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Analysis of Green Stone Aggregate Quality Improvement Using Cement as Cement-Treated Aggregate Base (LPAS)

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ABSTRACT

Road infrastructure requires base course materials that are strong, stable, and compliant with technical specifications. This study analyzed the quality improvement of Gunung Rambutan green stone aggregate through cement addition for use as cement-treated aggregate base, locally known as Lapis Pondasi Agregat Semen (LPAS). The analysis covered the physical and mechanical properties of the aggregate, its conformity with the 2025 Bina Marga General Specifications, and the effect of different cement contents on the compressive strength of LPAS classes A, B, S, and C. The study used a laboratory experimental method at the Civil Engineering Laboratory of Lambung Mangkurat University. Tests included unit weight, moisture content, silt content, specific gravity, absorption, Los Angeles abrasion, compaction, and seven-day compressive strength. The green stone aggregate had a Bulk SSD specific gravity of 2.387, water absorption of 2.817%, and silt content of 0.5%, indicating compliance with the required physical criteria. However, the untreated green stone showed a Los Angeles abrasion value of 41.39%, which exceeded the maximum allowable limit of 40%. Partial substitution with Jaro stone, which had an average abrasion value of 28.9%, reduced the blended abrasion value to 35.145% and enabled the mixture to meet the specification. Cement addition increased compressive strength linearly within the tested range. The cement contents required to achieve design strengths of 3.5 MPa and 4.2 MPa were 6.10% and 7.10% for LPAS-A, 6.70% and 7.50% for LPAS-B, 8.80% and 9.95% for LPAS-S, and 8.90% and 9.75% for LPAS-C. LPAS-A was the most efficient mixture because it required the lowest cement content to achieve the planned compressive strength.

Keywords: *Green stone aggregate, cement-treated aggregate base, cement, compressive strength, Los Angeles abrasion*

INTRODUCTION

Roads serve as a core component of land transportation because they support population mobility, logistics distribution, and regional economic development. The quality of road construction depends strongly on pavement layer performance, particularly the base course, which receives and distributes traffic loads to the subgrade. In pavement structures, cement-treated aggregate base, locally termed Lapis Pondasi Agregat Semen (LPAS), is used to improve layer stiffness and stability through the bond formed among aggregate, cement, and water. Therefore, the selection of aggregate and cement percentage is a critical factor in producing a base course that meets the required strength and durability standards (Direktorat Jenderal Bina Marga, 2025; Badan Standardisasi Nasional, 2015).

The use of locally sourced aggregate is an important consideration in road engineering because it can reduce material transportation costs, secure regional construction material supply, and support sustainable development. Studies on aggregate gradation show that particle shape, specific gravity, absorption capacity, fine material content, and abrasion resistance affect the bearing capacity of pavement layers. Alternative aggregates are also important because dependence on conventional materials continues to increase while their availability becomes more limited (Hakzah et al., 2024; Ramírez-Vargas et al., 2024).

Green stone from Gunung Rambutan has strong potential as a local aggregate in LPAS mixtures. Its application, however, requires detailed evaluation of physical and mechanical requirements, especially the Los Angeles abrasion value, because base course aggregate must resist friction, impact, and degradation during service life. Previous studies indicate that cement stabilization can improve base course performance. Nevertheless, the success of a mixture is influenced by the initial aggregate quality and its gradation (Tana et al., 2024; Lestari et al., 2025).

This study also formulates technical recommendations for using a combination of green stone aggregate and Jaro stone to ensure compliance with the 2025 Bina Marga General Specifications and relevant testing standards (Badan Standardisasi Nasional, 2018; Direktorat Jenderal Bina Marga, 2025). The main objective of this study was to analyze the physical and mechanical characteristics of green stone aggregate as an LPAS component and to evaluate the effect of cement content variation on the compressive strength of LPAS classes A, B, S, and C.

MATERIALS & METHODS

Research Location, Materials, and Approach

The research was conducted at the Civil Engineering Laboratory, Faculty of Engineering, Lambung Mangkurat University, Banjarbaru, South Kalimantan. The primary materials were green stone aggregate from Gunung Rambutan, Jaro stone aggregate used as a substitution material for selected fractions, Portland cement as the binding agent, and clean water for mixing. A laboratory experimental approach was applied because all primary data were obtained through a series of tests on materials and LPAS specimens (ASTM International, 1992; Badan Standardisasi Nasional, 2015).

Material and Specimen Testing

Cement testing included unit weight, normal consistency, specific gravity, and setting time. Aggregate testing included unit weight, moisture content, silt content, specific gravity, absorption capacity, gradation, and Los Angeles abrasion. The abrasion test was specifically used to identify green stone fractions that met the requirement and fractions that required substitution with Jaro stone. Compressive strength testing was conducted on cylindrical specimens after seven days of curing. The specimens covered LPAS classes A, B, S, and C with cement content variations adjusted to the requirements of each class (ASTM International, 1989; ASTM International, 1993; Badan Standardisasi Nasional, 2018).

