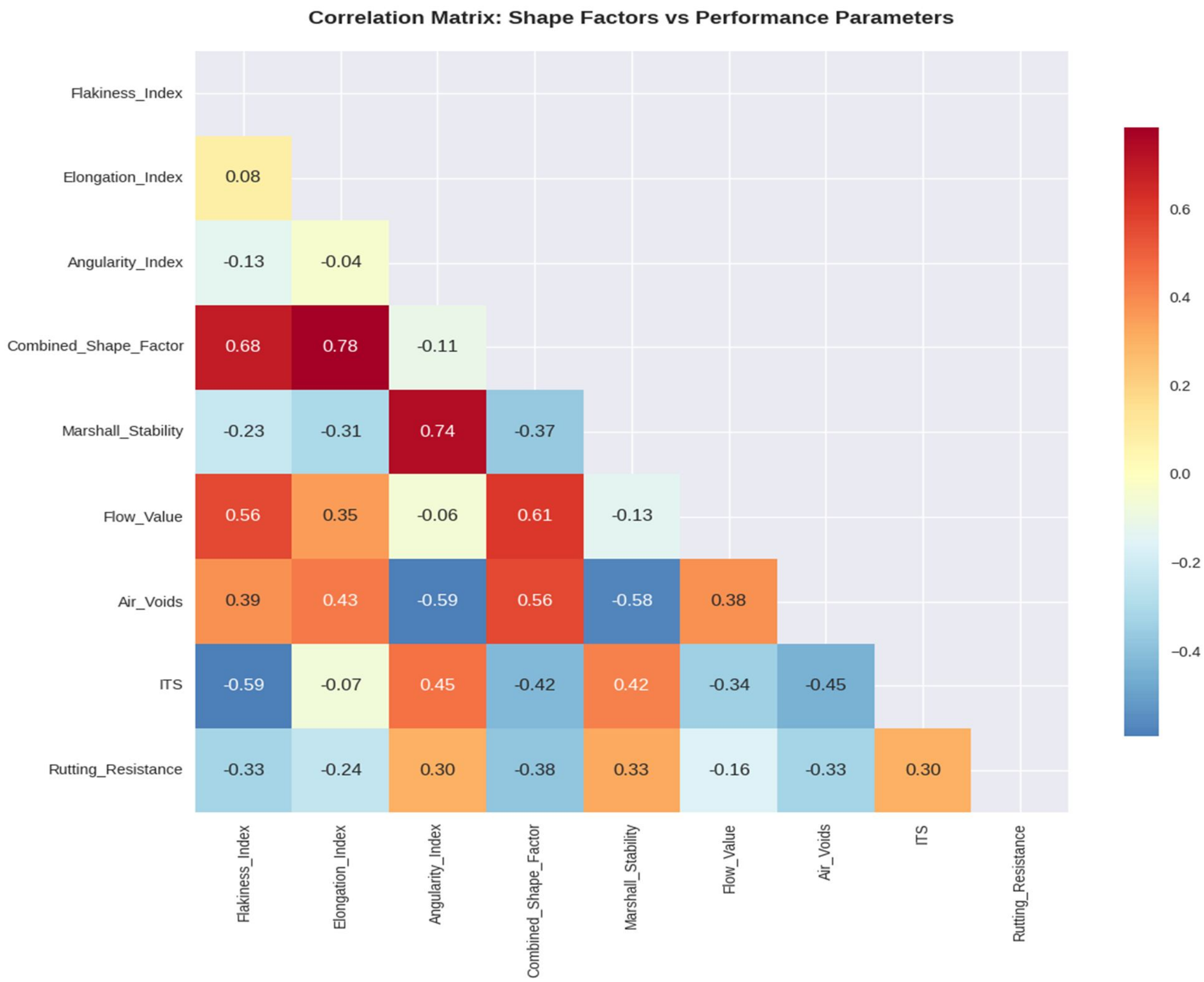


Figure 2. Representation of confusion matrix

The multi-panel plot titled "Influence of Shape Factors on Bituminous Mix Performance" presents a visual analysis of how coarse aggregate geometric characteristics—particularly combined shape factor, flakiness index, and angularity index—affect critical performance parameters of bituminous mixtures, including Marshall Stability, Air Voids, Indirect Tensile Strength (ITS), and Rutting Resistance. These four scatter plots illustrate underlying trends, variability, and interactions that reinforce statistical correlations observed in earlier heatmap analysis.

