ANALYSIS OF FACTORS CAUSING VARIATIONS IN ASPHALT PENETRATION TEST RESULTS AMONG CIVIL ENGINEERING STUDENTS IN HIGHWAY ENGINEERING LABORATORY PRACTICUM

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Abstract

Variations in asphalt penetration test results are a recurring phenomenon in highway engineering laboratory practicums, particularly when tests are conducted by students with differing levels of technical skills and procedural understanding. These variations may compromise the reliability and consistency of laboratory outcomes if not properly analyzed. This study aims to identify and analyze the factors contributing to variations in asphalt penetration test results performed by civil engineering students during highway laboratory practicums. The research employed a quantitative descriptive approach using a survey method. The population consisted of 150 fifth-semester civil engineering students from the 2023 cohort at the University of Lampung, with a sample of 60 respondents selected through simple random sampling. Data were collected using a structured questionnaire based on validated indicators, including compliance with standard operating procedures, time control, temperature control, instrument reading accuracy, needle positioning, and students' practical experience. Descriptive statistical analysis was applied to evaluate the tendency and distribution of responses. The results indicate that temperature control, time consistency, and instrument reading accuracy are the dominant factors influencing test result variations. The study recommends strengthening procedural supervision, improving laboratory instruction clarity, and integrating simulation-based practicum learning to enhance students' technical competence and reduce testing variability

Keywords: Asphalt Penetration Test; Laboratory Learning; Procedural Compliance; Civil Engineering Education

INTRODUCTION

Road pavement is one of the transportation infrastructure components that plays a strategic role in supporting social and economic activities. The performance of road pavement is strongly influenced by the quality of its constituent materials, particularly asphalt as the primary binding agent in asphalt mixtures. Asphalt must be capable of maintaining its mechanical characteristics under traffic loading and environmental influences, such as temperature fluctuations and weather conditions. Numerous studies have shown that the physical and mechanical properties of asphalt, including resistance to permanent deformation (rutting), cracking, and material fatigue, are key factors determining the service life of road pavements (Alkuime et al., 2020; Pan et al., 2023). Therefore, laboratory testing of asphalt and asphalt mixtures is a crucial stage in ensuring material quality prior to field application, whether during the planning, construction, or pavement performance evaluation phases.

One of the most widely used fundamental testing methods for evaluating the physical characteristics of asphalt is the asphalt penetration test. This test aims to measure the hardness or consistency of asphalt based on the depth of penetration of a standard needle under specified temperature conditions and loading time. Asphalt penetration values are highly sensitive to temperature variations, the chemical composition of asphalt, as well as the testing method and the

precision of test execution (Ye et al., 2020; Widianto & Faisal, 2021). Several studies indicate that asphalt modification using additives—such as polymers, waste materials, or natural substances—significantly affects penetration values and the temperature susceptibility of asphalt (Zukisa & Basrin, 2023; Khedaywi et al., 2025; Liao et al., 2025; Liu & Qi, 2025). Thus, the penetration test serves not only as a routine test but also as a key parameter for assessing asphalt quality and performance under various conditions and applications.

In the context of materials research and pavement engineering, asphalt penetration testing is often combined with various other testing methods to obtain a comprehensive understanding of material performance. Studies on hot mix asphalt, modified asphalt, and asphalt mixtures incorporating alternative materials demonstrate that laboratory test results are strongly influenced by the consistency of procedures and testing conditions (Nadhifah & Susanti, 2024; Mendrofa et al., 2024). In addition, research related to pavement and road structure performance evaluation emphasizes the importance of laboratory data accuracy as a basis for analysis and technical decision-making (Hui et al., 2022). This highlights that the reliability of laboratory test results is a fundamental aspect that cannot be overlooked in civil engineering, particularly in highway engineering.