Data Analysis

The test results were analyzed descriptively and comparatively. The values were compared with the 2025 Bina Marga General Specifications and relevant Indonesian National Standards. Compressive strength analysis was conducted by observing the relationship between cement content and seven-day compressive strength. Cement content requirements for design strengths of 3.5 MPa and 4.2 MPa were determined through trend interpretation and interpolation for each LPAS class (Direktorat Jenderal Bina Marga, 2025; Badan Standardisasi Nasional, 2015).

RESULTS AND DISCUSSION

Cement Characteristics

The test results showed that the binder had suitable characteristics for LPAS mixtures. Cement unit weight increased from 0.91 g/cm³ in loose condition to 1.05 g/cm³ in shaken condition and 1.15 g/cm³ after compaction. This increase indicates that cement becomes denser when subjected to compaction energy. This parameter is important in mix design because unit weight relates to the conversion of material requirements from mass units to volume units during mixing (ASTM International, 1992; Direktorat Jenderal Bina Marga, 2025).

The normal consistency of cement occurred at 26% water content, indicated by a Vicat needle penetration of 9 mm. This value represents the water demand needed to form cement paste with standard plasticity. The initial setting time was 87 minutes, while the final setting time was 150 minutes. This range provides sufficient working time for mixing, compaction, and specimen preparation. In aggregate-cement mixtures, setting that is too rapid can reduce compactability, whereas setting that is too slow can delay early strength development (ASTM International, 1993; Badan Standardisasi Nasional, 2015).

Table 1. Summary of cement test results

Parameter	Result	Interpretation
Loose unit weight	0.91 g/cm³	Initial condition without compaction
Shaken unit weight	1.05 g/cm³	Higher density
Compacted unit weight	1.15 g/cm³	Densest condition
Normal consistency	26%	Vicat needle penetration of 9 mm
Initial setting time	87 minutes	Beginning of plasticity loss
Final setting time	150 minutes	End of setting process

Physical Characteristics of Aggregate

Aggregate unit weight testing showed that Jaro stone had higher unit weight than green stone under all test conditions, namely loose, shaken, and compacted conditions. Jaro stone recorded 1.365 g/cm³ in loose condition, 1.534 g/cm³ in shaken condition, and 1.516 g/cm³ in compacted condition. Green stone recorded 1.216 g/cm³, 1.460 g/cm³, and 1.429 g/cm³ under the same conditions. This difference indicates that Jaro stone has a denser particle structure, although green stone still has adequate density for base course material when gradation and mixture composition are properly controlled (Badan Standardisasi Nasional, 2015; Direktorat Jenderal Bina Marga, 2025).

Measured moisture content was 0.50% for green stone and 0.62% for Jaro stone. These values indicate that both aggregates were relatively dry, making water correction during mixing easier. The silt content of green stone was low, with the suitability recap showing 0.5%, below the maximum limit of 1%. Low fine material content is important because silt can interfere with the bond between cement and aggregate surfaces and reduce LPAS strength (Badan Standardisasi Nasional, 2015; Direktorat Jenderal Bina Marga, 2025).

Table 2. Summary of aggregate physical characteristics

Parameter	Jaro Stone	Green Stone	Technical meaning
Loose unit weight	1.365 g/cm³	1.216 g/cm³	Initial material density
Shaken unit weight	1.534 g/cm³	1.460 g/cm³	Response to filling
Compacted unit weight	1.516 g/cm³	1.429 g/cm³	Density after compaction energy
Moisture content	0.62%	0.50%	Low water correction in mixture
Silt content	0.771%	0.5%-0.951%	Low but requires control

Specific gravity and absorption testing of the combined aggregate produced values that support its use as an LPAS component. The Bulk SSD specific gravity of green stone was 2.387, meeting the minimum requirement of 2.3. Its water absorption was 2.817%, below the maximum limit of 3%. These values indicate adequate aggregate density and moderate porosity. In aggregate-cement mixtures, absorption must be carefully controlled because highly porous aggregate can absorb excessive mixing water and disrupt cement hydration (Badan Standardisasi Nasional, 2015; Direktorat Jenderal Bina Marga, 2025).

Table 3. Comparison of aggregate properties with specifications

Parameter	Result	Requirement	Remark
Bulk SSD specific gravity	2.387	>= 2.3	Complies
Water absorption	2.817%	<= 3%	Complies
Silt content	0.5%	<= 1%	Complies
Blended abrasion	35.145%	<= 40%	Complies

Aggregate Abrasion and Substitution Requirement

The Los Angeles abrasion test was an essential component in evaluating green stone suitability. Aggregate used in base courses must have adequate resistance to friction and impact during both compaction and road service. Untreated green stone produced an average abrasion value of 41.39%, which did not meet the maximum limit of 40%. This nonconformity was mainly observed in gradations A, E, F, and G. The abrasion values of green stone were 44.74% for gradation A, 47.50% for gradation E, 45.37% for gradation F, and 42.55% for gradation G. These values indicate that some coarse fractions of green stone are more susceptible to degradation than allowed by the specification (Badan Standardisasi Nasional, 2018; Direktorat Jenderal Bina Marga, 2025).

