Technema: Journal of Intelligent Engineering and Computing
Vol 1 No 2 June 2026, Hal 194-203
ISSN: 3163-6020 (Print) ISSN: 3163-5997 (Electronic)
Open Access: https://sovereignresearch.org/technema

Evaluation of the Density of Class A Aggregate Foundation Layers Using the Sand Cone Method on the Taba Mulan–Simpang Nangka Road Improvement Project, Bengkulu Province

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Article Info :
Received:
10-06-2026
Revised:
20-06-2026
Accepted:
26-06-2026

Abstract

The Class A aggregate base course is a critical structural component of flexible pavements because its compaction quality directly influences load distribution, structural stability, and pavement service life. This study evaluated the field compaction quality of the Class A aggregate base using the Sand Cone method on the Nakau–South Sumatra Provincial Border Road Preservation Project, specifically the Taba Mulan–Simpang Nangka section, Bengkulu Province. A descriptive quantitative approach was employed using field measurements obtained from ten representative testing locations. Field dry density values determined through the Sand Cone test were compared with the laboratory maximum dry density obtained from the Modified Proctor test (2.23 g/cm³) to calculate the Degree of Compaction (DoC), which was subsequently evaluated against the Bina Marga General Specifications. The measured compaction values ranged from 99.10% to 101.79%, with an average DoC of 100.49%. Eight testing locations (80%) satisfied the minimum requirement of 100% Modified Proctor, whereas two locations (20%) recorded values slightly below the specification. Variations in compaction performance were associated with moisture content, aggregate gradation, layer thickness, roller passes, weather conditions, and construction quality control. The findings confirm that the aggregate base generally complied with national technical standards while highlighting the importance of continuous field quality control to achieve uniform compaction throughout road preservation projects.

Keywords: *Class A Aggregate Base, Degree of Compaction, Modified Proctor, Road Preservation, Sand Cone Method.*

INTRODUCTION

Road infrastructure plays a fundamental role in supporting social mobility, regional connectivity, and sustainable economic development, making its construction quality a strategic concern within modern intelligent engineering and computing practices. Continuous advancements in pavement engineering, digital construction management, and quality assurance systems have shifted the emphasis from corrective maintenance toward preventive quality control during construction, where field performance indicators are increasingly integrated into infrastructure asset management frameworks (Saputra & Elvaria, 2025). High-quality road networks improve accessibility, facilitate the movement of goods and services, strengthen regional competitiveness, and contribute to long-term socioeconomic resilience. From an engineering perspective, achieving the designed service life of pavement structures depends not only on material selection but also on strict compliance with technical specifications throughout every construction stage (Kementerian Pekerjaan Umum dan Perumahan Rakyat, 2020). This perspective has encouraged researchers and practitioners to regard construction quality assessment as an essential component of intelligent infrastructure management rather than merely a post-construction inspection process. National technical regulations likewise reinforce that road preservation and construction activities must satisfy standardized engineering requirements to ensure structural reliability throughout the pavement life cycle (Direktorat Jenderal Bina Marga, 2018).

One of the most critical structural components of flexible pavement is the Class A aggregate foundation layer, which functions as the primary load-distribution medium transferring traffic loads from the upper pavement layers to the underlying subgrade while maintaining structural stability under repetitive loading conditions. Classical geotechnical theory explains that the engineering performance of compacted aggregate materials is fundamentally controlled by density, moisture conditions, and particle interlocking, all of which directly influence bearing capacity and long-term deformation characteristics (Terzaghi et al., 1996). Previous investigations have consistently demonstrated that inadequate compaction leads to settlement, rutting, cracking, and premature pavement deterioration even when aggregate quality satisfies material specifications (Gobel et al., 2023). Experimental studies further indicate that aggregate gradation, compaction energy, moisture content, and gravel proportion significantly affect the density achieved in the field, illustrating that construction quality depends on multiple interacting variables rather than a single material characteristic (Sukmawati et al., 2024). Vibratory compaction research also confirms that optimizing aggregate densification substantially improves structural stiffness and pavement durability under increasing traffic demand (Karan et al., 2017). These findings collectively demonstrate that density control represents one of the most influential determinants of pavement performance throughout its operational service life.