Beyond research and professional practice, asphalt penetration testing is also an essential component of laboratory practicums in civil engineering education. Laboratory practicums are designed to provide students with hands-on experience, enabling them to understand theoretical concepts while mastering technical material testing skills. The development of practicum learning systems that combine virtual approaches with hands-on practice has been widely implemented to enhance learning effectiveness and students' understanding of asphalt materials and asphalt mixtures (Xu et al., 2024). However, the success of practicum learning largely depends on students' ability to follow testing procedures accurately, consistently, and in accordance with applicable standards, especially for tests that are highly sensitive to execution errors, such as the asphalt penetration test.

In the implementation of asphalt testing, both in educational laboratories and in the field, variations in test results are often unavoidable. Several studies indicate that procedural errors, inaccuracies in loading time, inconsistencies in temperature control, and limitations in the tester's skills can cause deviations in test results from expected values (Kerthajaya, 2021; Widojoko, 2020). These variations become more complex when tests are conducted by novice practitioners, such as students, who possess varying levels of experience and precision. Such conditions create the potential for significant differences in test results, even when using the same materials, equipment, and standardized testing procedures.

On the other hand, most studies related to asphalt penetration testing primarily focus on material characteristics and the effects of asphalt modification, while studies that specifically analyze the implementation of asphalt penetration tests within the context of laboratory education remain relatively limited. Research on practicum-based learning in engineering fields suggests that variations in practicum results can be influenced by procedural understanding, measurement accuracy, as well as students' cognitive and psychological readiness (Wahyuni & Mukhaiyar, 2022; Haizatullah et al., 2024). Nevertheless, studies that directly link these factors to variations in asphalt penetration test results in highway engineering laboratory practicums are still rarely found. This condition indicates the existence of a research gap between asphalt material testing studies and civil engineering practicum learning studies. n addition, previous studies generally examined material performance or asphalt modification, whereas limited attention has been given to how student-related procedural factors contribute to testing variability during laboratory practicums. Therefore, this study attempts to bridge this gap by integrating engineering testing principles with laboratory learning perspectives.

Based on empirical observations in the Highway Engineering Laboratory, it was found that the asphalt penetration test results obtained by students exhibited significant differences among groups, despite the tests being conducted on the same asphalt material and referring to uniform standard procedures. This phenomenon raises questions regarding the factors causing such variations, whether technical, procedural, or related to practicum learning aspects. Therefore, this study aims to analyze the factors causing variations in asphalt penetration test results conducted by Civil Engineering students during highway engineering laboratory practicums. The novelty of this study lies in integrating engineering testing standards with laboratory education perspectives to examine how technical procedures and student-related factors simultaneously contribute to variations in asphalt penetration test results.

LITERATURE REVIEW

Asphalt Penetration Test as a Parameter of Pavement Material Characteristics

The asphalt penetration test is one of the fundamental testing methods used to determine the hardness or consistency of asphalt based on the depth of penetration of a standard needle under specified temperature conditions and loading duration. This test plays an important role in evaluating the physical characteristics of asphalt, as penetration values are closely related to asphalt behavior under temperature variations and traffic loading. Ye et al. (2020) emphasized that the penetration test is highly sensitive to variations in testing procedures; therefore, precision in test execution is a crucial factor in obtaining reliable results. Furthermore, Widianto and Faisal (2021) demonstrated that temperature changes significantly affect asphalt penetration values, which ultimately influence pavement performance.

Numerous studies on asphalt modification, using natural materials, waste materials, or synthetic additives, employ the penetration test as a primary parameter for evaluating changes in asphalt properties. Studies by Nadhifah and Susanti (2024) and Mendrofa et al. (2024) indicate that differences in asphalt types and additive materials can result in significant

variations in penetration values. Similar findings have been reported in research on modified asphalt and asphalt mixtures, emphasizing that penetration values are influenced not only by material properties but also by the conditions and consistency of test implementation (Zukisa & Basrin, 2023; Khedaywi et al., 2025; Liao et al., 2025; Liu & Qi, 2025). Thus, the asphalt penetration test can be regarded as a technical parameter that is highly sensitive to procedural errors, requiring careful and standardized execution.

