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Original Article

The Influence of Compaction Energy on the Mechanical Properties and Performance of Cold-Mix Asphalt

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Abstract *- Cold-mix asphalt constitutes a practicable option for roadway preservation and rehabilitation, principally because its placement proceeds at ambient temperatures with comparatively modest energy expenditure; nonetheless, deficiencies in load-bearing capacity and serviceability across disparate traffic regimes necessitate technically robust, enduring interventions in Peru. Against this backdrop, the investigation scrutinised how differentiated levels of compaction energy affect the mechanical characteristics and functional performance of a commercially pre-mixed cold asphalt product furnished by Corporación Grinsa Aditivos para la Construcción. Procured in application-ready condition, the material was consolidated through 35, 50 and 75 hammer blows per specimen face, intensities provisionally associated with light, medium and heavy traffic, respectively. Marshall testing quantified stability and flow, the Cantabro procedure established particle disintegration, and Hamburg wheel tracking characterised susceptibility to rutting. The experimental evidence disclosed progressively ameliorated mixture performance with increasing compaction energy: mean Marshall stability advanced from 557.83 kgf with 35 blows to 676.78 kgf with 50 blows and 847.73 kgf with 75 blows, surpassing the adopted minimum criterion throughout; concomitantly, flow measurements of 2.69, 2.93 and 3.13 mm, respectively, remained inside the stipulated 2 to 4 mm interval. Correspondingly, particle loss receded from 7.93% to 5.73% and ultimately 4.93%, signifying heightened internal cohesion under more intensive consolidation. Specimens subjected to 75 blows per face manifested the smallest residual deformation during Hamburg wheel tracking and hence the most favourable rutting response. The investigation therefore establishes compaction energy as a consequential determinant of enhanced stability, diminished aggregate loss and attenuated rutting propensity for the commercial cold-mix asphalt examined, yielding applicable technical guidance for refining its preparation, field compaction and construction quality assurance during roadway maintenance.*

Keywords *- Cold mix asphalt, Flexible pavement, Low traffic, Medium traffic, Heavy traffic.*

1. Introduction

During 2024, the internationally aggregated market valuation of cold mix asphalt approached USD 3.2 billion, with forecasts anticipating a Compound Annual Growth Rate (CAGR) of approximately 5.3% throughout 2025–2034 and an eventual valuation near USD 5.3 billion in 2034. Such expansion reflects escalating requirements for road preservation and newly commissioned transport infrastructure, facilitated by the absence of thermal processing during placement [1].

Accordingly, this mixture occupies an increasingly conspicuous position in highway engineering, particularly through its extensive deployment in pavement conservation and rehabilitation operations. International production further corroborates its practical relevance: France manufactures roughly 1.5 million tonnes annually and Turkey about 2 million tonnes [2], whereas utilisation in the United Kingdom remains concentrated predominantly within pavement base and sub-base courses [3].

Within Peru, transport infrastructure expenditure during January through May 2025 exceeded USD 382.6 million, including approximately USD 17.7 million earmarked specifically for the roadway network. This allocation underscores the considerable national imperative to preserve, rehabilitate and incrementally develop essential transport infrastructure [4].

Within this technological framework, and specifically regarding constituent selection and ambient-temperature implementation,Cold Mix Asphalt (CMA) denotes a composite of mineral aggregates and bituminous binding agents, customarily asphalt emulsions or cutback binders, manufactured and emplaced under ambient-temperature conditions [5]. Its thermal independence renders the material

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particularly advantageous for roadway conservation, including expeditious pavement patching applications exemplified by Cold Patching Asphalt Mixture (CPA) [6]. Moreover, such formulations facilitate comparatively economical and environmentally judicious pavement construction by curtailing energy requirements and circumventing the emissions ordinarily attributable to asphalt heating [7]. Notwithstanding these operational and ecological benefits, cold asphalt mixtures remain susceptible to identifiable technological constraints. Insufficient strength during early service may preclude their utilisation under substantial traffic intensities [8]; excessive entrained air voids can impair structural integrity and diminish long-term durability [9]; and deficient stability when confronted by intense wheel loads or adverse climatic exposure may precipitate untimely pavement degradation [10]. Consequently, numerous investigators have examined supplementary modifiers intended to ameliorate such deficiencies. Glass-fibre reinforcement, for instance, may fortify cold asphalt, inhibit fissure development and augment durability through the establishment of an internal reinforcing network [11]. Related findings indicate that incorporating Reclaimed Asphalt Pavement (RAP) alongside cementitious additions, including cement or fly ash, can appreciably enhance mixture strength, stability and durability while simultaneously advancing environmental sustainability and economic expediency for paving projects [12]. The conjoint utilisation of RAP and asphalt emulsion has likewise demonstrated favourable effects on cracking and rutting resistance in cold asphalt mixtures [13]. Beyond constituent selection, however, construction-dependent consolidation parameters remain influential determinants of mixture performance. Available evidence specifically associates compaction energy and aggregate gradation with stability and durability; judicious consolidation improves mechanical resistance, whereas excessive densification may impart undesirable rigidity and accentuate susceptibility to cracking [14].

The distinctive contribution of this investigation resides in its appraisal of an otherwise conventional cold asphalt mixture without introducing supplementary chemical or mineral modifiers. By isolating the repercussions of differing compaction energy levels on the material's mechanical attributes, the research endeavours to elucidate its structural response more rigorously and delineate the conditions under which its use might be appropriate for contrasting vehicular traffic categories.

1.1. Literature Review

1.1.1. Compaction Dynamics and Volumetric Behavior

In Indonesia, researchers from the Civil Engineering Department at Petra Christian University conducted a study aimed at evaluating the properties of a cold-mix asphalt for the wearing course in relation to compaction energy and aggregate gradation; To this end, they carried out laboratory experiments following the Marshall mix design method, using local materials from East Java province, with aggregate from a quarry in Jember and CSS-1h cationic asphalt emulsion produced in Mojokerto. They prepared specimens with two types of gradation (dense type IV and open for the surface course), they tested five bitumen contents per mix type, ranging from 5.5% to 7.5% for the dense gradation and from 5% to 7% for the open-graded mix, in 0.5% increments; they pre-wetted the aggregates with 2% water relative to the total mix mass; they produced three replicates for each combination of bitumen content, gradation and compaction energy, compacted using a Marshall hammer at 50, 75 and 2×75 blows per face, cured the samples for 24 hours at room temperature and then for 24 hours at 40 °C, prepared a total of 90 compacted specimens, and measured stability and volumetric properties using the Marshall Test; as the most representative results, they found that in the dense-graded mixture, increasing the compaction energy slightly improved stability, whilst in the open-graded mixture, high compaction energy significantly improved stability when the bitumen content was lower; that the dense-graded mixture could be used in surface layers for medium and light traffic, whereas the open-graded mix showed potential for heavy traffic if adequately compacted; that increased compaction energy reduced the air void content in both gradations; that all samples met the specification for water absorption of less than 4%; and that over-compaction significantly increased the stiffness of the mix, with a potential risk of cracking, and therefore concluded that each type of gradation required a different compaction energy to achieve its best properties [14].

In Spain, researchers from the Department of Transport, Land Use and Urban Planning at the Polytechnic University of Madrid carried out a study aimed at assessing the influence of two compaction methods the modified Proctor procedure and rotary compaction on the volumetric design of cold-recycled mixtures using emulsion, focusing primarily on density and air void content; To this end, they worked with a mixture made from 100% RAP, without virgin aggregate, and a commercial slow-breaking cationic bituminous emulsion containing 60% residual bitumen, testing 16 formulations resulting from combining four emulsion percentages (1%, 2%, 3% and 4%) with four percentages of premix water (1%, 2%, 3% and 4%), preparing two specimens per dosage and averaging the results; in the modified Proctor test, they used approximately 5 kg of RAP per specimen in a standardised mould 152 mm in diameter and 127 mm in height, compacting in five layers with 60 blows per layer using a calibrated rammer weighing 4.535 kg and a drop height of 457 mm, whereas in the rotary compaction test, they used 1.1 kg of RAP per specimen, compacted for up to 100 revolutions, with an internal angle of 0.82°, 30 rpm and a maximum pressure of 600 kPa; furthermore, they calculated the maximum density using a pycnometer, the bulk density and the percentage of air voids after oven drying. As the most representative results, they observed that both methods produced consistent results

when applying the criterion of maximum bulk density, identifying 3% premix water and 3% emulsion as the optimal formulation, but rotary compaction achieved higher apparent densities than the modified Proctor and demonstrated practical advantages, as it required less material and yielded specimens suitable for subsequent mechanical testing; they therefore concluded that it was the preferable method for this type of volumetric design [15].

In China, researchers from the Department of Transportation at the School of Civil Engineering conducted a study aimed at analysing the compaction characteristics of Cold-Recycled Mixtures with asphalt Emulsion (CRME) using the Superpave Rotary Compactor (SGC) method, proposing compaction characterisation parameters, and suggesting a reasonable method for determining the optimum emulsion content, moisture content and compaction temperature. To this end, they used RAP from a motorway maintenance project in Henan containing 4.87% recycled asphalt; they designed mixtures with 90% RAP and 10% limestone gravel as the base gradation, as well as comparison gradations of 80% RAP + 20% limestone gravel and 70% RAP + 20% limestone gravel + 10% fine aggregate; they incorporated 1% PC32.5 cement by weight of the aggregates; they prepared a cationic emulsion using Zhenhai #70 asphalt; and they used the SGC to study densification curves and five compaction parameters; furthermore, they compared the SGC with the modified Marshall method using specimens 100 mm in diameter and 63.5 mm in height, with 30, 50, 75 and 100 turns in the SGC versus 75 blows in the Marshall test, and with emulsion contents of 3.0, 3.5, 4.0 and 4.5% by weight of the aggregates; they also carried out ITS tests on specimens under dry and wet conditions, and supplementary assessments of resistance to water damage, rutting and low-temperature behaviour. As the most representative results, they reported that the proposed parameters better described the compaction of CRME; that 50 revolutions in the SGC produced an effect similar to that of 75 Marshall blows; that the emulsion content and compaction temperature had a significant influence, whilst the aggregate gradation showed no significant effect; and that, upon increasing the temperature from 5 to 25 °C, the ITSd, ITSw and ITSR values increased by 15, 41 and 22 per cent, respectively; that the optimum water content obtained with SGC was reduced by 18 per cent and the density increased by 3.5 per cent compared to heavy compaction; and that the mixture compacted at 50 revolutions, 25°C, 4% emulsion and 2.6% mixing water met the technical requirements of standard JTG/T5521-2019 [16]. Collectively, these observations preclude evaluating compaction solely by counting hammer impacts or gyrations, because achievable density remains contingent on constituent materials and the particular consolidation protocol.