In contrast, Jaro stone showed better wear resistance. All Jaro stone gradations met the abrasion limit, with values of 27.67% for gradation A, 26.73% for B, 25.31% for C, 24.30% for D, 36.13% for E, 32.55% for F, and 29.81% for G. The use of Jaro stone as a substitute for nonconforming fractions reduced the blended abrasion value to 35.145%. This finding shows that the quality of green stone aggregate can be improved through a fraction-combination strategy rather than rejecting the entire local material (Badan Standardisasi Nasional, 2018; Nugraha, 2025).

Table 4. Summary of Los Angeles abrasion values for green stone and Jaro stone

Gradation	Green stone	Status	Jaro stone	Status
A	44.74%	Not compliant	27.67%	Compliant
B	38.28%	Compliant	26.73%	Compliant
C	36.19%	Compliant	25.31%	Compliant
D	35.61%	Compliant	24.30%	Compliant
E	47.50%	Not compliant	36.13%	Compliant
F	45.37%	Not compliant	32.55%	Compliant
G	42.55%	Not compliant	29.81%	Compliant

The technical implication of the abrasion results is the need for fraction segregation. Green stone can be retained for fractions that meet abrasion resistance criteria, particularly gradations B, C, and D. Jaro stone should replace fractions that exceed the specification limit. This strategy produces a more suitable combined aggregate for LPAS because the mechanical quality of the mixture becomes more balanced. Fraction-based substitution also supports the efficient use of local material because green stone remains usable selectively (Direktorat

Jenderal Bina Marga, 2025; Lestari et al., 2025).

Combined Specific Gravity and LPAS Gradation

Combined specific gravity analysis was carried out to verify that aggregate and cement combinations could form mixtures with optimal density. In LPAS-A, combined specific gravity increased from 2.588 at 3% cement to 2.620 at 4% cement and 2.651 at 5% cement. In LPAS-B, it increased from 2.600 at 4% cement to 2.631 at 5% cement and 2.663 at 6% cement. This pattern indicates that cement addition contributes to higher combined specific gravity because cement has higher specific gravity than some aggregate fractions (Badan Standardisasi Nasional, 2015; ASTM International, 1992).

In LPAS-S, combined specific gravity increased from 2.633 at 5% cement to 2.665 at 6% cement and 2.696 at 7% cement. Similarly, in LPAS-C, it increased from 2.666 at 6% cement to 2.698 at 7% cement and 2.729 at 8% cement. This increase shows that each cement addition raises the binder proportion in the mixture. However, higher combined specific gravity does not automatically ensure compressive strength efficiency because cement effectiveness still depends on gradation, interparticle voids, and compaction energy (Badan Standardisasi Nasional, 2015; Lestari et al., 2025).

Table 5. Combined specific gravity by LPAS class

Class	Cement content	Combined specific gravity	Note
LPAS-A	3%, 4%, 5%	2.588; 2.620; 2.651	Gradual increase
LPAS-B	4%, 5%, 6%	2.600; 2.631; 2.663	Gradual increase
LPAS-S	5%, 6%, 7%	2.633; 2.665; 2.696	Requires higher cement
LPAS-C	6%, 7%, 8%	2.666; 2.698; 2.729	Higher fine fraction

The combined gradations also differed among LPAS classes. LPAS-A used 30% of 2–3-inch aggregate, 39% of 1-1-inch aggregate, and 31% stone dust. LPAS-B used 23% of 2–3-inch aggregate, 37% of 1-1-inch aggregate, and 40% stone dust. LPAS-S consisted of 23% of 2–3-inch aggregate, 40% of 1-1-inch aggregate, and 37% stone dust. LPAS-C used 25% of 1–2-inch aggregate, 30% of 1-1-inch aggregate, and 45% stone dust. These compositional differences affect density and cement demand. A higher stone dust proportion and looser particle arrangement increase the paste volume needed to fill voids and form bonds (Direktorat Jenderal Bina Marga, 2025; Hakzah et al., 2024).

LPAS Compaction Characteristics

Compaction testing was conducted to determine optimum moisture content and maximum dry density. In LPAS-A, optimum moisture content increased from 7.39% at 3% cement to 8.27% at 4% cement and 9.29% at 5% cement. The maximum dry density of LPAS-A ranged from 2.061 to 2.073 g/cm³. This pattern indicates that cement addition tends to increase optimum water demand because cement particles require water for hydration and for particle lubrication during compaction (Badan Standardisasi Nasional, 2018; Tana et al., 2024).