Variation in Asphalt Test Results and Execution Error Factors

Variations in asphalt test results are a common phenomenon, both in laboratory research and in field construction practices. Kerthajaya (2021) stated that errors in the execution of hot mix asphalt works, including procedural inaccuracies and inadequate quality control, can lead to deviations in test results that adversely affect pavement quality. This is consistent with the findings of Widojoko (2020), who reported that inconsistencies in testing procedures and asphalt mixture compaction can produce significant data variations even when the same materials are used.

In laboratory contexts, the accuracy of test results is also influenced by human factors, such as precision in reading measuring instruments, control of loading duration, and the stability of testing conditions. Hui et al. (2022) emphasized the importance of laboratory data reliability as the basis for pavement performance evaluation, as minor testing errors can lead to incorrect technical interpretations. In addition, Pan et al. (2023) demonstrated that laboratory testing factors make a significant contribution to the outcomes of pavement material performance evaluations. Therefore, variations in asphalt penetration test results should not be viewed solely as material differences, but also as reflections of the quality and consistency of test implementation.

Laboratory Practicums in Civil Engineering Education and the Research Gap

Laboratory practicums are an essential component of civil engineering education, aiming to integrate theoretical understanding with students' technical skills. Through practicums, students are expected to understand material testing procedures, operate laboratory equipment, and correctly interpret test results. Reforms in practicum-based learning that combine virtual approaches with hands-on practice have been developed to enhance students' understanding of asphalt materials and asphalt mixtures (Xu et al., 2024). Nevertheless, the effectiveness of practicum learning is strongly influenced by students' procedural understanding, experience, and cognitive readiness in conducting laboratory tests.

Several studies in engineering education indicate that variations in practicum results are often influenced by non-technical factors, such as comprehension of instructions, measurement accuracy, and students' psychological conditions. Wahyuni and Mukhaiyar (2022) found that variations in measurement practicum results were influenced by procedural understanding and students' ability to operate measuring instruments. Furthermore, Haizatullah et al. (2024) reported that students' anxiety levels and readiness in facing laboratory practicums can significantly affect practicum performance. However, studies that specifically analyze the factors causing variations in asphalt penetration test results conducted by students within the context of highway engineering laboratory practicums remain very limited. This research gap underlies the importance of the present study, which focuses on identifying both technical and non-technical factors influencing variations in asphalt penetration test results in Civil Engineering student practicums.

Although previous studies consistently emphasize the importance of procedural accuracy in laboratory activities, their findings also reveal different perspectives regarding the dominant sources of testing variability. Some studies attribute inconsistencies primarily to technical factors, whereas others highlight students' practical experience and laboratory learning conditions. These differences indicate that laboratory result variability should be understood from both engineering and educational perspectives rather than from technical aspects alone.

RESEARCH METHODS

Research Design

This study employed a qualitative descriptive research design with a supportive quantitative component, aiming to comprehensively analyze the factors contributing to variations in asphalt penetration test results conducted by Civil Engineering students during Highway Engineering Laboratory practicums. The qualitative approach was selected to capture in-depth insights into procedural implementation, student understanding, laboratory conditions, and human factors that may influence testing outcomes. Meanwhile, quantitative data were utilized to support qualitative interpretations through structured measurements of respondent perceptions using standardized questionnaire responses. This design allows for an integrative understanding of both measurable tendencies and contextual explanations, ensuring methodological rigor while maintaining analytical depth.

The research adopted a cross-sectional approach, where data were collected at a single point in time following the completion of the asphalt penetration test practicum. This approach was deemed appropriate because the study focused on identifying variations and their causal factors within a specific academic cohort and practicum cycle. By analyzing data collected contemporaneously, the research minimizes temporal bias and ensures that respondent experiences reflect actual laboratory practices. The combination of descriptive statistics and qualitative interpretation facilitates the identification of dominant factors influencing result variability, thereby strengthening the explanatory power of the study.