1.1.2. Curing Conditions and Moisturerelated Mechanisms

In China, researchers from the School of Civil Engineering and the School of Transportation and Logistics at Dalian University of Technology, with support from the School of Energy and Power Engineering at Xi'an Jiaotong University, carried out research with the primary aim of proposing a relatively feasible laboratory production method for Cold-Recycled Mixtures with Asphalt Emulsion (CMAE), taking into account the curing and compaction history, to evaluate their volumetric and mechanical properties under different cement contents; To this end, they used RAP from a motorway in Liaoning Province, slow-setting cationic bituminous emulsion, limestone aggregates, ordinary Portland cement P.O 42.5 and limestone powder, maintaining a total filler content of 3%, with cement contents of 0%, 1% and 2% compensated by 3%, 2% and 1% limestone powder, respectively; they first set the initial emulsion content at 3.5% and tested additional water content between 1% and 5% until an optimum water content of 4.4% was determined; they then evaluated emulsion contents between 2% and 6% and established 4% as optimal, prepared Marshall specimens of approximately 1180 g and compared two accelerated curing regimes, one of 2 days at 60 °C and another mixed regime of 3 days at 20 ± 2 °C followed by 2 days at 60 °C, along with three Marshall hammer compaction methods: 50 blows per face, 75 blows per face and double compaction (50 blows per face plus 25 blows per face after curing), evaluating void content, indirect tensile strength, deformation at break, critical strain energy density, volumetric shrinkage, residual water and the microstructure of the mastic; as the most representative results, they found that simple curing reduced the void content and increased the ITS, strain at break and CSED when the cement content was low, whilst mixed curing reduced voids and significantly improved the ITS and CSED when the cement content was high, they also observed that double compaction further reduced the void content and improved the ITS and CSED compared to single compaction methods, and concluded that single curing should be recommended for relatively low cement contents, mixed curing for relatively high cement contents, and double compaction for producing laboratory specimens, as it better replicates field construction [17].

In Spain, researchers from the Polytechnic University of Madrid, from the Department of Transport, Land Use and Urban Planning, in collaboration with Repsol's asphalt technical support team and SACYR's pavements department, carried out a study aimed at determining the compaction conditions for cold-recycled asphalt mixtures using emulsion and 100% RAP, as well as to assess the influence of the emulsion and cement on the final properties of the mix; to this end, they employed an experimental methodology based on milled material from a deteriorated pavement, without adding virgin aggregate, mixing it with premix water, four commercial C60B5-type emulsions (E1, E2, E3 and E4) and Portland cement in different proportions, first conducting a study with 1%, 2%, 3% and 4% water and then setting the premix water content at 3% as it offered the best density, compacting specimens with a rotary compactor at an internal

angle of 0.82°, 30 rpm and 600 kPa, with 200 revolutions for specimens 100 mm in diameter and 100–110 mm in height, and 100 revolutions for specimens 100 mm in diameter and 60-63 mm in height; furthermore, they evaluated formulations containing 3% emulsion and 1.5% cement and 4% emulsion and 2% cement, applying standardised tests for bulk density, void ratio, water sensitivity, wheel tracking, stiffness modulus and fatigue, together with a 7-day curing period at 20 °C with partial plastic covering, followed by 3 days at 50 °C until constant weight, extended to 7 days at 50 °C for wheel tracking specimens; as the most representative results, they found that the percentage of emulsion was the factor that most affected compactability, that cement improved resistance to water action, resistance to permanent deformation, stiffness modulus and fatigue life, that an increase in emulsion content helped to prolong fatigue life, and that the formulation with 4% emulsion and 2% cement generally exhibited the best mechanical performance [18].

In Iran, researchers from the School of Civil Engineering at the Iran University of Science and Technology (IUST) in Tehran conducted a study aimed at evaluating the effect of calcium alginate capsules containing Waste Sunflower Oil (WSO) and Waste Engine Oil (WEO) on curing efficiency, strength development and the mechanical behaviour of cold-mix asphalt, whilst also considering different curing times and two compaction methods, Marshall and rotary; to this end, they produced capsules in four stages preparation of the rejuvenating solution and sodium alginate solution, mixing of the two, dripping the mixture into a calcium chloride solution, and subsequent washing and drying, they used WEO and WSO with densities of 0.91 and 0.95 g/cm³, respectively, and characterised the capsules using SEM-EDS mapping and TGA; in the latter test, they used a nitrogen atmosphere, a heating rate of 10 °C/min and a temperature range of 0-600 °C; they also designed the mixture in accordance with the MS-14 manual, determined the optimum moisture content using samples compacted with 50 blows of the Marshall hammer, added 1% by mass of ordinary Portland cement, prepared Marshall mixes with 50 and 75 blows per face and rotary mixes with 50 and 65 rotations, obtained air voids of around 9% for GCM65 and MCM75 and around 10% for GCM50 and MCM50, cured the mixtures for 28 days at room temperature and, additionally, evaluated samples cured for 7, 14 and 28 days; they also applied a modified humidity condition of 48 h at 25 °C, instead of 24 h at 60 °C, and carried out ITS, TSR, HWT and SCB tests, the latter at 0 °C and −20 °C with a loading rate of 0.5 mm/min, whilst the HWT was performed at 50 ± 1 °C, with a vertical load of 700 ± 20 N, a frequency of 40 ± 1 cycles/min and a minimum of 20,000 cycles; as results, they reported that mixtures containing 0.5% capsules lost more moisture and accelerated curing, that rotary-compacted samples achieved ITS values up to 90% higher than those compacted using the Marshall method, that the addition of capsules reduced the dry ITS by 7–15% but increased the TSR by up to 10%, that the fracture energy increased by between 18 and 22% at −20 °C in mixtures containing 1% WSO, that the capsules increased the rutting depth particularly at 1% and that those formulated with WEO produced deeper ruts than those with WSO; furthermore, ANOVA analysis showed that the compaction method was the factor with the greatest influence on ITS, TSR and fracture energy, whilst the type and content of capsules had a greater influence on rutting [19]. Importantly, these investigations dealt predominantly with asphalt-emulsion matrices, and their governing curing mechanisms cannot be uncritically transposed to cutback-bitumen systems without accounting for solvent volatilisation and disparities in binder composition.

1.1.3. Mechanical Performance and Resistance to Deterioration

In China, researchers from the Key Laboratory for Special Area Highway Engineering of the Ministry of Education at Chang'an University conducted a study aimed at evaluating the fatigue properties of Cold-Recycled Asphalt Mixtures with Emulsion (CEAMs) produced using two compaction methods: the Modified Marshall Method (MMCM) and the Vertical Vibration Test Method (VVTM); To this end, they employed an experimental methodology using SBS-modified emulsified bitumen, RAP materials obtained from the X115 county road in Jinhua City, Zhejiang Province, and limestone aggregates from Luonan County, Shaanxi Province.

They prepared specimens using the MMCM with 50 blows per face, drying at 60 °C for at least 40 hours, recompaction with 25 blows, and cooling for 12 hours; and for VVTM, with compaction for 60 seconds, drying at 60 °C for 48 hours and cooling for 12 hours; furthermore, on the VVTE equipment, they operated at a frequency of 35 Hz, a nominal amplitude of 1.2 mm and weights of 108 kg and 167 kg in the upper and lower systems, respectively; they determined the optimum moisture content with 4% emulsified asphalt and water contents between 3.5% and 5.5% in 0.5% increments, they then evaluated the optimum content of emulsified asphalt with dosages between 3.0% and 5.0%, also in 0.5% increments; they carried out six parallel tests per condition, indirect tensile tests following immersion for 1.5 hours at 15 °C and indirect immersion tests following 23 hours at 25 °C plus 1 hour at 15 °C, and indirect tensile fatigue tests at 15 °C under stress ratios of 0.3, 0.4, 0.5, 0.6 and 0.7, with a semi-vectorial sinusoidal load at 10 Hz, analysing the results using Weibull distribution and constructing fatigue equations; as the most representative results, they found that the average mechanical strength ratio between the samples manufactured by VVTM and the field cores was greater than 92%, whereas for those manufactured by MMCM it was less than 65%; that the CEAMs produced by VVTM reduced the optimum moisture content by 11% and the optimum emulsified asphalt content by 9%, but improved moisture stability by 4%-5%, crack resistance by 12% and rutting resistance by 35%, and that they also exhibited superior fatigue life, with increases of

36% at a stress ratio of 0.45 and 325% under a repeated load of 0.27 MPa compared to the mixtures produced by MMCM [20].

Unlike previous investigations that examined compaction alongside variations in aggregate gradation, asphalt emulsion content, recycled materials or cementitious additives [14-20], the present study maintained the original composition of a commercially manufactured MAC-2 cold-mix asphalt incorporating RC-250 cutback bitumen. The contribution of this research lies in evaluating the effect of three Marshall compaction levels (35, 50 and 75 blows per face) on the same unmodified formulation through complementary measurements of volumetric properties, Marshall stability and flow, Cantabro particle loss and Hamburg rutting resistance. This approach enables the mechanical and functional responses associated with increasing compaction energy to be examined without introducing deliberate changes in mixture composition. Consequently, the findings provide experimental evidence specific to the investigated commercial material, rather than extending conclusions obtained from emulsion-based or recycled asphalt mixtures to a different binder system.

2. Materials and Methods

2.1. Classification of Asphalt

Asphalt paving materials are customarily differentiated into two principal categories, hot mix asphalt and cold mix asphalt, whose engineering response, installation requirements and practical applications diverge materially [21]. Hot mix asphalt combines graded mineral aggregates with a bituminous binding constituent under elevated manufacturing temperatures, thereby facilitating thorough constituent homogenisation, satisfactory aggregate-film coverage and effective densification during construction; these characteristics ordinarily promote superior structural capacity and extended service life [22, 23]. Conversely, cold mix asphalt comprises aggregate particles and fluid bituminous binders placed without elevated temperatures, and its operational simplicity and economic accessibility make it especially useful for expedited roadway interventions; nevertheless, serviceability remains contingent upon deformation, abrasion and moisture resistance, the latter constituting a particularly salient vulnerability [24].

From an economic standpoint, hot mix asphalt usually entails more substantial initial capital expenditure owing to specialised mixing facilities and heating demands, notwithstanding comparatively lower subsequent maintenance expenses and greater emissions during production [25, 26]. Cold mix asphalt generally necessitates less machinery and thermal energy, thus reducing installation expenditure and environmental burdens, yet its comparatively limited endurance may occasion more frequent interventions despite the considerable advantage of rapid pavement restoration [27].

2.2. Cold-Mix Asphalt

The experimental material comprised a ready-manufactured commercial cold asphalt mixture obtained from Corporación Grinsa Aditivos para la Construcción. As declared in the supplier's technical documentation, this product belongs to the MAC-2 classification and incorporates mineral aggregates with a nominal maximum particle dimension of 1/2 inch, together with RC-250 cutback asphalt binder. Selection of this ready-to-place formulation permitted direct examination of mechanical and functional response under differentiated compaction energy levels, while eschewing any deliberate reformulation of aggregate grading or supplementary adjustment of constituent proportions.

Accordingly, the laboratory programme investigated three discrete compaction energy intensities, represented by 35, 50 and 75 hammer blows upon each specimen face, without intentional departures from the commercially supplied aggregate-to-binder formulation. This experimental delineation was adopted to distinguish the consequences of the consolidation operation from those of compositional alteration. Figure 1 depicts the pre-mixed commercial cold asphalt product employed throughout the investigation.



Fig. 1 Pre-Mixed cold mix asphalt used in the study

The manufacturer-declared specifications of the investigated product appear in Table 1, encompassing recommended placement conditions, density-related attributes, bituminous binder concentration and aggregate characteristics. These particulars served solely to characterise the commercial formulation; no independent confirmation was undertaken through granular sieve gradation, binder extraction or testing of the residual binder. Accordingly, the interpretations presented herein pertain exclusively to the particular purchased material and should not be indiscriminately extrapolated to cold asphalt formulations possessing dissimilar constituent compositions.