In the top-left panel, the plot shows the relationship between Combined Shape Factor and Marshall Stability. A clear negative trend is visible, with the regression line indicating that as the combined shape factor increases (i.e., more flaky and elongated particles), the Marshall stability of the mix decreases. This behavior reflects the weakening of internal structure due to poor inter-particle interlock and alignment of flat or needle-like aggregates during compaction. The scatter of points also shows variability across angularity, as represented by the color gradient, reinforcing the idea that higher angularity may mitigate some negative effects of poor shape.

The top-right panel visualizes Air Voids against Flakiness Index, where a positive trend is apparent. As the flakiness index increases, air void content also tends to rise, which is expected because flat particles stack inefficiently, trapping voids during compaction. The spread of data indicates that even small increases in flakiness can significantly disrupt the compacted mix's volumetric efficiency, leading to higher susceptibility to oxidation and moisture ingress over time.

The bottom-left panel, showing ITS versus Angularity Index, displays a moderate positive relationship, where increased angularity generally corresponds to higher indirect tensile strength. This supports the fundamental pavement engineering principle that angular aggregates enhance inter-particle friction and resistance to tensile cracking. The color-coded distribution (based on combined shape factor or another influencing metric) highlights how shape irregularities may counteract or amplify the strength benefits of angularity.

The bottom-right panel presents Rutting Resistance as a function of the Combined Shape Factor, with color shading denoting another dimension of performance (likely Marshall Stability or voids). This plot further confirms that higher shape irregularity (higher combined shape factor) tends to result in lower rutting resistance, as poorly shaped particles are more prone to movement and reorientation under repeated traffic loads. The downward slope in data distribution reveals the inverse association, while the scatter suggests interaction with other variables such as angularity or material stiffness.


Figure 3. Influence of Shape Factors on Bituminous Mix Performance

The set of box plots titled "Performance Parameters by Aggregate Type" offers a clear comparative view of how different coarse aggregate sources—Recycled Aggregate, Crushed Stone, and Natural Gravel—influence the distribution of key performance parameters in bituminous mixtures. This form of statistical visualization not only captures central tendencies (such as the median) but also illustrates variability, skewness, and the presence of outliers, thus providing deeper insights into the consistency and performance reliability of each aggregate type under simulated conditions.

In the top-left plot, the Marshall Stability Distribution reveals that both Recycled Aggregate and Crushed Stone mixes demonstrate slightly higher median stability compared to Natural Gravel, with Crushed Stone also exhibiting a more balanced interquartile range (IQR). Interestingly, Recycled Aggregates show a wider spread in stability values, indicating higher variability likely due to the heterogeneous nature of recycled materials. Nonetheless, the comparable medians of recycled and crushed aggregates challenge the traditional notion that recycled materials always underperform, suggesting that with proper processing, recycled aggregates can offer competitive strength.

The top-right plot on Air Voids Distribution demonstrates that Natural Gravel mixtures tend to have slightly lower air voids on average, which may be attributed to their smoother, rounded particles that facilitate better compaction. However, Recycled Aggregates and Crushed Stone both show wider IQRs and more variability in air void content, with recycled aggregates displaying several outliers toward both lower and higher extremes. This highlights the sensitivity of air voids to particle shape irregularities, particularly in recycled materials where flakiness and elongation are less controlled.