To ensure that the achieved density satisfies engineering requirements, field verification using standardized testing methods is indispensable during road construction. Among the available techniques, the Sand Cone method remains one of the most widely accepted approaches because it directly determines in-situ dry density by comparing field measurements with laboratory-derived maximum dry density values, enabling calculation of the degree of compaction in accordance with established engineering standards (ASTM D1556, 2007). Comparative studies have demonstrated strong agreement between Sand Cone measurements and laboratory compaction evaluations, confirming its reliability as a quality-control instrument for earthworks and aggregate base construction (Adenora et al., 2021). Other researchers have also reported that environmental conditions, particularly moisture variation during testing, may influence measurement accuracy, highlighting the importance of standardized procedures during field implementation (Park et al., 2021). Comparative analyses between Sand Cone and nuclear density testing reveal acceptable consistency while emphasizing the continued practicality of the Sand Cone method for infrastructure projects where advanced testing equipment is unavailable (Zorluer et al., 2020). These developments explain why the method continues to serve as a benchmark for evaluating compaction quality across a wide range of transportation infrastructure projects.

Despite substantial progress in density evaluation research, the existing literature still reveals several conceptual and empirical limitations that restrict broader application of current findings. Many recent studies primarily focus on reporting density compliance values without comprehensively examining the influence of construction practices, environmental variability, equipment performance, and field implementation on the consistency of compaction quality (Akbar et al., 2024). Similar evaluations conducted on Class A aggregate base layers have successfully demonstrated conformity with technical specifications, yet their analyses generally remain descriptive and provide limited interpretation regarding the engineering implications of density variation across construction sites (Febriana et al., 2024). Correlation analyses between Sand Cone measurements and other geotechnical indicators have contributed valuable insights into quality assessment, although these investigations are predominantly concentrated on subbase layers instead of Class A aggregate foundations under preservation projects (Yanis et al., 2022). Additional project-based studies likewise emphasize compliance assessment but provide limited discussion concerning the reproducibility of testing procedures under diverse field conditions (Yumardi et al., 2024). These inconsistencies indicate the need for further empirical studies capable of integrating standardized testing procedures with comprehensive engineering evaluation under actual construction environments.

The Taba Mulan–Simpang Nangka section of the Nakau–South Sumatra Border Road Preservation Project in Bengkulu Province represents a strategic case for investigating the field performance of Class A aggregate foundation layers because the project forms part of an important regional transportation corridor requiring strict adherence to national construction specifications. In practice, achieving uniform compaction remains challenging because field density is affected by material characteristics, moisture conditions, compaction equipment, operational procedures, and environmental influences that vary spatially throughout construction activities. Recent field investigations on comparable road improvement projects have demonstrated that Sand Cone testing provides objective evidence for assessing the conformity of aggregate base compaction with engineering specifications while supporting more effective construction quality assurance (Saputra & Elvaria, 2025). Similar case studies conducted in Indonesia consistently report that systematic density evaluation enables contractors and supervising engineers to identify deviations before pavement defects become structurally significant (Rausy & Mokui, 2024). From a broader engineering perspective, reliable density assessment also supports regulatory compliance mandated by national road legislation governing the implementation and preservation of public road infrastructure (Undang-Undang Republik Indonesia Nomor 2 Tahun 2022). This research is therefore positioned as an empirical investigation that strengthens existing knowledge by evaluating field compaction quality using standardized measurements within an actual road preservation project.

This study aims to evaluate the density of the Class A aggregate foundation layer on the Taba Mulan–Simpang Nangka Road Improvement Project using the Sand Cone method and to determine whether the achieved degree of compaction satisfies the applicable technical specifications. The research also seeks to identify the consistency of field compaction results across representative testing locations and to provide an objective assessment of construction quality under actual project conditions. Methodologically, this study contributes by applying a standardized and reproducible field-testing framework that combines direct in-situ density measurements with laboratory reference data for engineering evaluation. Theoretically, the findings are expected to enrich the body of knowledge concerning quality control of aggregate base construction within pavement engineering and intelligent infrastructure management. Practically, the results are intended to provide evidence-based recommendations for contractors, consultants, and supervising agencies in improving construction quality assurance and supporting more sustainable road preservation practices.