Table 1. Technical characteristics of the cold mix asphalt

Characteristic	Value
Theoretical yield	55 – 62 kg/m²
Type of asphalt mix	MAC-2
Maximum aggregate particle size	1/2"
Product shelf life	12 months
Application temperature	Ambient
Compaction density	2300 kg/m³
Density	1850 kg/m³
Binder content	5.955 %
Adhesion	≥ 95 %
Los Angeles Abrasion	≤ 25 %
Combined aggregate bulk specific gravity (Gsb)	2.67

2.3. Tests Performed

2.3.1. Marshall Test (Stability and Flow)

Marshall stability and flow determinations followed the methodological provisions of ASTM D6927 to characterise load resistance and deformational response in the commercial pre-mixed cold asphalt incorporating RC-250 cutback binder. Figure 2(a) depicts the manufacture of cylindrical test pieces inside Marshall moulds measuring 101.6 mm in diameter. Thereafter, as illustrated in Figure 2(b), a Marshall rammer of 4.5 kg delivered 35, 50 or 75 impacts on each specimen face, thereby establishing the three compaction energy conditions prescribed for the experimental comparison.

After the prescribed hammering sequence, specimens underwent approximately 30–60 minutes of cooling until they attained the surrounding air temperature; they were then carefully released from their forming moulds, as documented in Figure 2(c). Because their bituminous phase consisted of RC-250 cutback asphalt binder, the samples subsequently received conditioning inside a thermostatically controlled air enclosure at 25 ± 1 °C for 120–130 minutes, consistent with the treatment prescribed for cutback asphalt mixtures in ASTM D6927.

On completion of conditioning, each test piece was secured within the Marshall loading assembly illustrated in Figure 2(d) and subjected to a vertically directed force at a uniform crosshead displacement of 50 mm/min. Its greatest sustained load constituted the recorded Marshall stability, reported in kilogram-force (kgf) and illustrated by the measurement presented in Figure 4(e).



Fig. 2 Stability testing procedure

The Marshall flow determination proceeds concomitantly with the stability measurement, employing identical specimens and experimental settings. Prior to initiating mechanical loading, the displacement indicator is installed and calibrated to zero. As the apparatus advances at a controlled displacement velocity of 50 mm/min, it registers the successive deformations sustained by the specimen.

Flow is defined as the cumulative deformation corresponding precisely to attainment of the peak applied force, and may be stated either in Marshall units, each representing 0.25 mm, or directly in millimetres. This measurement affords an appraisal of the mixture's plastic deformability, distinguishing an excessively rigid composition from one unduly predisposed to irreversible displacement.

Volumetric characterisation of the asphalt mixture was undertaken to discern how compaction energy modulates densification and the internal arrangement of constituent particles. The indicators evaluated comprised compacted-mixture bulk specific gravity (Gmb), maximum theoretical specific gravity (Gmm), air void content (Va), Voids in Mineral Aggregate (VMA) and Voids Filled with Asphalt (VFA). Each of these quantities was established for the three investigated compaction energy intensities, namely 35, 50 and 75 hammer blows applied to every specimen face.

Bulk specific gravity (Gmb) of the consolidated specimens was established pursuant to ASTM D2726/D2726M by determining each sample's oven-dry mass, saturated surface-dry mass and apparent mass during immersion. These three experimentally obtained mass measurements provided the requisite inputs for calculating the bulk specific gravity through the expression reproduced below:

$$G_{mb} = \frac{A}{B - C}$$

Where: Gmb designates bulk specific gravity of the compacted asphalt mixture; A represents the specimen's dry mass (g); B corresponds to its saturated surface-dry mass (g); and C denotes its apparent mass when submerged in water (g).

Maximum theoretical specific gravity (Gmm) was additionally ascertained in conformity with ASTM D2041/D2041M, using portions of asphalt mixture that had not undergone compaction. Entrapped air was evacuated under vacuum so that the hypothetical air-void-free volume of the combined constituents could be determined, furnishing the corresponding theoretical specific-gravity value.

The proportion of air voids (Va) was then derived from the experimentally determined Gmb and Gmm measurements in accordance with the mathematical relationship specified by ASTM D3203/D3203M:

$$V_a = \left(1 - \frac{G_{mb}}{G_{mm}}\right) x\ 100$$

Where: Va denotes the percentage of air voids (%); Gmb signifies bulk specific gravity of the compacted mixture; and Gmm identifies the maximum theoretical specific gravity of the asphalt mixture.

The percentage of Voids in Mineral Aggregate (VMA) was similarly computed from the bulk specific gravity of the compacted composition, the combined bulk specific gravity of its aggregate fraction and the aggregates' percentage contribution to total mixture mass, according to the following formulation:

$$VMA = 100 - \left(\frac{G_{mb}\ x\ P_s}{G_{sb}}\right)$$

Where: VMA represents voids in mineral aggregate (%); Gmb is the bulk specific gravity of the compacted mixture; Ps denotes aggregate mass as a proportion of total mixture mass (%); and Gsb identifies the combined bulk specific gravity of the aggregates.

Lastly, Voids Filled with Asphalt (VFA) were determined by relating the mineral-aggregate void fraction to the measured air void content, as expressed in the ensuing mathematical relationship:

$$VFA = \left(\frac{VMA\ x\ V_a}{VMA}\right) x\ 100$$

Where: VFA denotes the percentage of voids filled with asphalt (%); VMA signifies voids in mineral aggregate (%); and Va represents air void content (%).

The resulting volumetric indices were subsequently juxtaposed across all three compaction energy conditions to elucidate the associations linking mixture densification, Marshall stability and Marshall flow response.

Marshall Stability Evaluation Criteria

Experimental Marshall stability measurements were benchmarked against the comparative requirement delineated in Section 424, Table 424-04, of Peru's Highway Manual: General Technical Specifications for Construction (EG-2013), promulgated by the Ministry of Transport and Communications.

For dense-graded cold asphalt mixtures, this provision identifies a minimum stability of 226.38 Kg.f. That prescribed threshold served as the reference for assessing the mechanical load-bearing response of the commercially produced cold asphalt material incorporating RC-250 cutback binder, rather than as evidence of unrestricted applicability to other formulations.

2.3.2. Wear Test (Cantabrian)

Abrasion-related particle disintegration was quantified using the Cantabrian, or UCL, test, in accordance with the procedures contemplated by ASTM D7064 and UNE-EN 12697-17. The principal objective was to establish the asphalt mixture's ability to withstand progressive material detachment. Specimens previously fashioned and consolidated through the Marshall procedure were first weighed to determine their initial masses (P1). Each briquette was then introduced separately into the Los Angeles abrasion drum, intentionally without metallic spheres, and exposed to 300 complete revolutions to replicate mechanically induced deterioration attributable to vehicular loading. Following termination, loose debris was removed and each specimen was weighed anew to establish its residual mass (P2). The corresponding abrasion or wear percentage (%) was calculated as the fractional mass diminution relative to the original specimen mass.

2.3.3. Hamburg Wheel Test

Hamburg wheel-tracking experimentation was conducted in accordance with the technical framework of AASHTO T 324 and UNE-EN 12697-22, with the purpose of examining whether differentiated compaction energy influences cold asphalt resistance to accumulated permanent deformation, or rutting, during reiterated wheel loading under moisture exposure. Three experimental consolidating intensities, 35, 50 and 75 blows, were prescribed to distinguish their repercussions for mechanical response. Cylindrical specimens were prepared with a nominal diameter of 150 mm and thickness of 60 mm, consistent with the dimensional configuration contemplated in AASHTO T 324. After fabrication, the samples equilibrated to ambient temperature before receiving the requisite cuts for their paired installation within the moulds of the Hamburg wheel-tracking assembly.

After emplacement and secure restraint within the testing assembly, the specimens were submerged in water thermostatically maintained at 50 ± 1 °C and underwent approximately 45 minutes of preconditioning.

As depicted in Figures 3(a) and 3(b), a steel tracking wheel with a diameter of 203.2 mm and a transverse width of 47 mm traversed the exposed sample surfaces repeatedly while imposing a vertical force of 703 ± 4.5 N, equivalent to approximately 71.6 ± 0.45 kgf.

Traversal proceeded at 52 ± 2 wheel passes per minute, with continuation permitted until 20,000 passages or the predefined termination condition, whichever occurred first. Throughout the procedure, the instrumentation shown in Figure 3(c) intermittently quantified the developing rut depth in millimetres (mm), enabling assessment of cumulative irreversible deformation and direct comparison of cold asphalt performance across the investigated compaction energy levels.

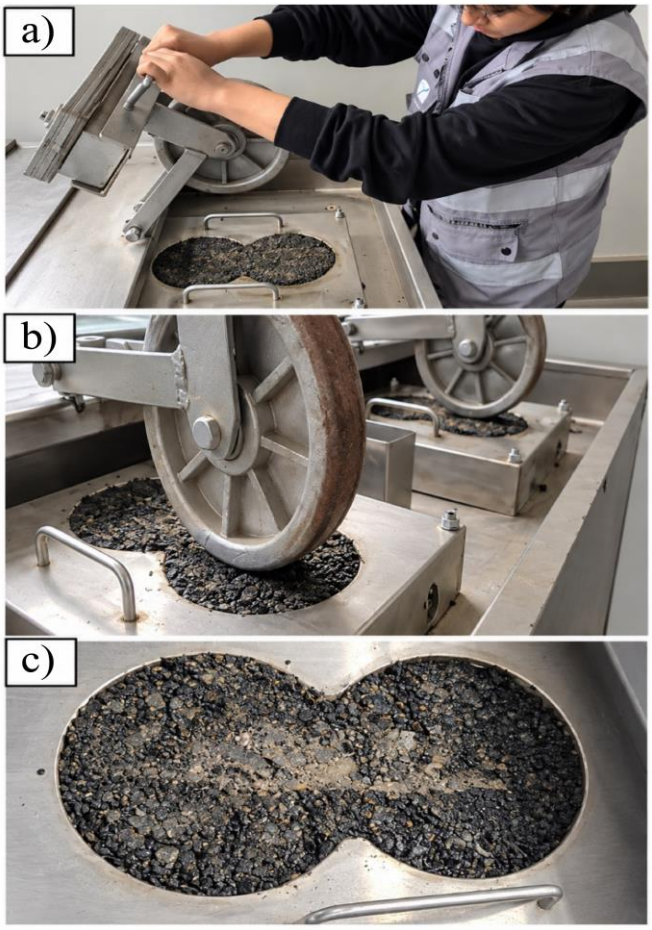

Fig. 3 Hamburg wheel test procedure

3. Results

3.1. Marshall Test

3.1.1. Volumetric Properties of the Asphalt Mixture

Table 2 collates the volumetric indices of the commercially pre-mixed cold asphalt material consolidated through 35, 50 and 75 blows per specimen face. Calculations indicate an orderly rise in compacted-mixture bulk specific gravity (Gmb), advancing from 2.270 to 2.370, whereas maximum theoretical specific gravity (Gmm) remained invariant at 2.470. This divergence accords with progressively more effective densification under greater compaction energy, producing a more tightly assembled aggregate-binder matrix with proportionately less unoccupied internal space.