In the bottom-left plot, which presents Indirect Tensile Strength (ITS) distributions, Recycled Aggregates surprisingly outperform both Natural Gravel and Crushed Stone in terms of median ITS values, indicating higher tensile strength on average. This could be attributed to the angular and irregular shape of recycled particles, which may promote better interlock despite their structural heterogeneity. Crushed Stone and Natural Gravel show relatively lower medians and tighter IQRs, suggesting more consistent but slightly weaker tensile behavior.

Finally, the bottom-right plot on Rutting Resistance Distribution shows that while all three aggregate types provide relatively similar median resistance, Crushed Stone exhibits a slightly better performance profile overall, with fewer extreme outliers and a tighter spread. Natural Gravel appears to have a slightly broader range and a lower median compared to Crushed Stone. Recycled Aggregates, while having comparable central tendency, show greater variability and some notably low outliers, indicating susceptibility to rutting in less-processed or poorly graded samples.

Collectively, these plots underscore the importance of aggregate type selection in mix design, revealing that Crushed Stone offers the most consistent performance across parameters, while Recycled Aggregates, despite showing promise, may require stricter control over processing and gradation to minimize variability. Natural Gravel, with its rounder particles, tends to yield more compactable but less mechanically robust mixtures. These findings validate the need for integrating shape and source-specific parameters into performance-based specifications, encouraging sustainable practices (through recycled use) without compromising pavement quality.