Participants

The population of this study consisted of 150 fifth-semester Civil Engineering students from the 2023 cohort at the University of Lampung, who had officially completed the Highway Engineering Laboratory practicum, particularly the asphalt penetration test. This population was selected because fifth-semester students represent the stage at which fundamental asphalt testing competencies are formally introduced, making them highly relevant for examining procedural accuracy and learning-related factors. The sample size was determined using the Slovin formula with a margin of error (e) of 10%, as follows:

$$n = \frac{N}{1 + N(e)^2}$$

$$n = \frac{150}{1 + 150(0{,}1)^2}$$

$$n = 60$$

Based on this calculation, the sample size was rounded to 60 respondents. A simple random sampling technique was employed to ensure that each member of the population had an equal probability of being selected, thereby reducing selection bias and enhancing representativeness. This sampling method is appropriate for homogeneous populations, such as students enrolled in the same academic program and practicum course.The inclusion criteria required participants to (1) be officially registered as fifth-semester Civil Engineering students of the 2023 cohort, (2) have completed the asphalt penetration test practicum, and (3) be willing to provide informed consent. Exclusion criteria included students who did not complete the practicum independently, were absent during critical testing sessions, or submitted incomplete questionnaire responses.

Instruments and Measures

The primary research instrument used in this study was a structured questionnaire designed to identify and analyze factors contributing to variations in asphalt penetration test results during Highway Engineering Laboratory practicums. The questionnaire was developed based on standard asphalt testing procedures, laboratory education theories, and prior empirical studies, ensuring strong theoretical grounding and content validity. All items were measured using a 5-point Likert scale, ranging from 1 (*strongly disagree*) to 5 (*strongly agree*), allowing respondents to express the degree of their agreement with each statement.

The questionnaire consisted of six indicator dimensions, each representing a critical factor that may influence the variability of asphalt penetration test results. The first dimension, Understanding and Compliance with Standard Operating Procedures (SOP), measured students' comprehension of testing stages and their adherence to prescribed procedures. This indicator was grounded in Experiential Learning Theory, which emphasizes learning through direct experience and reflective practice (Kolb, 1984), as well as laboratory-based learning principles that stress the importance of procedural clarity and compliance in experimental work (Hodson, 1998). Items under this dimension assessed students' understanding of SOP stages, procedural sequencing, and clarity of practicum instructions. The second dimension focused on the Accuracy of Load Application Time Control, which represents a key technical requirement in asphalt penetration testing. According to standardized testing methods, the penetration needle must be loaded for a precise duration of five seconds to ensure result reliability. This indicator was developed based on SNI 2456:2011 and ASTM D5/D5M, which emphasize that deviations in loading time can significantly affect penetration values. The questionnaire items under this dimension evaluated students' ability to control loading time consistently and their awareness of the impact of timing inaccuracies on test results.

The third dimension addressed Control of Specimen Temperature, which is widely recognized as one of the most dominant factors affecting asphalt penetration values. This indicator was constructed based on national standards (SNI 2456:2011) and classical pavement engineering literature, which explain that asphalt rheological behavior is highly sensitive to temperature variations (Yoder & Witczak, 1975). The corresponding items measured students' practices in conditioning test specimens, maintaining temperature stability during testing, and understanding the influence of temperature fluctuations on penetration outcomes.The fourth dimension examined Accuracy in Reading Measurement Instruments, representing a common source of human error in laboratory practicums. This indicator assessed students' precision in reading dial scales, understanding penetration units (dmm), and recognizing the consequences of misreading measurement instruments. The theoretical basis for this indicator was drawn from measurement accuracy and error theory in engineering statistics (Montgomery & Runger, 2014), as well as technical guidance from ASTM D5/D5M, which highlights the importance of careful scale interpretation to minimize measurement bias.