Table 2. Volumetric properties of the asphalt mixture according to compaction level

Parameter	35 blows	50 blows	75 blows
Gmb	2.270	2.330	2.370
Gmm	2.470	2.470	2.470
Air voids (Va) (%)	8.10	5.67	4.05
VMA (%)	20.05	17.94	16.52
VFA (%)	59.59	68.40	75.49

With respect to entrained air voids (Va), recorded values declined successively to 8.10%, 5.67% and 4.05% for 35, 50

and 75 blows, respectively, constituting a net decrease of 4.05 percentage points from the least to the most intensive compaction condition. The voids in mineral aggregate (VMA) underwent a parallel diminution, from 20.05% to 16.52%, while the proportion of voids filled with asphalt (VFA) rose from 59.59% to 75.49%.

3.1.2. Marshall Stability

The Marshall stability measurements tabulated in Table 3 correspond to cold asphalt specimens receiving 35, 50 or 75 impacts per face, intensities respectively associated, for comparative purposes, with light, medium and heavy vehicular traffic. Four independently prepared specimens were scrutinised at every compaction energy setting, facilitating examination of the mixture's mechanical load-bearing response under the three designated consolidation regimes.

Under the light-traffic representation of 35 blows per face, the four measured stability responses amounted to 556.15, 559.65, 561.05 and 554.45 kgf. Their restricted dispersion attested to reasonably reproducible mechanical behaviour during Marshall loading. The group attained a mean stability of approximately 557.83 kgf, materially surpassing the 226.38 Kg.f minimum comparative threshold stipulated for dense-graded cold asphalt mixtures in Peru's EG-2013 provisions.

Although this regime involved the least compaction energy, repeated rammer impacts nevertheless brought aggregate surfaces and the bituminous binder into more intimate contact, establishing a load-transmitting internal framework. Its comparatively elevated air void content, however, left the resulting structure less consolidated than those prepared at higher intensities, thereby contributing to the lower stability values manifested under the same loading procedure.

At the intermediate consolidation setting of 50 blows per face, corresponding to medium traffic, the four stability determinations were 678.25, 672.95, 674.85 and 681.05 kgf, giving a mean response of approximately 676.78 kgf. This appreciable enhancement over the light-traffic group coincided with the additional compaction energy imparted during specimen preparation.

Successively applied impacts encouraged more closely packed aggregate configurations, augmented overall mixture density and diminished entrapped air voids. Consequently, closer interparticle proximity and more effective interactions throughout the aggregate-binder network reinforced its capacity to withstand the imposed Marshall load. The resulting response thus evidenced an increment in load-carrying efficacy within the specified experimental compaction conditions.

In the heavy-traffic reference condition, specimens receiving 75 blows per face registered Marshall stability values of 845.15, 851.35, 844.65 and 849.75 kgf, equivalent to a mean of approximately 847.73 kgf. These represented the maximum stability measurements among all three consolidation regimes.

Their superiority was principally associated with the more substantial compaction energy introduced during preparation, which favoured closer aggregate packing, stronger intergranular contact and a reduced prevalence of air voids. Such structural refinements plausibly increased frictional engagement and aggregate interlocking, thereby contributing to the greater resistance recorded under Marshall loading.

Table 3. Marshall stability results at different compaction levels

Specimen	35 blows (kgf)	50 blows (kgf)	75 blows (kgf)
1	556.15	678.25	845.15
2	559.65	672.95	844.65
3	561.05	674.85	851.35
4	554.45	681.05	849.75

Figure 4 delineates the progressive evolution of Marshall stability for the cold asphalt mixture across the light-, medium- and heavy-traffic reference categories, showing a consistent upward tendency with increasingly intensive compaction energy. Under the light-traffic regime, the mean of approximately 557.83 kg-f exceeds the minimum prescribed comparative threshold, implying sufficient resistance to the relatively modest loads associated with this category.

At the intermediate setting, application of additional compaction energy raises mean stability to approximately 676.78 kg-f, a development plausibly attributable to more effective aggregate rearrangement, diminished intergranular voids and increased particulate contact. The tendency becomes still more pronounced at 75 blows, associated with heavy traffic, where stability approaches 847.73 kg-f. At this intensity, the denser constituent framework favours frictional mobilisation among aggregate particles and improved interaction with the asphalt binder.

Considered collectively, the graphic establishes that successive increments in compaction energy correspond to greater pre-deformation load resistance, with all three experimentally observed responses meeting the adopted Marshall stability criterion.

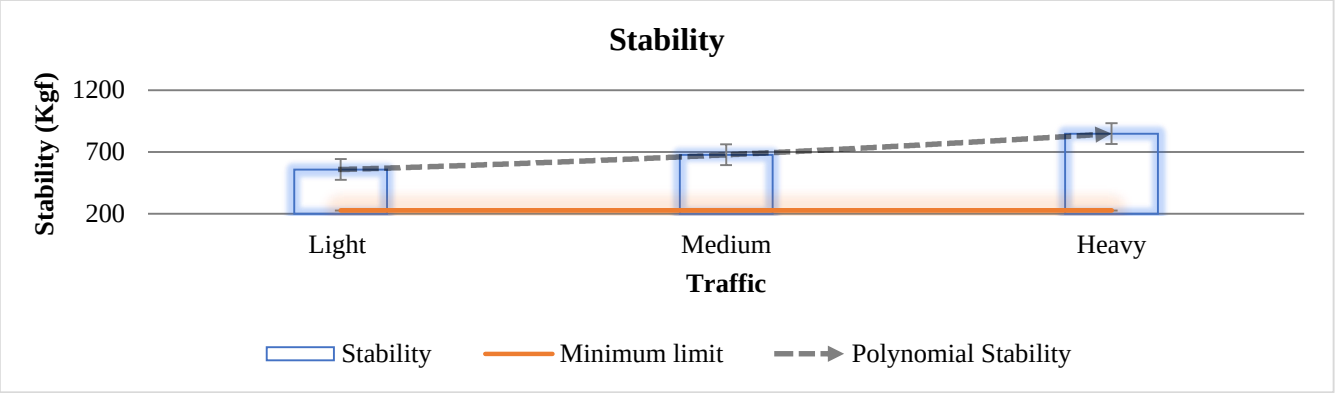

Fig. 4 Assessment of stability based on traffic levels

3.1.3. Marshall Flow Test Results

Table 4 compiles Marshall flow determinations for the commercial cold asphalt mixture subjected to 35, 50 and 75 impacts per face, representing the light-, medium- and heavy-traffic comparison groups; four specimens were examined under each compaction energy condition. For light traffic, flow measurements ranged between 2.58 and 2.78 mm, with a mean of 2.69 mm, denoting relatively uniform displacement associated with greater air void content and comparatively modest Marshall stability. At 50 blows, recorded flow lay between 2.88 and 2.97 mm and averaged 2.93 mm, consistent with increased deformability accompanied by improved stability, closer aggregate contact and enhanced densification. Under the 75-blow condition, flow values ranged from 3.09 to 3.15 mm, yielding a mean of 3.13 mm alongside the highest observed stability and density. Thus, although the flow response increased with compaction energy, every group mean remained inside the 2-4 mm reference interval adopted for the investigation.

Table 4. Marshall flow results at different compaction levels

Specimen	35 blows (mm)	50 blows (mm)	75 blows (mm)
1	2.58	2.88	3.12
2	2.75	2.97	3.09
3	2.78	2.91	3.15
4	2.66	2.96	3.14

Figure 5 depicts the variation of Marshall flow in cold asphalt specimens representing light, medium and heavy traffic, and discloses a systematic increase in displacement at peak loading as the number of consolidation blows rises.

With 35 blows, the mixture attained a mean flow of approximately 2.69 mm, consistent with moderate, bounded deformation under applied force and compliance with the comparative Marshall flow interval.

Introducing 50 blows increased the average to 2.93 mm; this response was attributed to more homogeneous binder distribution and closer aggregate juxtaposition promoted by the greater compaction energy.

At the maximum consolidation intensity of 75 blows, mean flow reached approximately 3.13 mm, indicating an increased capacity to accommodate deformation before peak-load failure and thereby dissipate the effects of repeated heavier vehicular actions more effectively.

Despite this increment, all observed means remained bounded by the admissible 2 mm to 4 mm interval. This concordance suggests an experimentally favourable compromise between mechanical load resistance and deformational adaptability, both relevant to pavement performance across contrasting traffic intensities.

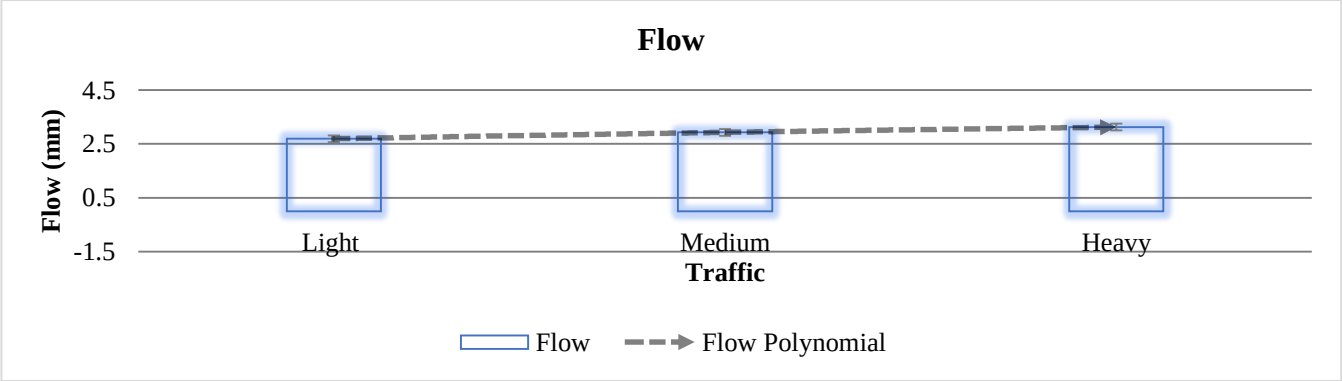

Fig. 5 Assessment of flow as a function of traffic levels

The calculated volumetric characteristics in Table 2 correspond closely with the mechanical response documented through Marshall experimentation. Between the 35- and 75-blow conditions, air void content contracted from 8.10% to 4.05% and compacted-mixture bulk specific gravity increased from 2.270 to 2.370; during the same progression, Marshall stability advanced from 557.83 to 847.73 kgf and Marshall flow rose from 2.69 to 3.13 mm. These concurrent changes suggest that enhanced aggregate-binder densification strengthened resistance to the imposed peak load, albeit with an accompanying increase in displacement at that loading point. Joint consideration of density-related indices, stability and flow thus affords a more discriminating interpretation of how compaction energy conditions the mechanical response of this cold asphalt composition.

3.2. Results of the Wear Test (UCL or Cantabrian)

3.2.1. Light Traffic

Figure 6 presents the Cantabro or UCL abrasion outcomes obtained for the cold-mix asphalt under the experimental conditions associated with light traffic. Four discrete briquettes were prepared for this assessment, and their recorded initial masses (P1) occupied the narrow interval between 1050.30 g and 1051.03 g, substantiating a high degree of consistency during specimen fabrication.