RESEARCH METHODS

This study employed an empirical quantitative approach based on field experimentation to evaluate the density of the Class A aggregate foundation layer using the Sand Cone method on the Nakau–South Sumatra Provincial Border Road Preservation Project, specifically the Taba Mulan–Simpang Nangka section in Bengkulu Province. The research adopted a descriptive quantitative design because the evaluation relied on numerical measurements of in-situ density obtained from direct field testing and subsequently compared with the specified engineering requirements. The study was conducted on sections of the completed Class A aggregate base that were considered ready for quality inspection according to the construction schedule. Representative testing locations were selected by considering field conditions, compacted work areas, eligible construction segments, and recommendations from the site supervision engineer to ensure that the sampling adequately reflected actual project conditions. Primary data consisted of field density measurements obtained using the Sand Cone apparatus, whereas secondary data included project drawings, technical specifications, laboratory maximum dry density (Modified Proctor) results, and quality-control documentation. The testing procedure followed the standardized Sand Cone method specified in ASTM D1556 for determining in-place dry density, while the acceptance criteria were evaluated according to the General Specifications for Highway Construction (Bina Marga 2018) (ASTM D1556, 2007). The overall research framework was designed to produce accurate, objective, and reproducible measurements of field compaction quality in accordance with national road construction standards (Direktorat Jenderal Bina Marga, 2018).

Field testing was performed at multiple representative locations after completion of the compaction process by excavating a test hole, determining its volume using calibrated standard sand, measuring the excavated aggregate mass and moisture content, and calculating the in-situ dry density before determining the Degree of Compaction (DoC). The calculated field dry density at each testing point was compared with the laboratory maximum dry density to evaluate compliance with the minimum compaction requirement specified for Class A aggregate base layers (Adenora et al., 2021). Quality validation was ensured through calibration of the Sand Cone apparatus, verification of moisture-content measurements, repeated observations at selected locations, and consistency checks between field measurements and laboratory reference data to minimize measurement uncertainty. The evaluation metrics consisted of in-situ dry density (Mg/m^3), maximum dry density (Mg/m^3), moisture content (%), and Degree of Compaction (%), which collectively served as quantitative indicators for assessing construction quality. The resulting data were analyzed descriptively to determine the conformity of each testing location with the applicable technical specifications and to identify possible density variations caused by material characteristics or construction practices. The application of standardized field procedures provides a reliable basis for evaluating aggregate base compaction quality and supports effective quality-control implementation in road preservation projects (Saputra & Elvaria, 2025).

RESULTS AND DISCUSSION

Study Area and Testing Procedure

The research was conducted on the Nakau–South Sumatra Provincial Border Road Preservation Project, specifically along the Taba Mulan–Simpang Nangka section in Bengkulu Province, which constitutes one of the strategic road corridors supporting regional connectivity and socioeconomic activities. The road functions as a primary transportation route linking several districts with the provincial boundary, facilitating the movement of agricultural products, construction materials, commercial goods, and public services. The increasing intensity of heavy vehicle traffic requires the pavement structure to possess sufficient bearing capacity to sustain repeated axle loads throughout its intended service life. From an engineering perspective, the long-term performance of flexible pavement is strongly influenced by the quality of its foundation layers, particularly the Class A aggregate base, which distributes traffic loads to the underlying subgrade while maintaining structural stability (Sukirman, 1999). Maintaining the required level of compaction during construction is therefore an essential aspect of quality assurance rather than merely a contractual obligation. This project provides an appropriate case study because the aggregate base course was constructed under active preservation works where compliance with national technical standards could be evaluated directly through field measurements.

Road preservation activities differ fundamentally from new road construction because they focus on restoring and maintaining structural performance while minimizing future rehabilitation costs and extending pavement service life. The preservation program implemented on the Taba Mulan–Simpang Nangka section included rehabilitation of the pavement foundation to improve structural integrity before the placement of subsequent pavement layers. The Class A aggregate foundation layer was selected as the primary object of investigation because its compaction quality directly affects pavement stiffness, resistance to permanent deformation, and long-term durability under operational traffic conditions. Indonesian road construction regulations require every pavement layer to satisfy specified engineering criteria before subsequent construction activities are permitted, emphasizing the importance of systematic field quality verification (Direktorat Jenderal Bina Marga, 2018). The implementation of standardized quality control also reduces the probability of premature pavement deterioration caused by inadequate field compaction. These characteristics make the investigated project representative of contemporary road preservation practices implemented within the national highway network.