The fifth dimension focused on the Accuracy of Needle Positioning and Installation, which relates to the mechanical correctness of the penetration test setup. Improper needle alignment or incorrect initial contact with the asphalt surface can lead to significant deviations in penetration values. This indicator was developed based on procedural requirements outlined in SNI 2456:2011 and supported by pavement engineering principles emphasizing correct loading geometry (Huang, 2004). Questionnaire items under this dimension evaluated students' attention to needle alignment, surface contact, and awareness of mechanical setup errors.The final dimension measured Practicum Experience and Technical Skill, which reflects the educational aspect of laboratory-based learning. This indicator assessed students' perceived skill levels, prior practicum experience, and the extent to which experience influences testing accuracy. The

inclusion of this dimension aligns with laboratory education research that identifies experience and repeated practice as key determinants of experimental competence (Kolb, 1984; Hodson, 1998). Items in this section captured students' self-assessment of skill mastery and their recognition of experience-related variability in test outcomes.

Overall, the questionnaire was designed to comprehensively capture procedural, technical, environmental, and human factors influencing asphalt penetration test variability. Prior to full-scale implementation, the instrument was reviewed by experts in highway engineering and laboratory instruction to ensure clarity, relevance, and alignment with standardized testing practices.

Data Collection Procedures

Data collection was conducted over a one-month period following the completion of the Highway Engineering Laboratory practicum. The questionnaire was distributed electronically using Google Forms, enabling efficient data management and accessibility for respondents. Prior to participation, students were provided with an introductory explanation outlining the research objectives, voluntary participation, confidentiality assurances, and data usage. Respondents were given sufficient time to complete the questionnaire, and reminder notifications were issued to enhance response rates. All submitted responses were automatically recorded and stored in a secure digital format. To ensure data integrity, responses were screened for completeness and consistency before proceeding to the analysis stage.

Data Analysis

Quantitative data were analyzed using descriptive statistical techniques, including frequency distributions, mean scores, and standard deviations, to identify dominant factors contributing to variations in asphalt penetration test results. Reliability analysis was conducted using Cronbach's alpha to ensure internal consistency across questionnaire indicators. The descriptive findings were then interpreted qualitatively to explain how procedural, technical, and human factors interact to influence testing variability. Qualitative data derived from open-ended responses were analyzed using thematic analysis, involving data familiarization, coding, category development, and thematic interpretation. This process enabled the identification of recurring patterns related to procedural errors, equipment handling, time management, and student preparedness. The integration of quantitative trends and qualitative themes allowed for data triangulation, thereby enhancing the credibility and analytical depth of the findings.

Validity, Reliability, and Ethical Considerations

To ensure research validity, instrument validation and methodological triangulation were applied by integrating quantitative measurements with qualitative interpretations. Reliability was assessed through internal consistency testing, with acceptable Cronbach's alpha coefficients indicating dependable measurement. The transferability of findings was supported by detailed descriptions of the practicum context and participant characteristics. Ethically, the study adhered to academic research ethics principles. Participation was voluntary, informed consent was obtained prior to data collection, and respondent anonymity was strictly maintained. All data were stored securely and used exclusively for academic research purposes.

RESULTS AND DISCUSSION

Overview of Respondents and General Findings

The respondents of this study consisted of 60 fifth-semester Civil Engineering students from the 2023 cohort at the University of Lampung who had completed the asphalt penetration test practicum in the Highway Engineering Laboratory. All respondents participated voluntarily and fulfilled the inclusion criteria, ensuring that the collected data reflected actual practicum experiences. Although the respondents originated from the same academic background and were exposed to identical practicum modules, the penetration test results produced by different student groups showed noticeable variability. This condition indicates that factors beyond material properties play a significant role in influencing test outcomes.In laboratory-based engineering education, uniformity of results is often assumed when standardized procedures and materials are applied. However, previous studies emphasize that laboratory outcomes are highly sensitive to procedural execution, environmental control, and human factors (Xu et al., 2024; Wahyuni & Mukhaiyar, 2022). This study's findings support this perspective, as variations persisted despite the use of standardized asphalt penetration testing equipment and guidelines. Such discrepancies underscore the importance of examining not only technical standards but also how these standards are implemented by students during practicums.