In LPAS-B, optimum moisture content was relatively stable at 7.44% for 4% cement, 7.36% for 5% cement, and 7.33% for 6% cement. Maximum dry density ranged from 2.044 to 2.059 g/cm³. This stable optimum moisture content shows that the LPAS-B particle structure responded consistently to cement variation. In LPAS-S, optimum moisture content ranged from 9.37% to 9.56%, with maximum dry density of 2.033 to 2.070 g/cm³. In LPAS-C, optimum moisture content ranged from 9.21% to 9.59%, with maximum dry density of 2.008 to 2.023 g/cm³. These results indicate that LPAS-S and LPAS-C require higher water contents because their gradations contain more voids and a higher proportion of fine particles (Badan Standardisasi Nasional, 2018; Direktorat Jenderal Bina Marga, 2025).

Table 6. Recapitulation of optimum moisture content and maximum dry density

Class	Cement content	OMC	MDD (g/cm³)
LPAS-A	3%	7.39%	2.073
LPAS-A	4%	8.27%	2.071
LPAS-A	5%	9.29%	2.061
LPAS-B	4%	7.44%	2.044
LPAS-B	5%	7.36%	2.059
LPAS-B	6%	7.33%	2.058
LPAS-S	5%	9.52%	2.070
LPAS-S	6%	9.56%	2.045
LPAS-S	7%	9.37%	2.033
LPAS-C	6%	9.59%	2.008
LPAS-C	7%	9.30%	2.015
LPAS-C	8%	9.21%	2.023

Technically, compaction results show that LPAS performance is not determined only by cement content. It also depends on the ability of the mixture to achieve maximum dry unit weight at optimum moisture content. A mixture with insufficient water is difficult to compact because interparticle friction increases. Conversely, excessive water can create water-filled voids and reduce density. Therefore, OMC and MDD values are key references for specimen preparation and field quality control (Badan Standardisasi Nasional, 2018; Direktorat Jenderal Bina Marga, 2025).

Compressive Strength of LPAS Classes A, B, S, and C

Seven-day compressive strength testing was conducted to evaluate the capacity of LPAS mixtures to resist loads after early hardening. The 2025 Bina Marga specification requires seven-day LPAS compressive strength of 35-42 kg/cm² for classes A, B, S, and C. Initial results showed that low cement contents did not meet this requirement. LPAS-A with 3%, 4%, and 5% cement produced average compressive strengths of 12.5 kg/cm², 17.3 kg/cm², and 25.0 kg/cm², respectively. After an additional sample with 8% cement was tested, the average strength increased to 49.1 kg/cm². This result indicates that the specification compliance point lies between the initial cement range and the additional cement content (Direktorat Jenderal Bina Marga, 2025; Badan Standardisasi Nasional, 2015).

LPAS-B showed a similar increasing pattern. At 4%, 5%, and 6% cement, the average compressive strengths were 12.5 kg/cm², 18.3 kg/cm², and 28.9 kg/cm². An additional sample with 8% cement produced an average strength of 47.1 kg/cm². This value confirms that cement addition directly improves interparticle bonding. However, excessive cement is not always economically efficient because it increases mixture cost and may produce an overly stiff base layer if not controlled (Badan Standardisasi Nasional, 2015; Lestari et al., 2025).

LPAS-S with 5%, 6%, and 7% cement produced average compressive strengths of 11.5 kg/cm², 17.3 kg/cm², and 23.1 kg/cm². An additional sample with 11% cement produced 49.1 kg/cm². LPAS-C with 6%, 7%, and 8% cement produced average strengths of 15.4 kg/cm², 20.2 kg/cm², and 26.0 kg/cm². An additional sample with 12% cement produced 61.6 kg/cm². These data indicate that LPAS-S and LPAS-C require higher cement contents to achieve the planned compressive strength because their gradations are less efficient than LPAS-A and LPAS-B in forming dense structures (Direktorat Jenderal Bina Marga, 2025; Nugraha, 2025).

Table 7. Average seven-day compressive strength

Class	Initial cement content	Initial strength	Additional content	Additional strength
LPAS-A	3%, 4%, 5%	12.5; 17.3; 25.0	8%	49.1
LPAS-B	4%, 5%, 6%	12.5; 18.3; 28.9	8%	47.1
LPAS-S	5%, 6%, 7%	11.5; 17.3; 23.1	11%	49.1
LPAS-C	6%, 7%, 8%	15.4; 20.2; 26.0	12%	61.6

Analysis of the graph showing the relationship between cement content and compressive strength indicates that strength increased linearly within the tested range. LPAS-A required 6.10% cement to reach 3.5 MPa and 7.10% to reach 4.2 MPa. LPAS-B required 6.70% and 7.50%. LPAS-S required 8.80% and 9.95%. LPAS-C required 8.90% and 9.75%. These differences show that mixture efficiency is influenced by gradation characteristics. Denser gradation generally requires lower cement content because the paste does not need to fill excessive voids (Badan Standardisasi Nasional, 2015; Direktorat Jenderal Bina Marga, 2025).