The study adopted an empirical quantitative approach based on direct field experimentation using the Sand Cone method to evaluate the in-situ density of the completed Class A aggregate foundation layer. Testing locations were determined after field reconnaissance to ensure that each sampling point represented actual construction conditions while covering different segments of the completed work area. The selection process considered pavement readiness, accessibility, uniformity of aggregate placement, recommendations from the supervising engineer, and the completion status of compaction activities before density testing was initiated. The investigation was designed to minimize sampling bias by distributing observations throughout the project section rather than concentrating measurements within a limited area. This approach improves the representativeness of the collected data and enables a more objective assessment of construction quality across the investigated road segment. Similar sampling strategies have been widely implemented in field density investigations because they provide reliable information regarding the spatial consistency of aggregate compaction (Gobel et al., 2023).

The field testing procedure followed the standardized Sand Cone method to determine the in-place dry density of the compacted aggregate layer through direct measurement of excavated material and calibrated sand volume. Before testing commenced, all equipment, including the Sand Cone apparatus, calibrated standard sand, base plate, digital balance, excavation tools, moisture-content containers, and sampling accessories, was inspected to ensure proper operational performance. Equipment calibration and procedural verification were performed to minimize systematic measurement errors and maintain consistency among testing locations. Standardized operating procedures are essential because relatively small measurement deviations may significantly influence the calculated degree of compaction, particularly when field density values approach specification limits (ASTM D1556, 2007). Each testing location underwent identical preparation, excavation, measurement, and documentation procedures to preserve methodological consistency throughout the investigation. The application of uniform testing procedures also enhances the reproducibility of the resulting engineering evaluation.

Following completion of field measurements, the excavated aggregate samples were weighed, moisture content was determined, and the corresponding dry density values were calculated for every testing location. The computed field dry density was subsequently compared with the maximum dry density obtained from the Modified Proctor laboratory test to determine the Degree of Compaction (DoC), which served as the principal performance indicator in this investigation. The quantitative evaluation framework enabled objective comparison between observed field conditions and the minimum acceptance criteria specified for Class A aggregate foundation layers. This analytical approach provides a direct assessment of construction quality because density measurements reflect the effectiveness of compaction under actual project conditions rather than controlled laboratory environments. Previous studies have similarly demonstrated that comparison between laboratory reference density and field measurements represents one of the most dependable approaches for evaluating compaction quality in road construction projects (Adenora et al., 2021). The resulting dataset therefore provides a robust basis for assessing compliance with applicable engineering specifications.

The overall research workflow consisted of preliminary site investigation, collection of supporting project documentation, field density testing, laboratory verification of moisture content, quantitative calculation of density parameters, and engineering evaluation of compaction performance. Descriptive statistical analysis was subsequently employed to summarize the distribution of field density values by calculating the minimum, maximum, and average degree of compaction observed throughout the investigated section. The analytical process also examined whether individual testing locations complied with the minimum compaction requirement established in the national highway construction specifications. Engineering interpretation was then performed by relating the observed density characteristics to potential construction factors, including moisture conditions, aggregate gradation, compaction efficiency, and field implementation practices. This systematic workflow ensures that the interpretation of compaction quality is supported by objective measurements rather than qualitative observations alone. The methodological framework therefore establishes a reliable foundation for the subsequent analysis of field density results and engineering performance presented in the following section.

Field Density Test Results

The field density evaluation was carried out at ten representative testing locations distributed along the completed Class A aggregate foundation layer on the Taba Mulan–Simpang Nangka Road Improvement Project. The measurements were performed after the compaction process had been completed and the construction segment was considered ready for quality inspection according to project requirements. Each testing point was analyzed by determining the in-situ dry density using the Sand Cone method and comparing the calculated value with the maximum dry density obtained from the Modified Proctor laboratory test. This comparison produced the Degree of Compaction (DoC), which served as the primary indicator for evaluating compliance with the applicable technical specifications. The measured values demonstrate the actual quality of field compaction achieved during construction and provide objective evidence regarding the effectiveness of the implemented compaction process. The resulting dataset also enables quantitative assessment of density variation throughout the investigated road section.