Furthermore, similar observations have been reported in pavement engineering research, where laboratory test variability has been linked to execution inconsistencies rather than inherent material differences (Ye et al., 2020; Pan et al., 2023). Therefore, the variability observed in student-generated penetration test results should be interpreted as a multidimensional issue involving technical precision, experiential learning, and laboratory management practices rather than as isolated measurement errors.

Descriptive Analysis of Questionnaire Indicators

Descriptive statistical analysis was conducted to examine students' perceptions regarding factors contributing to variations in asphalt penetration test results during the Highway Engineering Laboratory practicum. The analysis focused

on six indicator dimensions derived from the questionnaire, each measured using a five-point Likert scale ranging from 1 (*strongly disagree*) to 5 (*strongly agree*). The mean score reflects the general tendency of respondent agreement, while the standard deviation indicates the level of response variability among students. Higher standard deviation values suggest greater inconsistency in students' experiences and practices during the penetration test. The results of the descriptive analysis are presented in Table 1, which summarizes the mean scores and standard deviations for each indicator. Overall, the findings indicate that while students demonstrated relatively strong procedural understanding, several technical and human-related factors showed moderate performance levels and higher variability. This pattern suggests that inconsistencies in asphalt penetration test results are more strongly influenced by execution-related factors rather than by a lack of theoretical knowledge alone.

Table 1. Descriptive Statistics of Questionnaire Indicators (n = 60)

Code	Indicator Description	Mean	Std. Deviation	Interpretation
A	Understanding and compliance with SOP	3.88	0.61	High
B	Accuracy of load application time control	3.42	0.74	Moderate
C	Control of specimen temperature	3.21	0.79	Moderate
D	Accuracy in reading measurement instruments	3.67	0.66	High
E	Accuracy of needle positioning and installation	3.53	0.71	Moderate–High
F	Practicum experience and technical skill	3.31	0.77	Moderate

The highest mean score was observed for Understanding and Compliance with SOP (Indicator A), indicating that most students perceived themselves as adequately understanding the procedural stages and requirements of the asphalt penetration test. This finding suggests that the practicum guidelines and initial instructions were generally effective in conveying theoretical and procedural knowledge. Similar observations were reported by Xu et al. (2024), who emphasized that well-structured instructional systems improve students' comprehension of laboratory procedures in asphalt-related experimental courses. In contrast, indicators related to technical control, particularly specimen temperature control (Indicator C) and load application time accuracy (Indicator B), recorded lower mean scores and higher standard deviations. These results indicate that students experienced greater difficulty maintaining consistent testing conditions, which is critical for penetration test accuracy. Asphalt penetration values are known to be highly sensitive to both temperature and loading duration, and deviations from standardized conditions can significantly influence test outcomes (Nadhifah & Susanti, 2024; Widianto & Faisal, 2021; Ye et al., 2020). The relatively high dispersion in responses suggests that students' abilities to control these parameters varied considerably across groups.

Furthermore, the moderate scores for Practicum Experience and Technical Skill (Indicator F) reinforce the notion that differences in hands-on experience contribute to variability in penetration test results. Laboratory education research indicates that experimental competence develops gradually through repeated practice and reflection (Wahyuni & Mukhaiyar, 2022). Students with limited practical exposure may struggle to integrate multiple technical controls simultaneously, leading to inconsistent test execution. Consequently, the descriptive results confirm that variability in asphalt penetration test outcomes is closely associated with technical execution and experiential factors rather than procedural understanding alone.