Table 8. Optimum cement content to achieve design compressive strength

LPAS class	Target 3.5 MPa	Target 4.2 MPa	Interpretation
LPAS-A	6.10%	7.10%	Most efficient
LPAS-B	6.70%	7.50%	Moderately efficient
LPAS-S	8.80%	9.95%	High cement demand
LPAS-C	8.90%	9.75%	Requires gradation control

Detailed Analysis of LPAS-A

LPAS-A showed the most favorable response to cement addition. At 3%, 4%, and 5% cement, the average compressive strengths were 12.5 kg/cm², 17.3 kg/cm², and 25.0 kg/cm². These values remained below the 35-42 kg/cm² requirement, so the initial formulation cannot be recommended for operational use. However, after testing an additional sample with 8% cement, the strength increased to 49.1 kg/cm². This increase confirms that the LPAS-A gradation structure responds effectively to cement addition because it has relatively smaller interparticle voids and allows cement bonding to act more evenly on aggregate surfaces (Badan Standardisasi Nasional, 2015; Direktorat Jenderal Bina Marga, 2025).

Interpolation showed that 6.10% cement was sufficient to achieve 3.5 MPa, while 7.10% was needed to achieve 4.2 MPa. This range indicates superior efficiency compared with the other classes. In practice, LPAS-A is suitable for projects that require planned strength with lower cement consumption. Nevertheless, cement content must be controlled so that it does not substantially exceed the design requirement. Excessive cement can increase production cost and produce an overly rigid base layer. Economic and technical considerations therefore need to be assessed simultaneously (Lestari et al., 2025; Tana et al., 2024).

Detailed Analysis of LPAS-B

LPAS-B showed a relatively stable increase in compressive strength. At 4%, 5%, and 6% cement, the average strengths were 12.5 kg/cm², 18.3 kg/cm², and 28.9 kg/cm². Although these values did not yet meet the 35-42 kg/cm² standard, the increasing pattern was consistent. The additional 8% cement sample produced an average strength of 47.1 kg/cm². This value exceeded the upper limit of the requirement, indicating that the effective cement content is below 8%. The trend shows that LPAS-B still maintains good efficiency, although it requires more cement than LPAS-A (Direktorat Jenderal Bina Marga, 2025; Badan Standardisasi Nasional, 2015).

The optimum cement contents for LPAS-B were 6.70% for 3.5 MPa and 7.50% for 4.2 MPa. Compared with LPAS-A, LPAS-B required approximately 0.60% more cement for the 3.5 MPa target and 0.40% more for the 4.2 MPa target. Although these differences appear small, they may substantially affect total cement volume in large projects. LPAS-B can therefore be considered an alternative when LPAS-A gradation requirements or material availability cannot be consistently met on site (Lestari et al., 2025; Nugraha, 2025).

Detailed Analysis of LPAS-S

LPAS-S required higher cement contents than LPAS-A and LPAS-B. At 5%, 6%, and 7% cement, the average strengths were only 11.5 kg/cm², 17.3 kg/cm², and 23.1 kg/cm². These values indicate that the initial cement contents were insufficient to form strong interparticle bonds. When the cement content was increased to 11%, the average strength reached 49.1 kg/cm². Although the increase was substantial, it also required a higher cement content. This condition can be explained by the LPAS-S gradation, which requires a greater cement paste volume to fill voids and create effective bonding (Badan Standardisasi Nasional, 2015; Direktorat Jenderal Bina Marga, 2025).

Interpolation showed that LPAS-S required 8.80% cement to achieve 3.5 MPa and 9.95% to achieve 4.2 MPa. Technically, this formulation can meet the specification if the cement proportion is increased. From an efficiency perspective, however, LPAS-S is less favorable than LPAS-A and LPAS-B. Its use should be considered only when the project specifically requires this gradation or when local material availability limits the ability to produce denser gradation. Field implementation of LPAS-S requires tighter control of optimum moisture content and density to ensure cement effectiveness (Tana et al., 2024; Lestari et al., 2025).

Detailed Analysis of LPAS-C

LPAS-C also showed substantial cement demand. At 6%, 7%, and 8% cement, the average strengths were 15.4 kg/cm², 20.2 kg/cm², and 26.0 kg/cm². These values did not meet the required specification. The additional sample with 12% cement produced 61.6 kg/cm², far above the upper limit of the specified range, indicating that the effective point should be below 12%. LPAS-C has a larger stone dust proportion, which tends to increase water and cement demand. A significant fine fraction increases particle surface area and therefore requires more cement paste (Direktorat Jenderal Bina Marga, 2025; Hakzah et al., 2024).