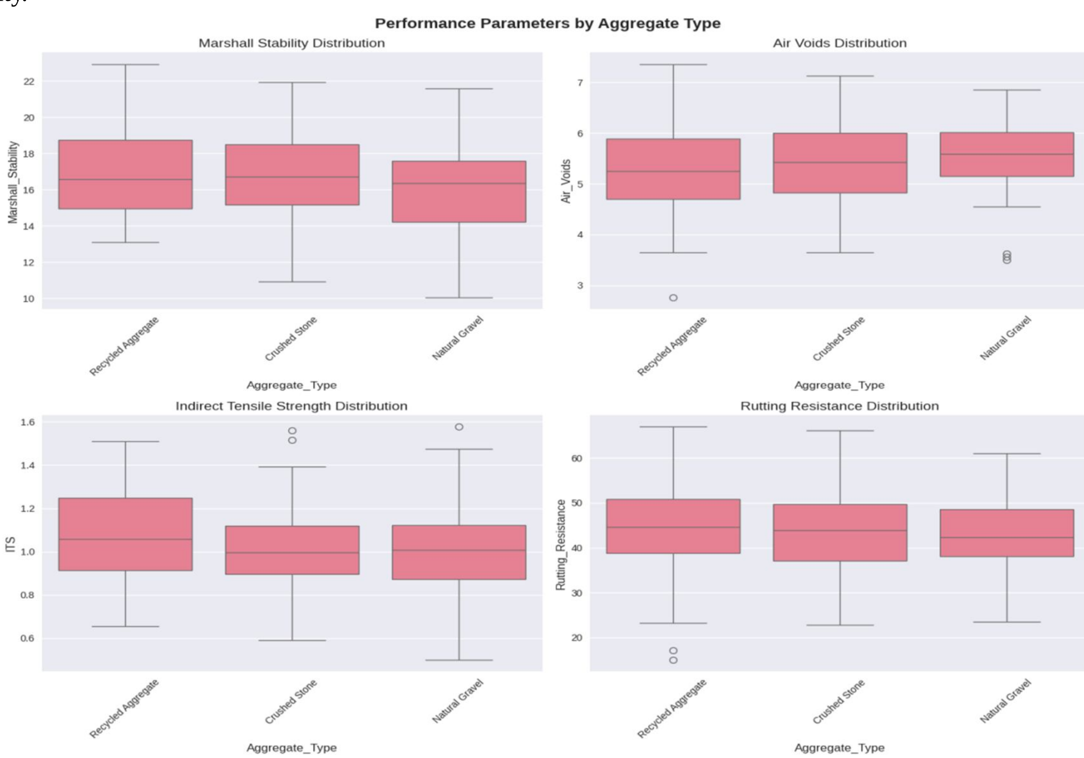


Figure 4. Performance Parameters by Aggregate Type

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Figure 5. presents a focused statistical modeling of the relationships between aggregate shape characteristics and key performance parameters of bituminous mixtures. Each scatter plot is fitted with a second-degree polynomial regression line, revealing non-linear trends, while the coefficient of determination ($R^2$) values quantify how much of the variance in the dependent variable can be explained by the respective shape factor. This analysis provides essential insight into the predictive potential of aggregate geometry in determining pavement performance.

In the top-left plot, the relationship between Marshall Stability and Combined Shape Factor shows a mildly negative trend, as visualized by the slightly downward-bending regression curve. The $R^2$ value of 0.146 indicates that approximately 14.6% of the variation in Marshall stability can be attributed to changes in combined shape factor. Although the explanatory power is modest, the negative trend aligns well with engineering principles—flaky and elongated particles (i.e., higher shape factor) reduce interlock and structural stability, lowering Marshall Stability. The curvature in the regression line suggests a non-linear response, where the impact of shape irregularity may intensify beyond a threshold.

The top-right plot, showing Air Voids vs Flakiness Index, yields an $R^2$ of 0.155, indicating that about 15.5% of the variability in air void content is influenced by flakiness alone. The regression curve suggests that air voids increase as flakiness increases, but the slope plateaus slightly at higher flakiness values. This pattern reflects a known compaction behavior—flat particles disrupt the packing structure, increasing void spaces, especially in the mid-to-upper range of flakiness indices.

The bottom-left plot, which investigates Indirect Tensile Strength (ITS) as a function of Angularity Index, demonstrates the strongest correlation in this panel, with an $R^2$ of 0.207. This implies that approximately 20.7% of the variation in ITS can be explained by aggregate angularity, which is significant for a single-parameter regression. The upward trend in the regression line confirms that higher angularity leads to better particle interlock and stress transfer, thereby enhancing tensile strength. The relatively strong association makes angularity a promising parameter for predictive modeling and material selection focused on tensile performance.

Finally, the bottom-right plot, examining Rutting Resistance vs Combined Shape Factor, mirrors the trend seen in Marshall stability. With an $R^2$ of 0.146, it suggests a moderate inverse relationship—higher combined shape factors correlate with lower rutting resistance. The regression line's consistent downward slope illustrates how shape irregularities negatively affect load distribution and resistance to permanent deformation. As rutting is a critical long-term distress in asphalt pavements, this trend underscores the need to control flakiness and elongation during aggregate selection.

Although none of the $R^2$ values exceed 0.25, which might be expected in complex, multi-variable engineering systems, the directionality and consistency of the trends lend strong support to the hypothesis that aggregate shape indices are important contributors to performance. These relationships, though not individually decisive, can be powerfully predictive when combined in a multivariate framework, suggesting the need for ensemble models or machine learning approaches in future research.

This regression analysis substantiates the quantitative impact of shape factors, strengthens the rationale for including them in mix design specifications, and offers a data-driven foundation for predictive tools in flexible pavement engineering.