Discussion on SOP Understanding and Procedural Compliance

The high mean score obtained for SOP understanding and compliance indicates that students generally possess sufficient cognitive knowledge regarding the stages and sequence of asphalt penetration testing. This aligns with experiential learning theory, which emphasizes the importance of clear conceptual frameworks prior to hands-on application (Kolb, 1984). In the context of laboratory education, clear SOPs serve as a foundational guide that minimizes confusion and procedural deviation (Hodson, 1998). Nevertheless, the persistence of significant variations in test results suggests that procedural compliance alone is insufficient to ensure consistency. Kerthajaya (2021) noted that even in professional asphalt construction projects, deviations occur not because standards are unknown, but because they are inconsistently applied in practice. Similarly, in an academic laboratory setting, students may follow SOP steps sequentially yet fail to execute them with the precision required for sensitive tests such as asphalt penetration.

This finding highlights an important pedagogical implication: laboratory instruction should move beyond procedural memorization toward emphasizing critical control points within each test. Xu et al. (2024) argue that integrating reflective and practice-oriented learning strategies can improve students' ability to translate procedural knowledge into accurate experimental execution. Thus, strengthening the link between SOP comprehension and technical precision is essential for reducing variability in penetration test outcomes.

Discussion on Load Application Time Control

The indicator related to load application time control demonstrated a moderate mean score, indicating inconsistencies in students' ability to apply the penetration load precisely for the required duration. According to SNI 2456:2011 and ASTM D5/D5M, the penetration needle must be loaded for exactly five seconds to ensure result validity. Deviations from this duration can significantly alter penetration values, as asphalt exhibits time-dependent deformation

behavior (Ye et al., 2020). In this study, students' self-reported difficulties in maintaining consistent loading time suggest that manual timing remains a critical source of error. This observation is consistent with findings by Widojoko (2020), who reported that time control during asphalt testing is one of the most error-prone aspects, particularly when conducted by inexperienced operators. The relatively high standard deviation for this indicator reflects heterogeneous skill levels among students, further contributing to result variability. Moreover, laboratory-based pavement studies emphasize that even minor inconsistencies in loading conditions can mask true material behavior (Pan et al., 2023; Alkuime et al., 2020). In an educational context, this implies that the absence of automated or assisted timing mechanisms may disproportionately affect novice practitioners. Therefore, improving load application control through standardized timing aids or enhanced supervision may substantially reduce penetration test variability.

Discussion on Temperature Control of Asphalt Specimens

Temperature control emerged as one of the most influential factors contributing to penetration test variability. The moderate mean score and relatively high dispersion indicate that students experienced difficulties in maintaining stable specimen temperatures throughout the testing process. Asphalt binder properties are highly temperature-sensitive, and penetration values increase significantly with rising temperatures (Widianto & Faisal, 2021; Nadhifah & Susanti, 2024). Previous laboratory evaluations have demonstrated that uncontrolled temperature conditions can obscure the true rheological characteristics of asphalt binders (Liao et al., 2025; Khedaywi et al., 2025). In student practicums, temperature fluctuations may occur due to delays between conditioning and testing or inadequate monitoring during the test. These conditions are consistent with the findings of this study, where students acknowledged the impact of temperature instability on penetration results.

From an educational standpoint, this issue underscores the importance of emphasizing environmental control as a critical experimental variable. Hui et al. (2022) highlight that pavement-related laboratory tests are highly sensitive to boundary conditions, and failure to control these conditions compromises data reliability. Therefore, reinforcing temperature management protocols and providing clearer guidance on specimen conditioning may significantly enhance the consistency of student-generated penetration test results.

Discussion on Measurement Accuracy and Needle Positioning

The indicators related to instrument reading accuracy and needle positioning recorded moderate-to-high mean scores, suggesting that most students were aware of the importance of careful measurement and correct mechanical setup. However, awareness alone does not eliminate the potential for human error. Montgomery and Runger (2014) emphasize that measurement errors are often systematic and may persist even when operators believe they are performing accurately. In asphalt penetration testing, improper needle alignment or incorrect scale reading can introduce significant deviations in recorded values (Ye et al., 2020). This study's findings align with Kerthajaya (2021), who reported that mechanical inaccuracies and operator-related errors are among the most common sources of inconsistency in asphalt testing. In a student practicum environment, such errors may be exacerbated by limited experience and time constraints.