Interpolation showed that LPAS-C required 8.90% cement to achieve 3.5 MPa and 9.75% to achieve 4.2 MPa. These values were slightly lower than LPAS-S at the 4.2 MPa target but remained higher than LPAS-A and LPAS-B. Therefore, LPAS-C requires careful control of gradation, moisture content, and compaction energy. Without adequate control, the mixture may experience substantial strength variation. In practice, LPAS-C is more appropriate when project specifications and material conditions specifically require this gradation, not as the main option for cement efficiency (Badan Standardisasi Nasional, 2015; Nugraha, 2025).

Table 9. Evaluation of LPAS classes

Class	Effective cement range	Note
A	6.10-7.10%	Efficient
B	6.70-7.50%	Alternative
S	8.80-9.95%	Requires water control
C	8.90-9.75%	Requires gradation control

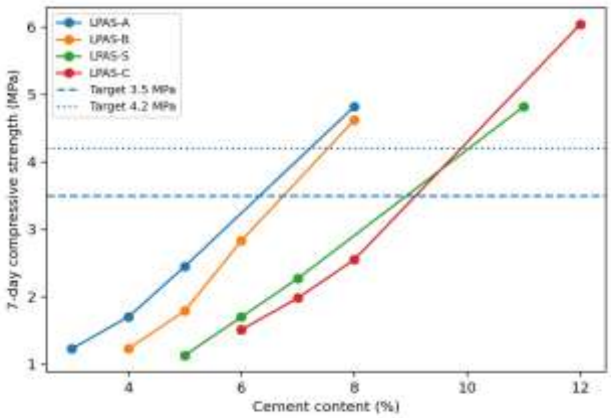

Figure 1. Relationship between cement content and LPAS compressive strength

Figure 1 visualizes the relationship between cement content and compressive strength in the four LPAS classes. All curves show a clear increasing trend. The main difference is not the direction of the relationship but the relative position of each curve against the planned strength zone. LPAS-A and LPAS-B reached the specification zone faster, whereas LPAS-S and LPAS-C required higher cement contents. This result confirms that gradation has a critical role in cement-use efficiency (Direktorat Jenderal Bina Marga, 2025; Lestari et al., 2025).

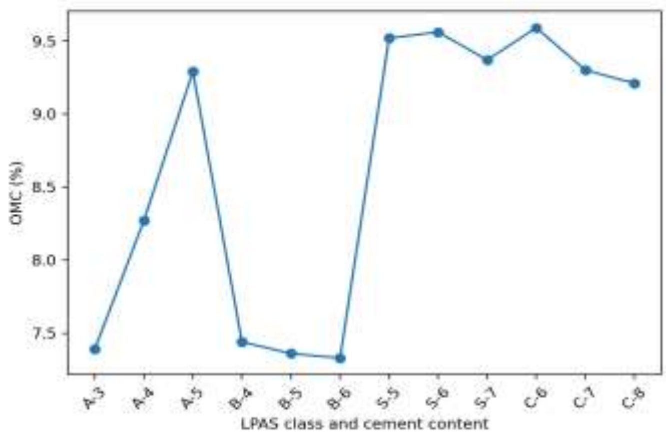

Figure 2. Optimum moisture content across LPAS class and cement-content variations

Figure 2 illustrates the trend of optimum moisture content across different LPAS classes and cement contents. LPAS-A and LPAS-B showed lower OMC than LPAS-S and LPAS-C. This difference indicates that gradation and fine fraction proportion influence water demand. The larger the particle surface area that must be wetted, the higher the optimum water requirement needed to achieve maximum density. This condition must be controlled in field implementation because either excessive or insufficient water affects density, strength development, and base course durability (Badan Standardisasi Nasional, 2018; Tana et al., 2024).

Technical Discussion of Combined Aggregate Quality

The suitability of combined aggregate is not determined by a single parameter. Green stone has good physical characteristics but faces a limitation in abrasion resistance. Jaro stone shows superior wear resistance. Therefore, its use as a substitute should focus on fractions that require improvement to optimize green stone utilization. This combination represents a rational quality-improvement strategy. Local material that does not fully meet the requirement is not immediately eliminated but is improved through integration with another aggregate that has stronger performance in critical parameters (Badan Standardisasi Nasional, 2018; Ramirez-Vargas et al., 2024).

From a base course structural perspective, aggregate with low abrasion value has better resistance to degradation during compaction and loading. If the aggregate wears easily, the mixture gradation may change after compaction. This gradation change can increase unwanted fine fractions, reduce effective voids, and disturb cement bonding. Therefore, reducing the blended abrasion value to 35.145% is a significant finding because it indicates that the combination of green stone and Jaro stone successfully improved a fundamental mechanical parameter for LPAS application (Direktorat Jenderal Bina Marga, 2025; Badan Standardisasi Nasional, 2018).