Each specimen was subsequently introduced independently into the Los Angeles abrasion apparatus, without the addition of metallic spheres, and exposed to 300 complete drum revolutions. Following mechanical conditioning, the residual masses (P2) were measured between 951.75 g and 977.77 g, directly evidencing material attrition induced by the repeated rotational action.

The resulting mass-loss percentages equalled 7.64% for specimen M-01, 9.40% for M-02, 6.97% for M-03 and 7.73% for M-04. Of the evaluated samples, M-02 underwent the most pronounced attrition (9.40%), revealing comparatively weaker resistance to particle separation, whereas M-03 sustained the smallest loss (6.97%), implying relatively stronger internal cohesion.

The dispersion from 6.97% to 9.40% can be associated with specimen-level variations in internal cohesion, which in turn reflect the spatial distribution of bituminous binder, the efficacy of aggregate-to-binder adhesion and the extent of achieved consolidation. An elevated abrasion-loss percentage accordingly signals diminished resistance to disaggregation under mechanically imposed traffic-like actions, attributable to weaker constituent interconnection.

Viewed in aggregate, the outcomes indicate comparatively homogeneous, reproducible behaviour of the cold asphalt formulation, with the measured attrition rates suggesting adequate service-related resistance for the light-traffic reference condition.

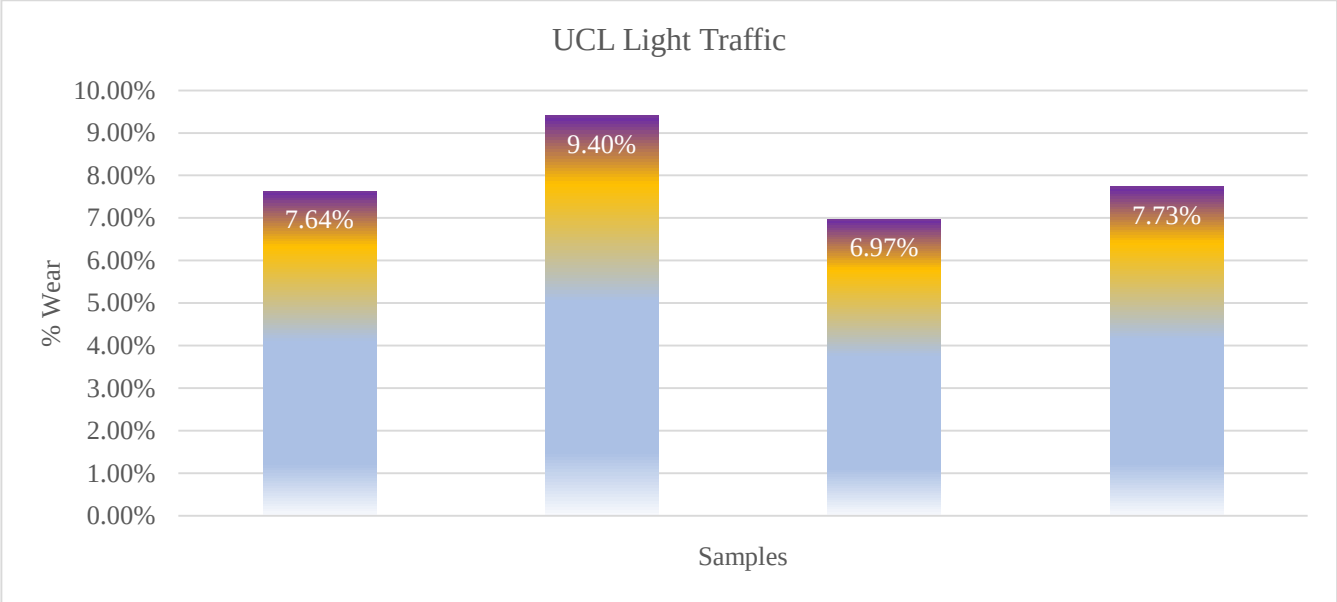

Fig. 6 Final particle loss percentages obtained from the Cantabro test (UCL) at 35 blows per face (light traffic)

3.2.2. Medium Traffic

The Cantabro (UCL) measurements depicted in Figure 7 characterise the extent of aggregate detachment for cold-mix asphalt consolidated under the conditions designated for medium traffic. Four replicate specimens were fabricated for this determination; their pre-test masses (P1), between 1050.34 g and 1051.11 g, occupied a notably confined interval and consequently corroborated the uniformity of specimen preparation. Thereafter, each test piece was loaded separately into the Los Angeles abrasion drum without steel spheres and subjected to 300 successive revolutions. The masses retained at test completion (P2) ranged from 982.64 g to 998.85 g,

demonstrating the magnitude of constituent material detached through the stipulated mechanical abrasion procedure.Measured abrasion loss was 6.49% in specimen M-05, 4.93% in M-06, 5.83% in M-07 and 5.65% in M-08. The greatest percentage was therefore associated with M-05 (6.49%), whereas M-06 exhibited the smallest (4.93%), evidencing its comparatively superior capacity to resist granular disintegration. The obtained results occupied a 4.93% to 6.49% interval, lying below the corresponding attrition percentages observed for the light-traffic specimens. This distinction denotes more substantial mixture cohesion and mechanical stability when exposed to the Cantabro abrasion sequence. The response is consistent with stronger physicomechanical interaction between mineral aggregates and asphalt binder under more effective consolidation, which restricts the detachment of constituent particles.

Taken together, these observations substantiate a coherent performance profile for the cold asphalt formulation, with comparatively limited aggregate loss supporting its suitability under the experimental conditions representative of medium traffic.

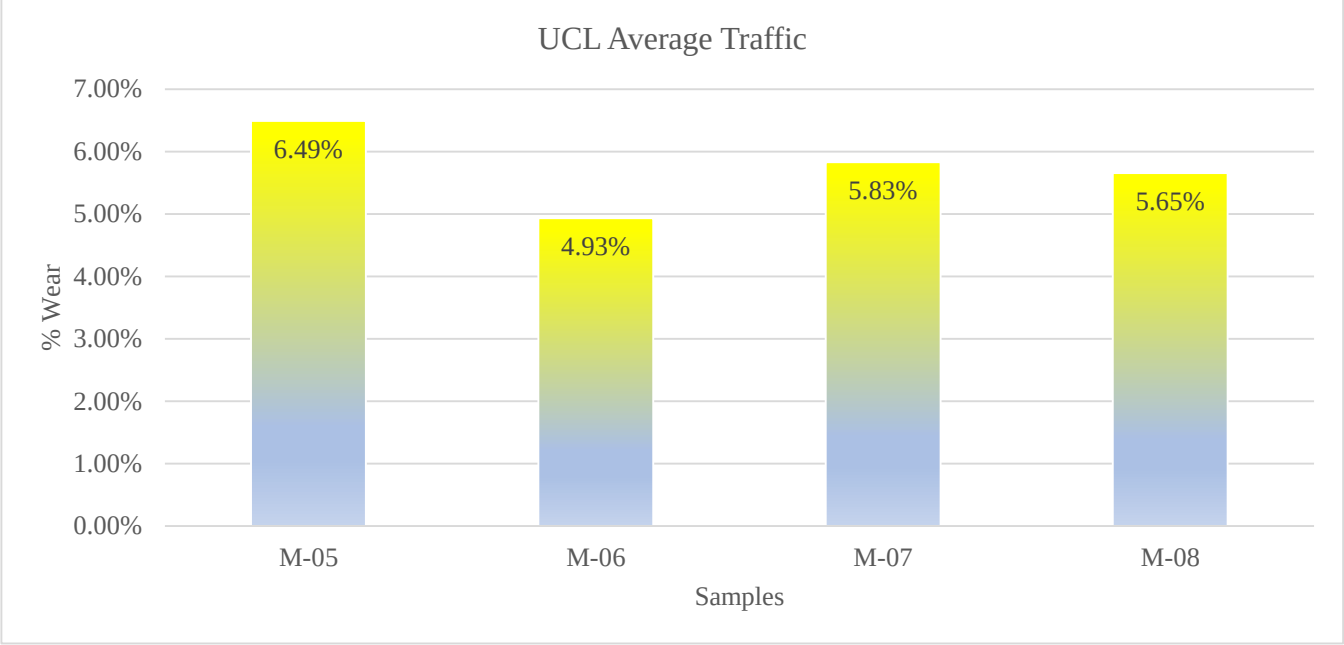

Fig. 7 Final particle loss percentages obtained from the Cantabro test (UCL) at 50 blows per face (medium traffic)

3.2.3. Heavy Traffic

Figure 8 documents the development of Cantabro (UCL) abrasion loss for the cold-mix asphalt under the consolidation regime assigned to heavy traffic. Four specimens received 75 compacting impacts and exhibited closely clustered initial masses (P1), between 1050.18 g and 1051.37 g, reaffirming consistency in the experimental preparation and initial specimen dimensions.

Subsequently, the individual specimens underwent 300 complete revolutions within the Los Angeles abrasion apparatus in the absence of metallic spheres. Final post-test mass determinations (P2) ranged from 994.87 g to 1001.33 g, with the measured diminution attributable to the imposed rotational mechanical action and concomitant particle detachment.

Abrasion-loss percentages were 4.79% for sample M-09, 4.76% for M-10, 5.27% for M-11 and 4.90% for M-12. Specimen M-11 thus sustained the maximum recorded attrition (5.27%), while M-10 yielded the minimum (4.76%), corresponding to the greatest resistance to particle disaggregation among the four samples.

The notably constrained range of 4.76% to 5.27% corroborates the superior resistance to aggregate loss attained at the compaction energy level employed as a heavy-traffic reference. These values also remained below the analogous measurements for both light and medium traffic, signifying improved internal coherence and stability of the cold asphalt mixture even under the more intensive specimen preparation conditions. This response is attributable, in the context of the present tests, to the additional 75-blow consolidation, which promotes more intimate contact and adhesion between aggregate surfaces and their bituminous binder, thereby limiting mechanically generated material loss.

Collectively, the findings disclose both restricted particulate attrition and relatively consistent specimen performance, demonstrating the mixture's comparatively greater resistance to disintegration at the 75-blow compaction energy level employed to represent heavy traffic.