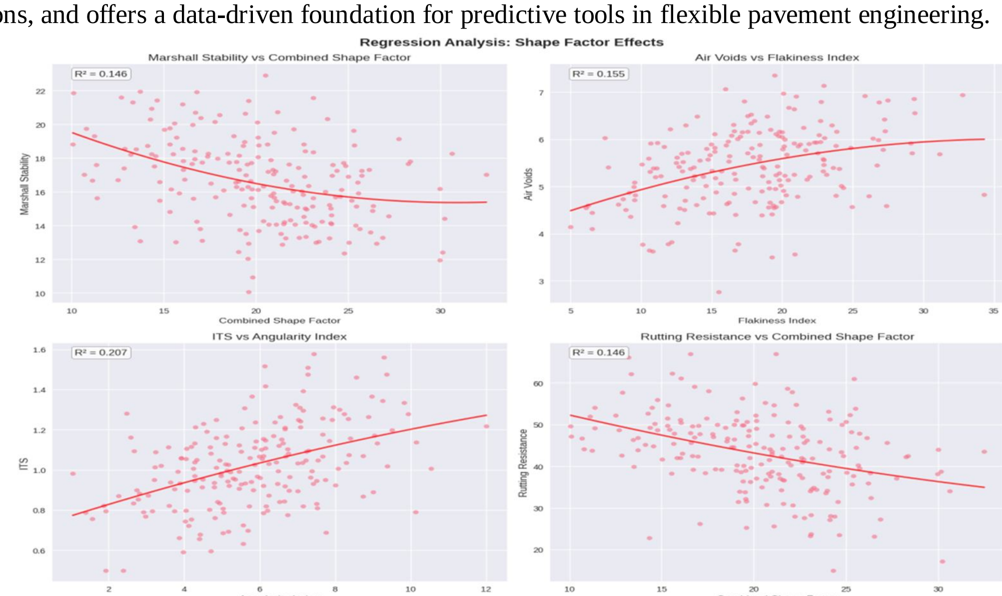


Figure 5. relationship between Marshall Stability and Combined Shape Factor

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Figure 6 presents a comprehensive summary of the interaction between aggregate geometric properties and bituminous mix performance metrics using a compact and information-rich layout. This dashboard serves as a powerful decision-support tool, integrating shape distributions, correlation insights, scatter plots, and descriptive statistics—all of which collectively provide a nuanced understanding of how aggregate shape affects pavement behavior.

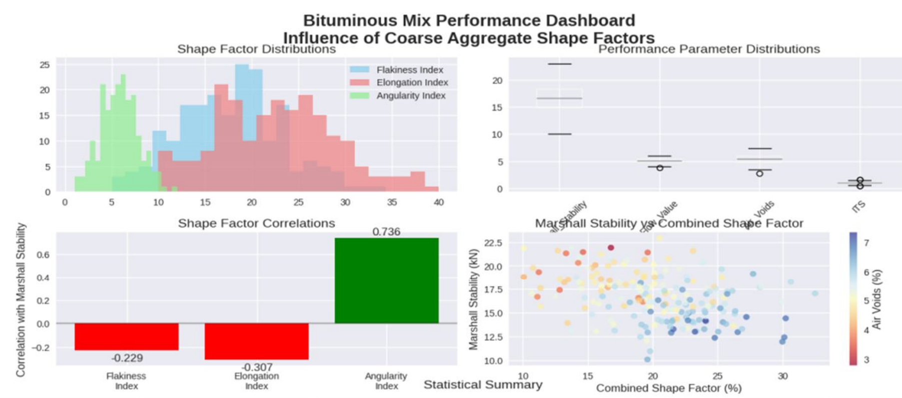
In the top-left panel, the Shape Factor Distributions histogram showcases the spread and frequency of three primary indices: Flakiness Index (blue), Elongation Index (red), and Angularity Index (green). The histograms indicate that flakiness and elongation indices are more widely distributed across their respective ranges (approximately 5–35% for flakiness and 10–40% for elongation), while angularity exhibits a tighter distribution (roughly 1–12), reflecting the physical nature of typical aggregates. These distributions confirm that the dataset is well-balanced and spans realistic engineering values, allowing for robust comparative analysis across shape profiles.

On the top-right, the Performance Parameter Distributions are presented via box plots for Marshall Stability, Flow Value, Air Voids, and Indirect Tensile Strength (ITS). These visualizations highlight central tendencies, variation, and outliers. Marshall Stability exhibits a fairly wide range, consistent with the influence of both shape and angularity. Flow and air voids show relatively narrower distributions, while ITS has the tightest range, indicating that tensile behavior is more sensitive and potentially less variable across different shape profiles under controlled mix conditions.