Field Quality Control Implications

If the laboratory results are used as the basis for field work, several critical control points must be considered. First, aggregate fraction sorting must be implemented from the material production stage. Green stone fractions that do not meet the abrasion criterion must be replaced with Jaro stone or another aggregate with better wear resistance. Second, aggregate moisture content must be checked before mixing because actual moisture content affects additional water demand. Third, cement content must be determined based on the intended compressive strength, not a general estimate. Fourth, compaction must be performed at optimum moisture content to prevent reduced maximum dry density (Badan Standardisasi Nasional, 2018; Direktorat Jenderal Bina Marga, 2025).

Quality control should also include periodic sampling during construction. Local aggregate may show quality variation due to differences in quarry location, weather conditions, and crushing methods. Therefore, the findings of this study should be treated as an initial design basis that must be validated through field production. Abrasion, gradation, silt content, moisture content, and compressive strength tests need to be conducted periodically to ensure that the mixture remains compliant with specifications. Through this approach, green stone utilization can support material efficiency without compromising road construction quality (Lestari et al., 2025; Tana et al., 2024).

Feasibility and Mixture Efficiency Analysis

The test results indicate that green stone cannot be used entirely in all fractions because its average abrasion value still exceeds the 40% limit. However, after substitution with Jaro stone, the combined aggregate met the abrasion requirement with a value of 35.145%. Physically, specific gravity, absorption, and silt content also met the specified requirements. Therefore, green stone is conditionally feasible as LPAS material. It can be used if fractions that do not meet abrasion criteria are replaced or combined with aggregate that has higher wear resistance (Badan Standardisasi Nasional, 2018; Direktorat Jenderal Bina Marga, 2025).

From the mixture perspective, LPAS-A is the most efficient option because it requires the lowest cement content to achieve the planned compressive strength. This efficiency relates to more optimal gradation and a denser mixture structure. LPAS-B remains a feasible alternative because its cement demand is not much higher than LPAS-A. In contrast, LPAS-S and LPAS-C require higher cement contents and therefore need more careful cost evaluation, moisture control, and field density control. In construction practice, cement content should not focus only on achieving maximum compressive strength. It should also consider specification requirements, cost, constructability, and the risk of cracking due to excessive stiffness (Lestari et al., 2025; Tana et al., 2024).

The findings reaffirm the critical role of laboratory testing in local material utilization. Local aggregate does not always have uniform quality across all particle sizes. Fraction-based evaluation is essential so that acceptable material can be used and weaker fractions can be improved through substitution. This strategy supports more efficient use of local resources and reduces dependence on aggregate from outside the region while maintaining compliance with road work technical standards (Hakzah et al., 2024; Ramirez-Vargas et al., 2024).

Technical Recommendations for Green Stone Utilization

Based on the results, Gunung Rambutan green stone is recommended for fractions that meet the abrasion requirement. For coarse fractions that do not meet the requirement, Jaro stone can be used as a substitution material. During mixture production, optimum moisture content must be maintained according to the LPAS class because moisture deviation can reduce density and compressive strength. LPAS-A should be prioritized when the objective is to achieve planned strength with the most efficient cement use. LPAS-B can be used as the next alternative, while LPAS-S and LPAS-C require tighter control of gradation, compaction, and cement content (Badan Standardisasi Nasional, 2015; Direktorat Jenderal Bina Marga, 2025).

A field-scale trial is also recommended before broad implementation. Although laboratory testing provides a strong initial basis, field conditions may be influenced by variations in moisture content, temperature, compaction equipment, mixing duration, and aggregate-size distribution at the work site. Therefore, a trial section is needed to validate laboratory results, especially for mixtures with cement contents near the lower specification limit. Further testing on durability, flexural strength, and wet-dry cycle resistance is also important to evaluate LPAS performance more comprehensively (Sianturi, 2023; Nugraha, 2025).

Comparison of Laboratory Results with Specifications

The comparison between laboratory results and technical requirements indicates that material feasibility assessment must be conducted in stages. Physical parameters of green stone, such as Bulk SSD specific gravity, water absorption, and silt content, met the required limits. Specific gravity above the minimum value indicates that the aggregate has adequate density to form a stable base layer. Water absorption below the maximum limit indicates that the aggregate is not excessively porous. Low silt content indicates that aggregate surfaces are relatively clean, allowing the cement bond to develop more effectively (Badan Standardisasi Nasional, 2015; Direktorat Jenderal Bina Marga, 2025).

The most critical parameter in this study was Los Angeles abrasion. Untreated green stone did not meet the requirement because its average abrasion value exceeded the maximum limit. This finding shows that aggregate with apparently good physical characteristics does not necessarily have sufficient mechanical resistance. In base course layers, aggregate wear resistance is important because the aggregate must withstand repeated loads, interparticle friction, and compaction energy. If aggregate breaks easily, gradation changes during construction and can reduce layer performance. Therefore, substitution with Jaro stone was based on a mechanical parameter directly related to material durability (Badan Standardisasi Nasional, 2018; Direktorat Jenderal Bina Marga, 2025).