The calculated Degree of Compaction ranged from 99.10% to 101.79%, indicating relatively small variation among the ten testing locations despite differences in field conditions during construction. Eight testing points achieved compaction values equal to or greater than the required minimum of 100% Modified Proctor, while two locations recorded values slightly below the specified threshold. The overall average Degree of Compaction reached 100.49%, suggesting that the aggregate base generally satisfied the density requirement established in the national highway specifications. Similar findings have been reported in recent investigations, where the majority of testing locations fulfilled specification limits while minor local variations remained unavoidable because of differences in construction conditions (Febriana et al., 2024). The observed results indicate that the implemented compaction procedure was capable of producing relatively consistent engineering performance across the investigated project. The remaining deviations, however, require further interpretation to determine their possible engineering significance.

The numerical results obtained from each testing location are summarized in Table 1, which presents the calculated Degree of Compaction together with the corresponding compliance status for every observation point. The table indicates that the highest compaction value was achieved at STA 1+300, whereas the lowest value occurred at STA 0+900, illustrating that field density was not perfectly uniform across the construction area. Such variation is expected in practical road construction because aggregate characteristics, moisture distribution, and operational conditions may differ slightly between working segments even when identical construction procedures are applied. The distribution of the measured values nevertheless remains relatively concentrated around the design target, reflecting satisfactory implementation of field quality control.

Table 1. Field Density Test Results of the Class A Aggregate Foundation Layer

Testing Point	Station (STA)	Degree of Compaction (%)	Compliance Status
1	0+100	100.62	Compliant
2	0+300	99.55	Non-compliant
3	0+500	100.18	Compliant
4	0+700	100.94	Compliant
5	0+900	99.10	Non-compliant
6	1+100	100.87	Compliant
7	1+300	101.79	Compliant
8	1+500	100.36	Compliant
9	1+700	100.58	Compliant
10	1+900	100.91	Compliant
Average	–	**100.49**	**Compliant**

The results presented in Table 1 demonstrate that 80% of the testing locations satisfied the minimum density requirement, while 20% remained marginally below the specified acceptance criterion. Although the differences between compliant and non-compliant locations were numerically small, these deviations remain technically important because pavement foundation layers are designed to function as an integrated structural system. Localized reductions in density may create weak zones that experience greater compressibility under repeated traffic loading than surrounding areas. Previous studies have similarly reported that even slight reductions in field density may influence pavement performance when such conditions persist over extensive sections of the aggregate base (Akbar et al., 2024). The overall distribution nevertheless indicates that the compaction process was implemented with a high degree of consistency across the investigated project. The statistical pattern also confirms that quality control measures adopted during construction were generally effective in achieving the intended engineering requirements.

The highest recorded Degree of Compaction, 101.79%, indicates that the applied compaction energy successfully produced a dense aggregate structure capable of providing adequate structural support for the overlying pavement layers. Conversely, the lowest value of 99.10% suggests that certain local conditions may have reduced compaction efficiency, although the deviation remained relatively small when compared with the specified minimum requirement. Engineering theory explains that density variation commonly reflects differences in moisture content, aggregate particle arrangement, and field compaction effectiveness rather than deficiencies in aggregate quality alone (Das, 1995). The relatively narrow range observed in this study demonstrates that the construction process maintained acceptable operational consistency despite the inevitable variability associated with field implementation. These findings also indicate that the selected construction methodology successfully controlled most factors influencing aggregate densification during compaction. The remaining density differences therefore warrant engineering evaluation rather than immediate classification as major construction deficiencies.

From a construction quality perspective, the average Degree of Compaction of 100.49% indicates that the Class A aggregate foundation layer generally fulfilled the technical requirements specified for national road preservation projects. Adequate field density contributes directly to increased bearing capacity, improved load distribution, and greater resistance to permanent deformation throughout the pavement service life. Classical geotechnical principles emphasize that increasing dry density enhances particle interlocking and reduces void ratio, thereby improving the mechanical stability of compacted aggregate layers under repeated traffic loading (Bowles, 1991). The quantitative results obtained in this investigation therefore provide empirical evidence that the implemented compaction process achieved an acceptable level of engineering quality across most of the evaluated road section. These findings establish a reliable basis for examining the factors responsible for density variation and for evaluating their implications for long-term pavement performance in the subsequent discussion section.