The middle-left bar chart titled Shape Factor Correlations shows the Pearson correlation coefficients of each shape factor with Marshall Stability, providing a quick and interpretable snapshot of relationship strength and direction. Angularity Index demonstrates a strong positive correlation (r = 0.736), reinforcing its importance in enhancing mix strength through increased inter-particle friction and better mechanical interlock. In contrast, Flakiness Index (r = -0.229) and Elongation Index (r = -0.307) both exhibit negative correlations, indicating that flatter or elongated particles tend to weaken the structural integrity of the mix by reducing contact effectiveness and disrupting compaction.

The middle-right plot, a scatter diagram titled Marshall Stability vs Combined Shape Factor, uses a color gradient to map Air Voids (%) as a third variable. This multidimensional visualization highlights a subtle but significant trend: Marshall Stability generally decreases as Combined Shape Factor increases, while higher void content is clustered in regions of high shape factor and low stability. This triangulated interpretation supports the hypothesis that poorly shaped aggregates not only reduce strength but also hinder densification, leading to excessive voids and greater susceptibility to moisture-induced damage or early fatigue.

Finally, the bottom section provides a statistical summary table of all relevant variables—Flakiness Index, Elongation Index, Angularity Index, Marshall Stability, Air Voids, and ITS. This table presents count, mean, standard deviation, minimum, quartiles (25th, 50th, 75th), and maximum values. From this, we observe, for example, that the mean flakiness index is 17.77%, elongation index is 22.65%, and angularity index is 5.83, indicating a moderate level of shape irregularity across the dataset. Performance parameters show that the average Marshall Stability is 16.64 kN, which is reasonable for a dense-graded mix, while the mean ITS is 1.02 MPa, and air voids average at 5.42%, suggesting an overall balance between workability and durability in the simulated mixtures.




Statistical Summary

| | Flakiness Index | Elongation Index | Angularity Index | Marshall Stability | Air Voids | ITS |
|---|---|---|---|---|---|---|
| count | 200.0 | 200.0 | 200.0 | 200.0 | 200.0 | 200.0 |
| mean | 17.77 | 22.65 | 5.83 | 16.64 | 5.42 | 1.02 |
| std | 5.55 | 6.54 | 1.99 | 2.48 | 0.81 | 0.21 |
| min | 5.0 | 10.0 | 1.06 | 10.07 | 2.77 | 0.5 |
| 25% | 13.77 | 17.76 | 4.41 | 14.87 | 4.84 | 0.89 |
| 50% | 17.97 | 22.55 | 5.84 | 16.61 | 5.42 | 1.02 |
| 75% | 21.01 | 26.81 | 7.14 | 18.27 | 5.97 | 1.15 |
| max | 34.32 | 40.0 | 12.0 | 22.93 | 7.36 | 1.58 |

Figure 7. Bituminous Mix Performance Dashboard – Influence of Coarse Aggregate Shape Factors

## IV. CONCLUSION

This research was undertaken to investigate the critical role that aggregate geometric characteristics—specifically flakiness index, elongation index, and angularity index—play in influencing the mechanical and volumetric behavior of bituminous mixtures used in flexible pavement construction. Through the generation of a synthetic yet realistic dataset, supported by regression modeling, statistical correlation analysis, and high-quality visual dashboards, the study provided evidence-based insights into how aggregate shape affects key performance parameters such as Marshall stability, flow value, air voids content, indirect tensile strength (ITS), and rutting resistance.

The findings of the research clearly demonstrate that aggregate geometry is not merely a secondary consideration in mix design, but a primary factor that significantly governs pavement performance. High values of flakiness and elongation were consistently associated with reduced Marshall stability, increased air voids, and lower rutting resistance, indicating that poorly shaped particles disrupt the internal structure of the mix, hinder compaction, and compromise load-bearing capacity. In contrast, angularity index showed strong positive correlations with both Marshall stability and ITS, confirming that angular aggregates contribute to improved inter-particle friction, mechanical interlock, and overall mix strength.