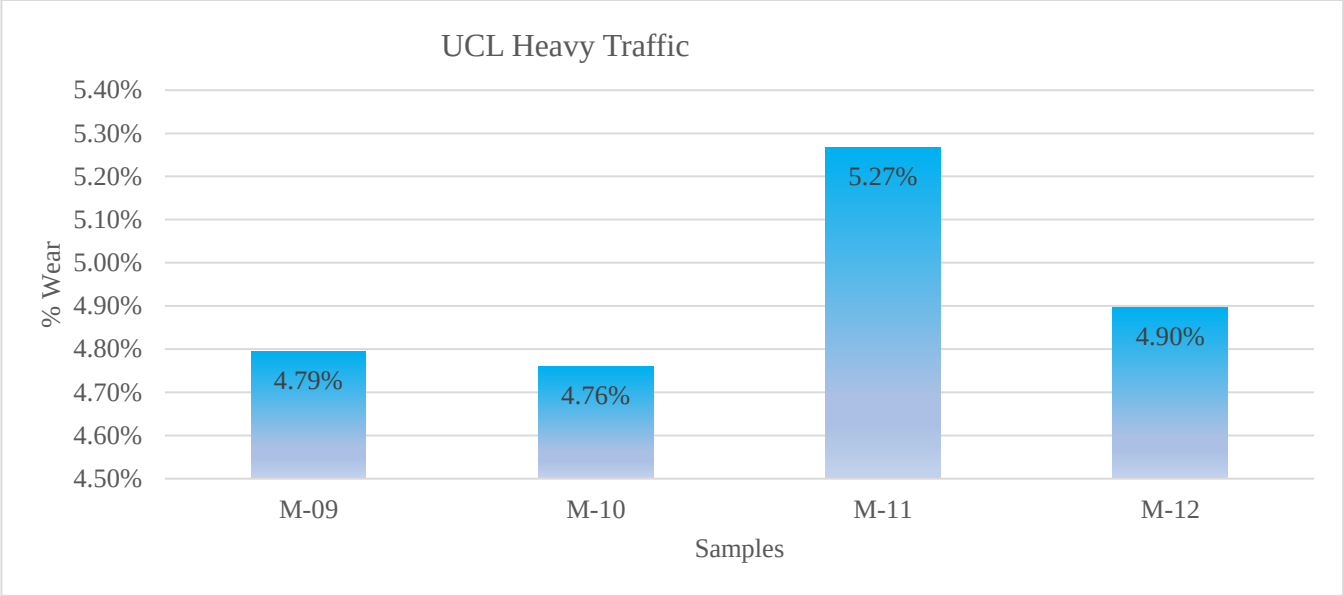

Fig. 8 Final particle loss percentages obtained from the Cantabro test (UCL) at 75 blows per face (heavy traffic)

A consolidated synthesis of the Cantabro (UCL) findings is provided below and graphically portrayed in Figure 9, thereby facilitating comparative interpretation of abrasion-loss tendencies across traffic classifications and the corresponding intensities of compaction energy applied.

Group-average material-loss percentages amounted to 7.93% for light traffic, 5.73% for medium traffic and 4.93% for heavy traffic. This ordered progression delineates a sustained diminution in abrasion susceptibility as the investigated compaction energy intensity increases.

Such behaviour corroborates the proposition that additional hammer impacts generate a more densely integrated mineral-binder framework, strengthening intergranular cohesion within the cold-mix asphalt and enhancing adhesive engagement between aggregate surfaces and the asphalt binder. Accordingly, detachment of material during repeated abrasion becomes progressively less pronounced.

The most favourable abrasion response was consequently associated with the heavy-traffic consolidation regime, for which the smallest particle-loss measurements occurred; conversely, the least intensive light-traffic treatment displayed greater vulnerability to disaggregation. This demonstrable association between applied compaction energy and material-retention capacity accentuates the necessity of stringent construction-process control if the mixture is to achieve the intended level of in-service performance.

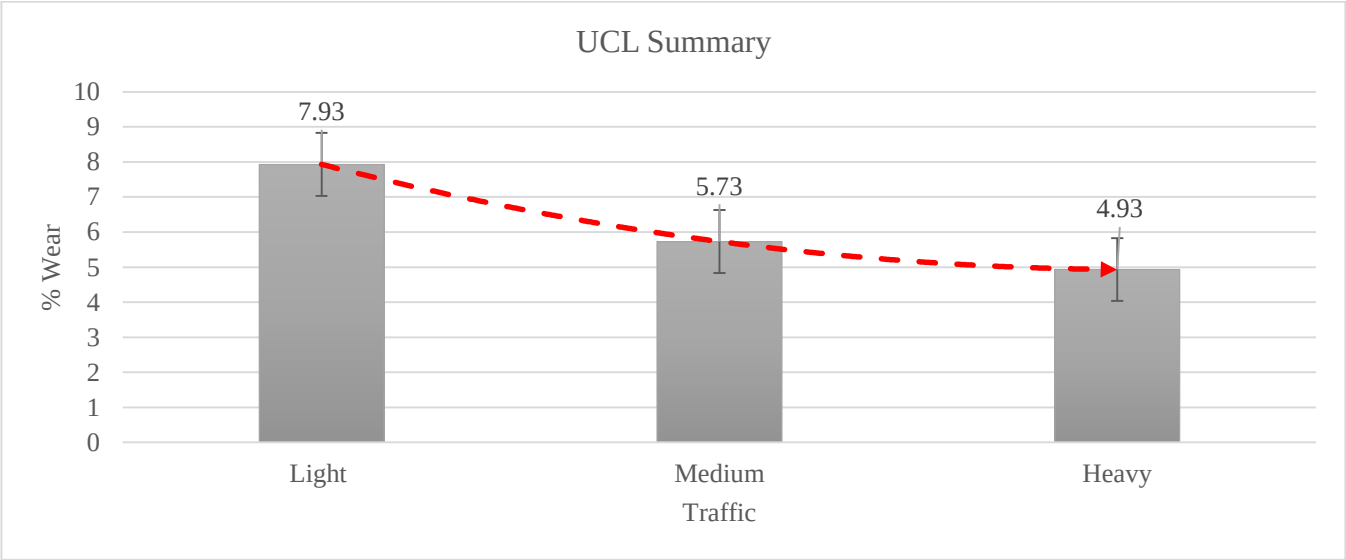

Fig. 9 Average percentage of wear (UCL test) in cold-mix asphalt mixtures for light, medium and heavy traffic

3.3. Rutting

3.3.1. Light Traffic

The permanent-deformation response of the light-traffic specimen, assessed using the Hamburg wheel-tracking apparatus, is displayed in Figure 10. The commercially pre-mixed cold asphalt test piece underwent Marshall consolidation with 35 blows on each face in conformity with the preparation conditions designated for this experimental traffic category.

Wheel tracking proceeded through 20,000 repeated passages while the conditioning temperature was held at 50 °C and the maximum admissible rut depth was set at 10 mm. These combined parameters constitute a demanding experimental framework for examining susceptibility to irreversible surface deformation, given the temperature-induced softening of bituminous binder and the cumulative effect of repeatedly imposed wheel loads.

The deformation trajectory registered beneath the first tracking wheel remained below the designated limit, indicating a comparatively stable mechanical response. This performance was attributed to the consolidation effected by 35 blows per specimen face, which improved the internal density of the granular matrix, curtailed aggregate mobility and augmented resistance to lateral particulate displacement under applied loading.

The corresponding deformation history beneath the second tracking wheel is illustrated in Figure 11 under otherwise identical conditions. Close correspondence between the two plotted rutting trajectories corroborates specimen-level structural uniformity and a reproducible mechanical response, consistent with satisfactory binder distribution and cohesive interactions between the mineral aggregates and bituminous phase.

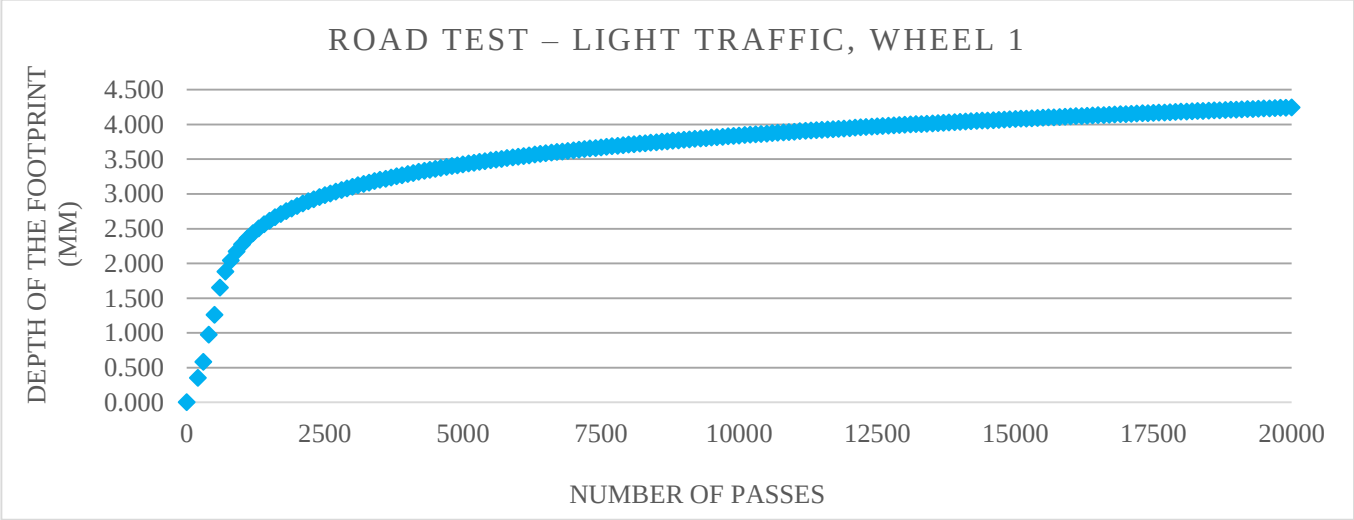

Fig. 10 Changes in rutting depth in the rutting test for cold mix asphalt under light traffic – wheel 1

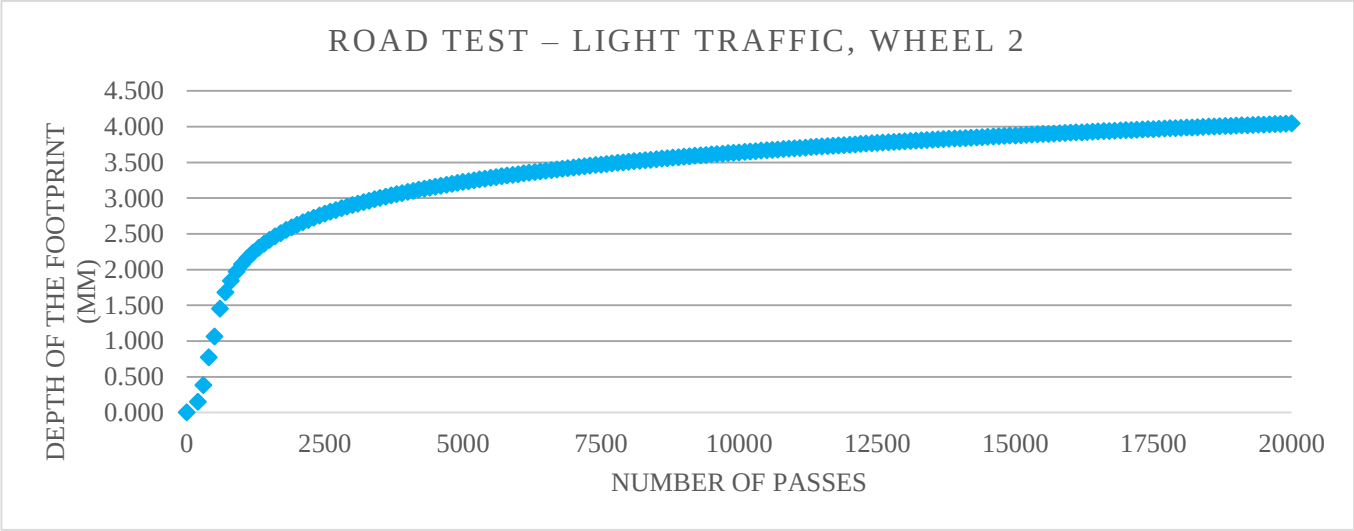

Fig. 11 Development of rutting depth in the rutting test for cold-mix asphalt under light traffic – wheel 2

3.3.2. Average Traffic

Figure 12 delineates the Hamburg wheel-tracking deformation response of a pre-mixed cold asphalt specimen prepared under the medium-traffic reference regime. The cylindrical test piece received 50 Marshall hammer impacts on each face in accordance with the established experimental procedure, producing a greater level of densification than that associated with the light-traffic specimens.