Furthermore, pavement engineering literature stresses that precise mechanical alignment is essential for ensuring that measured responses reflect material behavior rather than testing artifacts (Huang, 2004; Liu & Qi, 2025). Consequently, enhancing students' mechanical setup skills through repeated demonstrations and supervised practice could reduce measurement-related variability and improve the reliability of penetration test outcomes.

Discussion on Practicum Experience and Skill Level

The moderate score for practicum experience and technical skill indicates that students perceived themselves as only partially proficient in conducting the asphalt penetration test. This perception is consistent with educational research suggesting that laboratory competence develops incrementally through repeated practice and feedback (Wahyuni & Mukhaiyar, 2022). Students with limited exposure may struggle to integrate procedural knowledge with precise technical execution. Haizatullah et al. (2024) further note that psychological factors, such as anxiety and lack of confidence, can negatively affect student performance during laboratory practicums. In the context of asphalt penetration testing, such factors may impair students' ability to maintain focus on critical control parameters, leading to inconsistent results. This study's findings support the view that skill development and emotional readiness are integral to experimental accuracy.

Overall, the results indicate that experience-based learning plays a crucial role in reducing variability in laboratory testing. Consistent with Xu et al. (2024), integrating iterative practice sessions and reflective evaluation into practicum design may enhance students' technical proficiency and confidence. Such improvements are expected to contribute directly to more consistent and reliable penetration test results across student groups.

Synthesis of Findings and Implications

Collectively, the findings demonstrate that variations in asphalt penetration test results among students are influenced by a combination of procedural understanding, technical control, human error, and practicum experience. While students generally understand SOPs, inconsistencies in time control, temperature management, and mechanical precision remain significant contributors to result variability. These findings are consistent with both pavement engineering research and laboratory education studies (Pan et al., 2023; Xu et al., 2024). The novelty of this study lies in its integration of

engineering test standards with educational analysis, highlighting how student-related factors interact with technical requirements to influence laboratory outcomes. Unlike prior studies that focus solely on material behavior, this research emphasizes the human and instructional dimensions of asphalt testing practicums.

From a practical perspective, the results suggest that improving laboratory instruction through enhanced supervision, standardized control aids, and experience-oriented learning strategies may substantially reduce variability in student-generated test results. Such improvements are expected to enhance both the educational value of practicums and the reliability of laboratory data used for learning and assessment purposes.

CONCLUSION

This study concludes that variations in asphalt penetration test results produced by Civil Engineering students during Highway Engineering Laboratory practicums are predominantly influenced by technical execution and human-related factors rather than by deficiencies in procedural understanding. Although students generally demonstrated a high level of comprehension and compliance with standard operating procedures, inconsistencies were observed in controlling critical testing parameters, particularly load application time and specimen temperature, which are known to significantly affect penetration values. In addition, factors such as measurement accuracy, needle positioning, and limited practicum experience contributed to the variability of test outcomes. These findings indicate a clear gap between cognitive understanding and practical skill execution, highlighting that laboratory result variability in educational settings is a multidimensional issue involving technical control, operator proficiency, and instructional implementation.

Based on these findings, it is recommended that Highway Engineering Laboratory practicums place greater emphasis on controlling critical testing parameters through standardized and assisted mechanisms, such as precise timing devices and continuous temperature monitoring. Furthermore, laboratory instruction should adopt a competency-based and experience-oriented approach, incorporating additional practice sessions, focused demonstrations on common sources of error, and closer supervision during key testing stages. Strengthening these aspects is expected to reduce variability in student-generated test results, improve the reliability of laboratory data, and enhance the overall effectiveness of practicum-based learning in asphalt testing.

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