After substitution, the combined aggregate met all major evaluated parameters. This result shows that local material quality can be improved through mixture engineering. In regional development, this strategy is significant because it allows green stone to remain used as a local resource while improving its quality through combination with a more wear-resistant material. Compliance with specifications can therefore be achieved not only by searching for new material but also by managing material composition more accurately (Ramirez-Vargas et al., 2024; Lestari et al., 2025).

Table 10. Technical meaning of specification-comparison results

Parameter	Main result	Meaning for LPAS
Specific gravity	Complies	Supports mixture stability and density
Water absorption	Complies	Moisture variation risk is relatively controlled
Silt content	Complies	Cement-aggregate bonding is not disturbed by fine material
Initial green stone abrasion	Not compliant	Requires improvement through fraction substitution
Combined aggregate abrasion	Complies	Mixture is feasible as LPAS material

Relationship among Gradation, Compaction, and Compressive Strength

The results indicate a close relationship among gradation, compaction, and compressive strength. Denser gradation supports the formation of an interlocking aggregate structure. This structure requires less cement paste to fill voids and form bonds. This phenomenon explains why LPAS-A and LPAS-B require lower cement contents than LPAS-S and LPAS-C. In mixtures with larger voids, cement functions not only as a binder but also as a void-filling material, increasing cement demand (Hakzah et al., 2024; Badan Standardisasi Nasional, 2015).

Compaction is also a decisive factor for mixture success. At optimum moisture content, water acts as a lubricant among particles and allows aggregate to arrange more densely. After cement reaction, the dense structure transforms into a semi-rigid layer. If water content is below optimum, compaction becomes ineffective because interparticle friction is too high. If water content is excessive, voids may form after water evaporates or leaves the mixture. Therefore, OMC and MDD must be integrated into quality control, not treated only as laboratory procedures (Badan Standardisasi Nasional, 2018; Tana et al., 2024).

The linear increase in compressive strength within the tested range indicates that cement still worked effectively in forming bonds in the mixture. However, this relationship will not always remain linear at higher cement contents. At a certain point, additional cement may produce smaller strength gains because the main voids have been filled and interparticle bonds have already formed. Therefore, optimum cement content should be determined in the zone that meets the specification, not at the level that produces the highest compressive strength. This approach makes the findings more relevant to field work because it considers quality, cost, and binder-use efficiency (Direktorat Jenderal Bina Marga, 2025; Lestari et al., 2025).

Research Limitations and Further Study Direction

This study provides a technical basis for evaluating the feasibility of green stone as LPAS material, but it has limitations. All tests were performed at laboratory scale. Field conditions such as temperature variation, humidity change, mixing homogeneity, transportation time, and variation in compaction energy were not fully represented. Therefore, the optimum cement contents should be viewed as initial references that must be confirmed through field trials. Such trials are important to observe whether mixture strength, density, and stability remain consistent when the material is produced in larger volumes (Badan Standardisasi Nasional, 2015; Direktorat Jenderal Bina Marga, 2025).

Further studies should examine mixture durability, flexural strength, resistance to wet-dry cycles, and changes in compressive strength at longer curing ages. These tests are necessary because LPAS must not only develop strength at seven days but also maintain stability throughout road service life. Cost analysis should also compare LPAS-A, LPAS-B, LPAS-S, and LPAS-C based on cement demand, green stone availability, Jaro stone hauling distance, and combined aggregate production cost. Recommendations should therefore consider not only strength but also economic efficiency and constructability (Sianturi, 2023; Lestari et al., 2025).

Table 11. Quality control and further research directions

Aspect	Technical direction	Objective
Aggregate abrasion	Periodic testing by fraction	Ensure wear resistance
Combined gradation	Control the proportion of green stone and Jaro stone	Maintain mixture consistency
Moisture content	Adjust to the OMC of each class	Achieve maximum density
Compressive strength	Test at seven days and later ages	Validate mixture strength
Trial section	Conduct field-scale testing	Evaluate laboratory-field consistency

CONCLUSION

The physical characteristics of green stone aggregate, including Bulk SSD specific gravity of 2.387, water absorption of 2.817%, and silt content of 0.5%, met the standards specified in the 2025 Bina Marga specification. However, the abrasion value of untreated green stone aggregate reached 41.39%, exceeding the maximum limit of 40%. Partial replacement with Jaro stone, which had an average abrasion value of 28.9%, reduced the blended abrasion value to 35.145%, enabling the combined aggregate to meet the specification. The relationship between cement content and compressive strength showed a linear pattern within the evaluated range. The cement contents required to achieve design strengths of 3.5 MPa and 4.2 MPa were 6.10% and 7.10% for LPAS-A, 6.70% and 7.50% for LPAS-B, 8.80% and 9.95% for LPAS-S, and 8.90% and 9.75% for LPAS-C. Based on the analysis, LPAS-A was the most efficient mixture formulation because it required the lowest cement content to achieve the planned compressive strength.

Declaration by Authors

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