Testing comprised 20,000 wheel-loading cycles at a maintained temperature of 50 °C, with a permissible maximum surface deformation of 10 mm. The investigated specimens additionally had a diameter of 150 mm and a height of 60 mm, geometrical dimensions indicated for this evaluation. Together, these operating parameters reproduce repeated loading under thermally demanding conditions, in which the asphalt mixture may exhibit heightened susceptibility to accumulating permanent deformation.

The displacement recorded in the first wheel track was smaller than its light-traffic counterpart, a distinction ascribed to the more intensive consolidation achieved by 50 blows per face. This increment in compaction energy fostered a tighter particle framework, a smaller volume fraction of voids and enhanced stability of the mineral aggregate skeleton, thereby constraining interparticle migration beneath successive wheel loads.

Figure 13 provides the companion deformation trajectory registered beneath the second Hamburg tracking wheel in the same medium-traffic testing configuration. The substantial similarity of the paired curves attests to consistent structural behaviour, supporting the interpretation that binder dispersion remained satisfactory and the constituent aggregate-binder network responded comparably to repetitive loading and thermal conditioning.

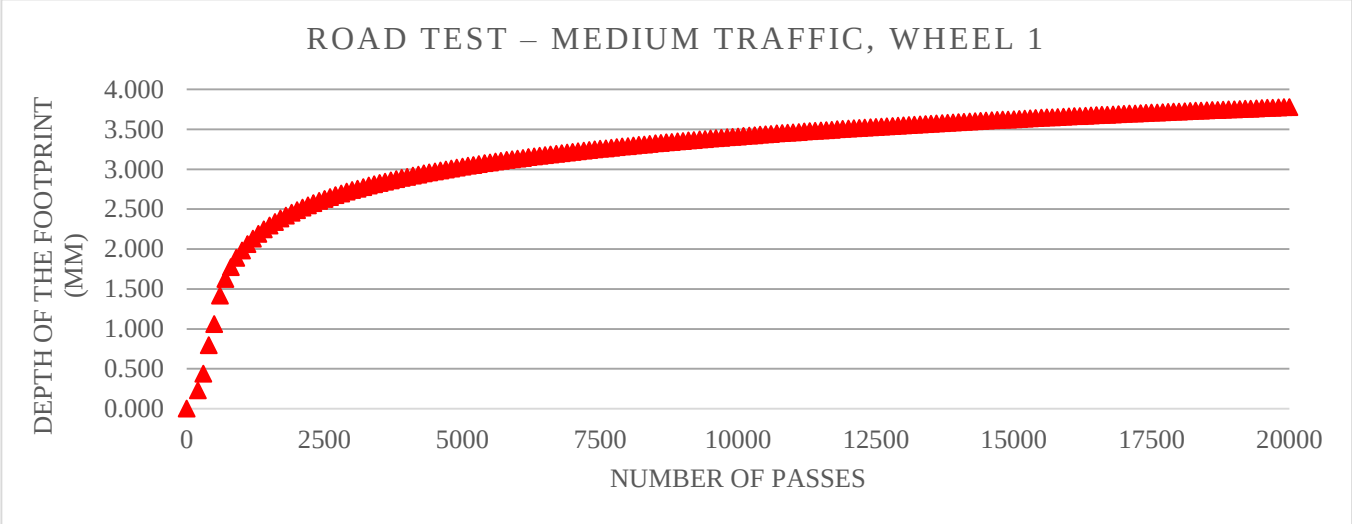

Fig. 12 Development of rutting depth in the rutting test for cold-mix asphalt under medium traffic – wheel 1

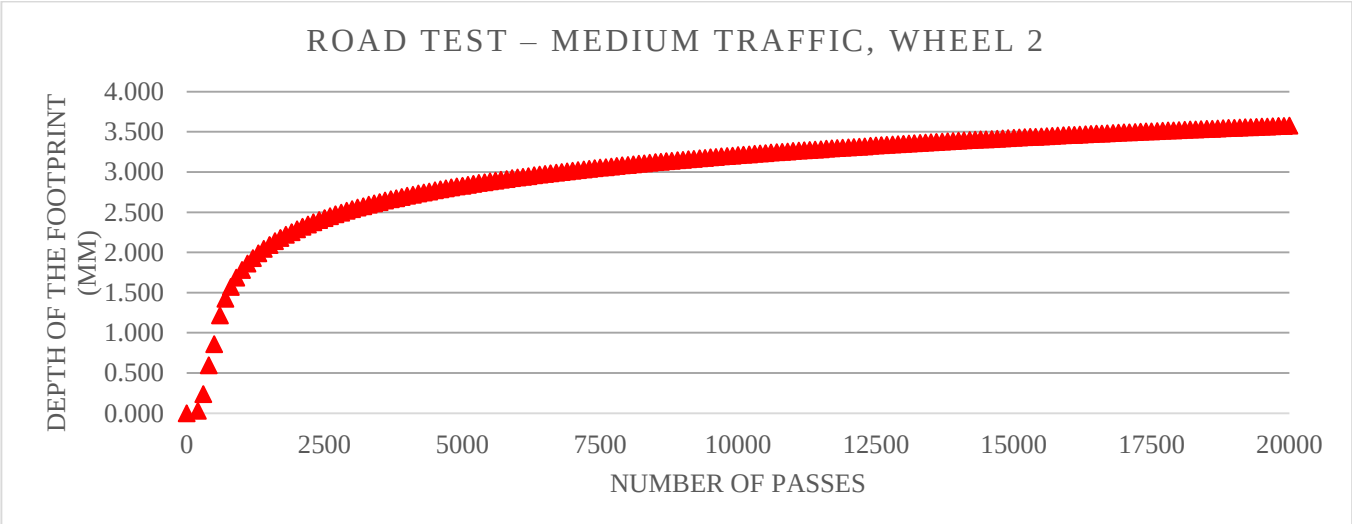

Fig. 13 Development of rutting depth in the rutting test for cold-mix asphalt under medium traffic – wheel 2

3.3.3. Heavy Traffic

Figures 14 and 15 portray the progression of permanent surface deformation in cold asphalt specimens associated with the heavy-traffic regime and consolidated by 75 blows on each face. Both tracking wheels initially generated a comparatively steep increase in rut depth, after which the incremental deformation rate abated progressively. At the completion of 20,000 wheel passages, rut depths approximated 3.10 mm for wheel 1 and 3.30 mm for wheel 2, leaving a relatively modest interwheel disparity of 0.20 mm. This close agreement indicates reproducible performance under sustained loading, while the limited terminal deformation reflects favourable resistance to wheel-induced rut accumulation. The results thereby underscore the advantageous mechanical response of the particular mixture at the greatest compaction energy investigated.

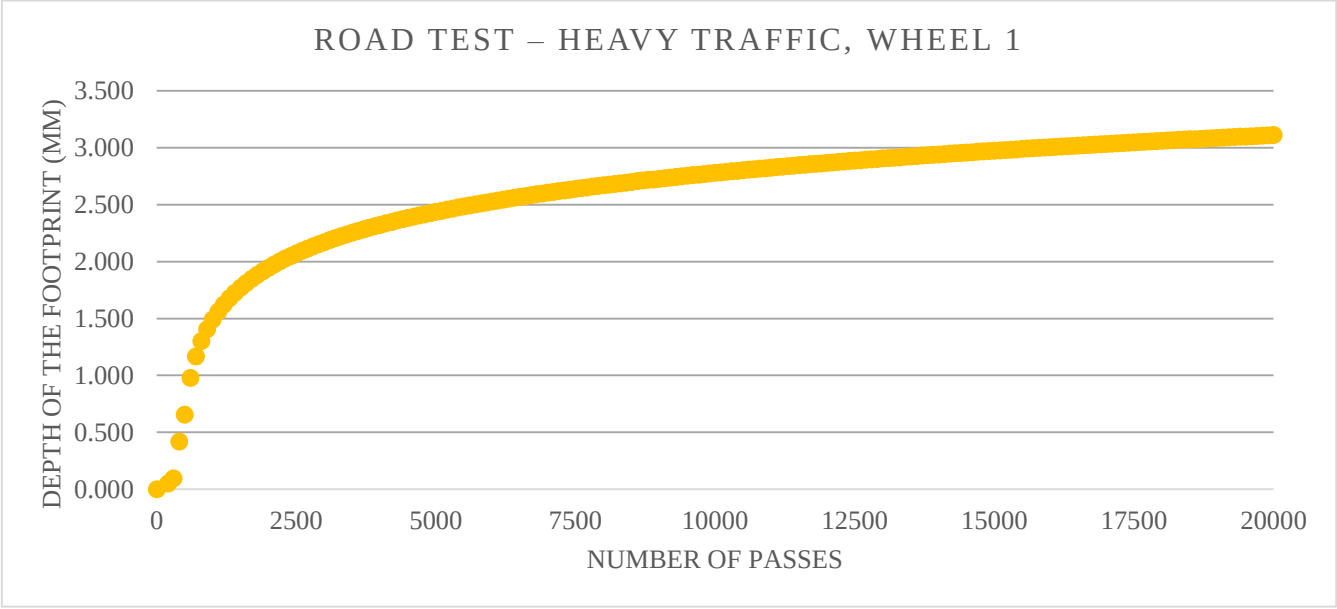

Fig. 14 Development of rutting depth in the rutting test for cold-mix asphalt under heavy traffic – wheel 1

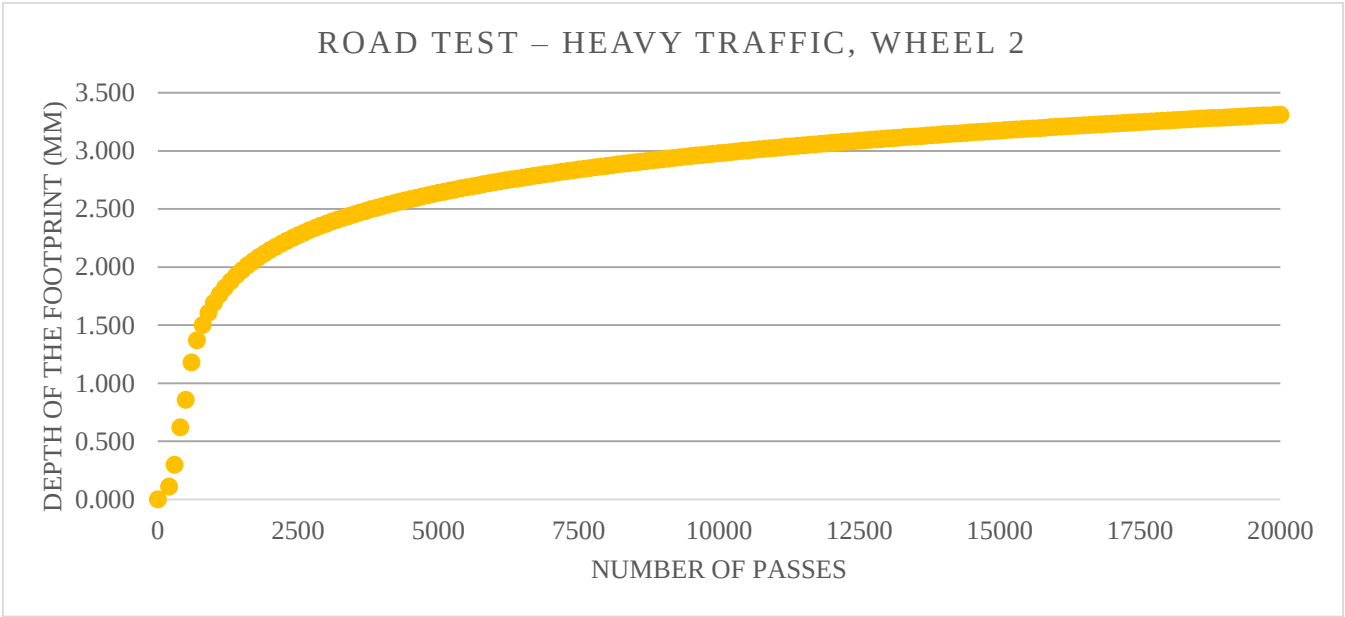

Fig. 15 Development of rutting depth in the rutting test for cold-mix asphalt under heavy traffic – wheel 2