Engineering Evaluation of Compaction Performance

The average Degree of Compaction (DoC) of **100.49%** indicates that the Class A aggregate foundation layer achieved the minimum engineering requirement specified for national road construction projects. This result reflects that the field compaction process was generally capable of producing a dense aggregate structure with adequate mechanical stability for supporting subsequent pavement layers. The effectiveness of aggregate compaction is closely associated with the reduction of air voids and the improvement of particle interlocking, which together enhance the bearing capacity of the pavement foundation (Das, 1995). Granular materials that reach the required density exhibit greater resistance to repeated traffic loading because stress can be distributed more uniformly throughout the compacted layer. The measured average density also demonstrates that the implemented construction procedures were sufficiently effective under actual field conditions. From a pavement engineering perspective, achieving the target density is essential for maintaining structural performance throughout the intended service life. The obtained results provide empirical evidence that the preservation project successfully met the principal compaction requirement for the investigated aggregate base layer.

Although the overall compaction quality satisfied the specified standard, two testing locations remained below the minimum acceptance criterion, recording Degree of Compaction values of **99.55%** and **99.10%**, respectively. The numerical deviation from the specification is relatively small, yet localized reductions in density may influence pavement behavior when subjected to continuous heavy traffic loading. Previous investigations reported that isolated areas with insufficient density frequently become locations where permanent deformation or differential settlement develops during long-term pavement service (Akbar et al., 2024). Such localized deficiencies should not be interpreted as evidence of inadequate construction throughout the project because the remaining testing locations demonstrated satisfactory performance. Engineering quality control is intended to identify these isolated variations before the placement of subsequent pavement layers. Corrective actions such as additional roller passes or moisture adjustment would normally be sufficient to increase density to the specified level. Early identification of these locations reduces the probability of maintenance interventions during future pavement operation. The observed results demonstrate the practical importance of conducting systematic field density evaluation before construction progresses to the next stage.

The variation in measured density can be explained by several interacting construction factors rather than by a single operational parameter. Moisture content during compaction is one of the most influential variables because aggregate particles achieve optimum rearrangement only when the material approaches its optimum moisture condition. Experimental studies have demonstrated that excessive or insufficient moisture reduces compaction efficiency and directly affects the density measured using the Sand Cone method (Park et al., 2021). Aggregate gradation also contributes to density variation because well-graded materials generally produce lower void ratios than poorly graded aggregate mixtures. The relatively narrow density range observed in this investigation suggests that aggregate quality remained reasonably consistent throughout most construction segments. Minor differences between testing locations are likely associated with local moisture fluctuations, aggregate distribution, or slight operational variations during compaction activities. Similar engineering behavior has been observed in field evaluations where density variability remained within a relatively small range despite uniform construction procedures (Sukmawati et al., 2024). These findings indicate that continuous monitoring of material conditions during construction remains essential for maintaining density uniformity.

Compaction equipment and field implementation practices also influence the engineering quality achieved during aggregate base construction. Roller type, vibration frequency, travel speed, layer thickness, and the number of compaction passes collectively determine the amount of energy transmitted into the aggregate layer. Research on vibratory compaction has shown that optimized rolling parameters significantly improve aggregate densification and produce more uniform structural stiffness across the pavement foundation (Karan et al., 2017). The satisfactory average density recorded in this investigation indicates that the applied compaction strategy was generally effective under project conditions. The existence of only two non-compliant testing locations suggests that operational variability was relatively limited throughout the investigated construction area. Proper supervision during rolling operations remains important because small differences in field execution may generate measurable variations in the final density. Maintaining consistent construction procedures across consecutive work sections contributes directly to the long-term reliability of pavement performance. These operational observations reinforce the importance of integrating equipment control with systematic field quality verification.