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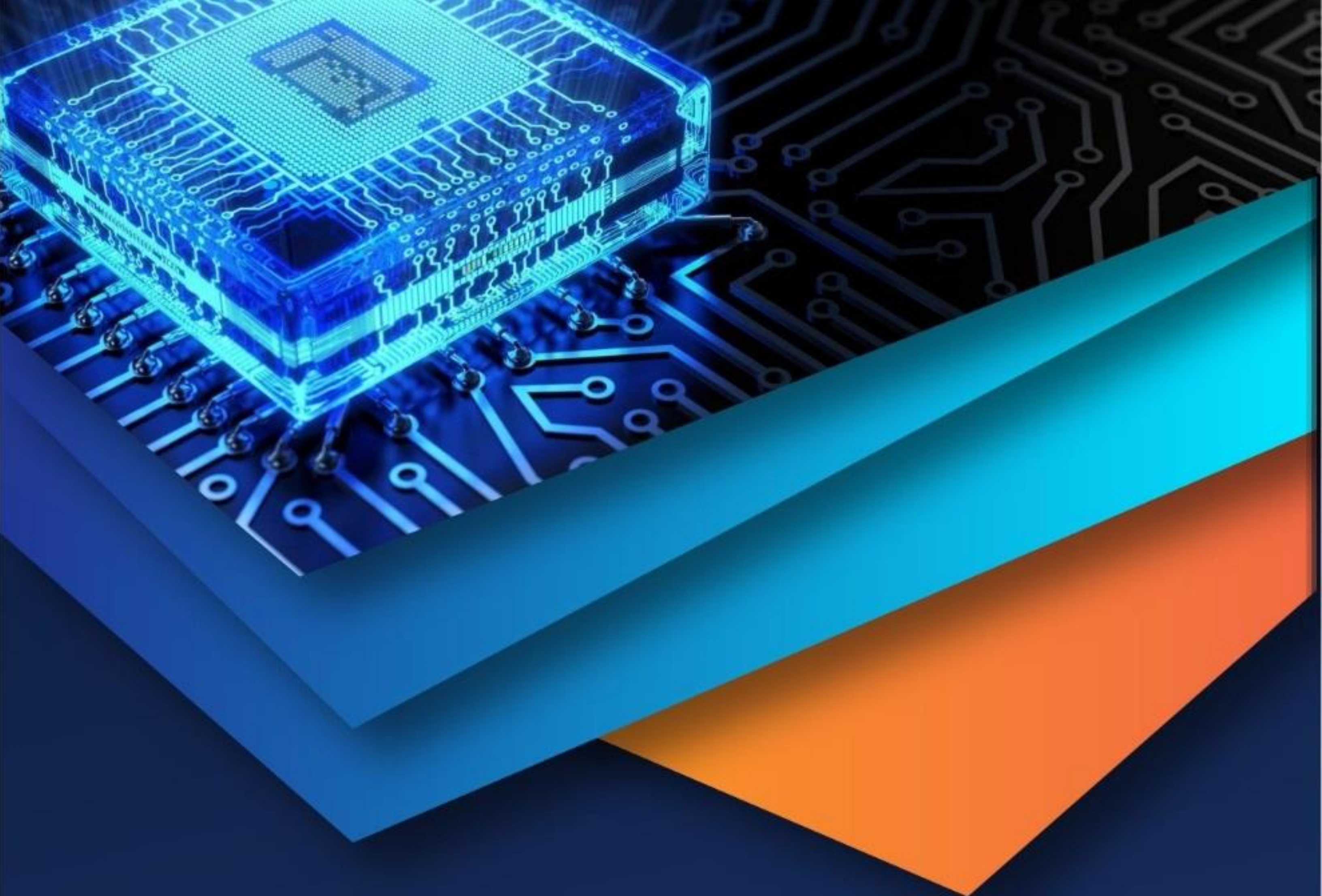

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