The reliability of the measured results is supported by the application of standardized testing procedures throughout the investigation. The Sand Cone method remains one of the most widely accepted techniques for evaluating in-place density because it provides direct measurement of field conditions using standardized operational procedures. Comparative studies have demonstrated that Sand Cone measurements produce results that are highly consistent with other accepted field density evaluation methods when calibration and testing procedures are properly implemented (Zorluer et al., 2020). The testing sequence adopted in this study followed ASTM D1556 requirements through equipment verification, calibrated standard sand, moisture-content determination, and comparison with laboratory maximum dry density values. Previous investigations likewise reported that standardized Sand Cone testing provides reliable information for evaluating the compaction quality of aggregate base layers under actual construction conditions (Saputra & Elvaria, 2025). The consistency between laboratory reference data and field measurements increases confidence in the calculated Degree of Compaction obtained for each testing location. Reliable field measurements provide an objective basis for engineering decision-making during road preservation projects. This level of measurement consistency strengthens the validity of the present evaluation and supports its practical application within construction quality management.

The engineering interpretation developed in this investigation is consistent with findings reported in comparable studies evaluating aggregate base compaction under Indonesian road construction conditions. Similar research has shown that average density values exceeding the specification threshold generally indicate satisfactory construction quality even though isolated locations occasionally require localized corrective measures (Febriana et al., 2024). Comparable observations were also reported by Gobel et al. (2023), Yumardi et al. (2024), and Yanis et al. (2022), who emphasized that systematic density evaluation provides valuable information for predicting pavement performance and verifying compliance with construction specifications. The implementation of standardized quality-control procedures also aligns with the technical requirements established in the General Specifications for Highway Construction and national regulations governing road infrastructure management (Direktorat Jenderal Bina Marga, 2018). Compliance with these engineering standards supports the broader objective of maintaining safe, durable, and sustainable transportation infrastructure throughout its design service life. The present findings contribute additional empirical evidence demonstrating that the Sand Cone method remains an effective tool for evaluating the quality of Class A aggregate foundation layers in road preservation projects. The analytical results also strengthen the integration of quantitative field testing with engineering decision-making for infrastructure quality assurance. Such evidence provides practical guidance for contractors and supervising engineers in improving consistency during future pavement construction and preservation activities.

CONCLUSION

The evaluation of the Class A aggregate foundation layer using the Sand Cone method demonstrated that the compaction quality achieved on the Taba Mulan–Simpang Nangka Road Improvement Project generally satisfied the technical requirements established for national road construction. The measured Degree of Compaction ranged from 99.10% to 101.79%, with an average value of 100.49% relative to the laboratory maximum dry density of 2.23 g/cm³ obtained from the Modified Proctor test. Eight of the ten testing locations achieved compaction values equal to or exceeding the minimum specification of 100% Modified Proctor, whereas two locations recorded slightly lower values of 99.55% and 99.10%. These findings indicate that the implemented compaction process produced a structurally adequate aggregate base capable of supporting the overlying pavement layers under anticipated traffic loading. The relatively narrow variation in field density also reflects satisfactory consistency in construction practices across the investigated project section. Minor deviations observed at several testing locations suggest that localized operational factors influenced compaction efficiency without significantly affecting the overall quality of the completed aggregate foundation. The quantitative results confirm that the Sand Cone method provides reliable field measurements for evaluating the quality of aggregate base construction within road preservation projects.

The engineering evaluation further indicates that compliance with the General Specifications for Highway Construction was achieved at the project level because the average Degree of Compaction exceeded the minimum acceptance criterion despite the presence of limited non-compliant locations. The observed density variations are considered to be associated with differences in moisture conditions, aggregate gradation, compaction energy, layer thickness, and operational implementation during construction activities. Localized areas with density values below the specified threshold should receive corrective recompaction before subsequent pavement layers are constructed to ensure uniform structural performance along the entire road section. Continuous monitoring of moisture content, aggregate placement, and roller operation should remain integral components of construction quality assurance to minimize future variability in field density. Routine application of standardized Sand Cone testing is also recommended as part of periodic quality-control procedures because it enables early identification of construction deficiencies before they affect pavement performance. Future studies are encouraged to expand the number of testing locations, investigate different road sections, and integrate additional field evaluation techniques such as the Nuclear Density Gauge or Dynamic Cone Penetrometer to strengthen engineering interpretation. Further research examining the relationship between aggregate density, California Bearing Ratio, resilient modulus, and long-term pavement performance would provide a more comprehensive understanding of the contribution of compaction quality to pavement durability and infrastructure sustainability.

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