Figure 16 juxtaposes Hamburg rutting responses for cold asphalt mixtures subjected to the three prescribed compaction energy intensities of 35, 50 and 75 blows per specimen face, provisionally representing light (sky blue), medium (red) and heavy traffic (yellow). Following 20,000 loading passages, the respective rut depths were approximately 4.13, 3.70 and 3.20 mm, demonstrating successively diminished residual deformation with greater consolidation. Relative to the light-

traffic reference specimen, the 75-blow mixture manifested approximately 22.5% less accumulated rutting. Each response curve was distinguished by a pronounced early-stage increase followed by a progressive attenuation of the incremental rutting rate. Taken together, the evidence suggests that enhanced compaction energy bolstered resistance to irreversible displacement, plausibly through more effective aggregate interlocking and reduction of entrained air voids.

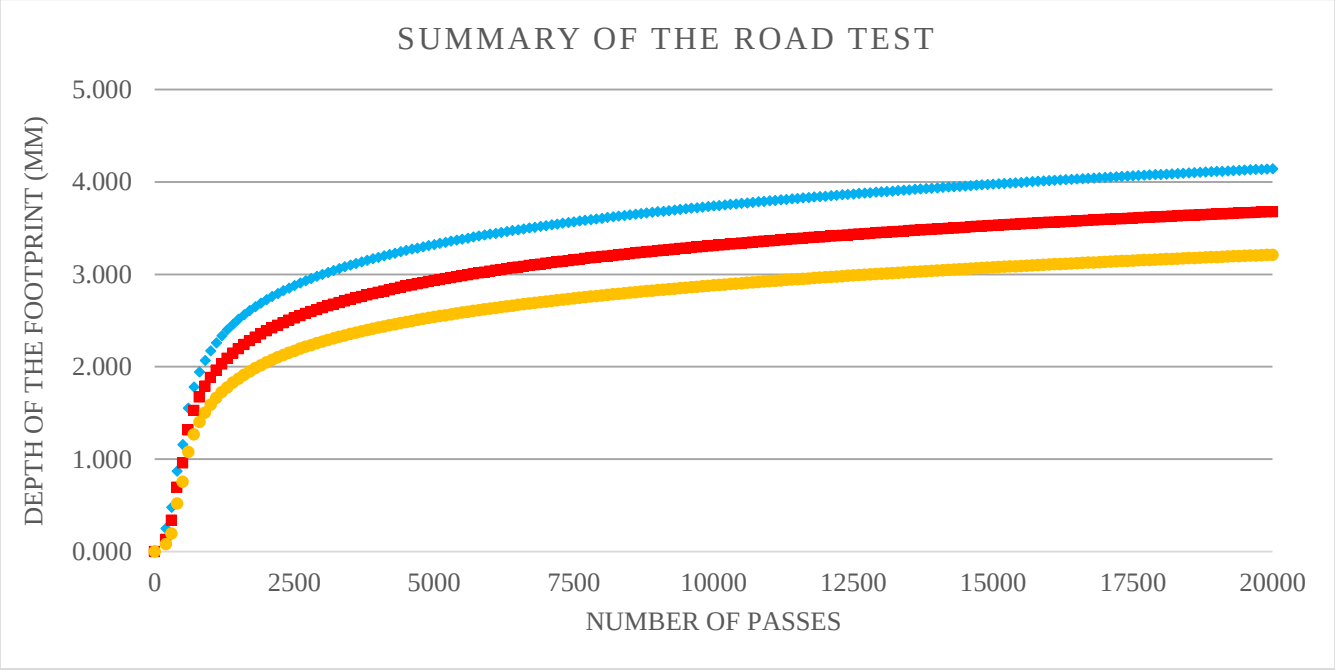

Fig. 16 Summary of the rutting test (Hamburg) on cold-mix asphalt based on traffic volume

3.4. Statistical Analysis

The descriptive statistics assembled in Table 5 encompass Marshall stability, Marshall flow and Cantabro particle loss (UCL) measured at 35, 50 and 75 blows per face, with four replicate samples contributing to every experimental group. Mean Marshall stability increased from 557.83 to 847.73 kgf, while standard deviations ranged from 3.05 to 3.60 kgf and the corresponding Coefficients of Variation (CV) remained below 0.55%, denoting limited interspecimen dispersion. In parallel, mean Marshall flow rose from 2.693 to 3.125 mm, accompanied by a decline in CV from 3.37% to 0.85%. Cantabro material loss exhibited the opposing pattern, decreasing from 7.935% to 4.930%, while its CV contracted from 13.03% to 4.76%. These convergent observations associate increased compaction energy with superior stability, greater flow at peak load, diminished particle disintegration and generally more reproducible measured outcomes.

Table 5. Descriptive statistics of experimental results

Test	Compaction Level	Mean	Standard Deviation (SD)	CV (%)
Marshall stability (kgf)	35 blows	557.83	3.05	0.55
	50 blows	676.78	3.60	0.53
	75 blows	847.73	3.33	0.39
Marshall flow (mm)	35 blows	2.693	0.091	3.37
	50 blows	2.930	0.042	1.45
	75 blows	3.125	0.026	0.85
Cantabro particle loss (UCL, %)	35 blows	7.935	1.034	13.03
	50 blows	5.725	0.641	11.20
	75 blows	4.930	0.235	4.76

Table 6 summarises the one-way Analysis of Variance (ANOVA) applied to Marshall stability, Marshall flow and Cantabro particle loss (UCL). For all three response variables, the compaction groups displayed statistically significant overall differences, with $F(2,9)$ values of 7641.65, 52.49 and 18.95, respectively, and $p < 0.001$. In aggregate, the inferential evidence associates increasing compaction energy with heightened Marshall stability and flow and reduced Cantabro

particle loss, consistent with greater resistance to constituent disintegration. It consequently confirms an appreciable influence of the consolidation regime upon the mixture's mechanical response.

Table 6. One-way ANOVA results for Marshall stability, Marshall flow, and Cantabro particle loss (UCL).

Evaluated property	SS	df	MS	F	p
Marshall stability	169886.6867	2	84943.3433	7641.65	<0.001
Marshall flow	0.375317	2	0.187658	52.49	<0.001
Cantabro particle loss (UCL)	19.394867	2	9.697433	18.95	0.000594

Note: SS = between-group sum of squares; df = degrees of freedom; MS = between-group mean square; F = Fisher's F-statistic; p = significance level.

4. Discussion

Within the Indonesian context, Wulandari and Tjandra [14] investigated how compaction energy and aggregate grading condition the response of cold-mix asphalt, evaluating both densely and openly graded assemblages, binder proportions between 5% and 7.5%, and consolidation regimes of 50, 75 and 2 × 75 blows. Their measurements indicated that openly graded mixtures could surpass 800 kg in Marshall stability when subjected to pronounced consolidation; nevertheless, after 75 blows, their air void fractions remained above 15% because of the inherent geometrical disposition of the aggregate framework. They further documented that excessive compactive effort could sharply elevate the Marshall Quotient, reflecting increased mixture rigidity. The present findings accord with those observations regarding the favourable effect of compaction energy upon Marshall stability, which rose from 557.83 to 847.73 kgf as the number of impacts advanced from 35 to 75 per face, an approximate improvement of 52%. Simultaneously, the measured air void proportion contracted from 8.10% to 4.05% and Cantabro particle loss declined from 7.94% to 4.93%. A notable divergence nevertheless arose in volumetric evolution: the Indonesian open-graded systems preserved appreciable air void volumes despite intensive compaction, whereas the MAC-2 commercial formulation investigated here exhibited sustained reductions. Accordingly, the comparison establishes that aggregate gradation, as well as applied compaction energy, governs the volumetric arrangement and mechanical resistance of asphalt composites.

Research conducted in Spain by Flores et al. [15] examined the ramifications of modified Proctor versus gyratory compaction for the volumetric constitution of emulsion-based cold-recycled asphalt mixtures, considering premixing water and emulsion contents spanning 1% to 4%. Their experimental results disclosed greater bulk density after gyratory consolidation than after the modified Proctor procedure, with maximum densification favoured by a formulation incorporating 3% water and 3% emulsion. Importantly, the smallest air void percentage did not invariably coincide with maximum bulk density, owing to variations in theoretical maximum specific gravity related to emulsion concentration. The current results concur with the authors' identification of the decisive role of consolidation conditions in shaping mixture volumetrics: compacted-mixture bulk specific gravity rose from 2.270 to 2.370 and air void content diminished from 8.10% to 4.05% as the compactive treatment increased from 35 to 75 blows per face. However, whereas the Spanish investigation documented interacting influences of water dosage, emulsion concentration and consolidation methodology, the differences established here stemmed from modifying compaction energy while retaining one unaltered commercial formulation. Because aggregate proportions and binder composition remained intentionally unchanged, the measured differences can be considered in relation to the varying compactive treatment rather than to intentional modifications of the supplied formulation. This distinction permits densification to be interpreted within each material's particular preparation regime, without incorrectly treating bulk density and void content as interchangeable indices.

In China, Yang et al. [17] appraised cold-recycled asphalt composites formulated with bituminous emulsion and cement additions of 0%, 1% and 2%, using 50-blow, 75-blow and sequential double-compaction procedures. Their programme also contrasted a 2-day curing treatment at 60 °C with a combined regime comprising 3 days at 20 °C followed by 2 days at 60 °C. Enhanced compactive treatment diminished entrapped air voids and increased indirect tensile strength, whereas curing-related mechanical improvements depended upon the dosage of cement.

The investigation reported herein exhibits a comparable relationship between void reduction and improved material resistance: air void content decreased from 8.10% to 4.05%, Marshall stability increased from 557.83 to 847.73 kgf, and Cantabro particle loss receded from 7.94% to 4.93%. Nonetheless, the studies differ fundamentally in their binder systems. The Chinese experiments concerned recycled composites incorporating emulsion and cement, whereas the present work considered an unmodified commercial MAC-2 cold-mix asphalt with RC-250 cutback bitumen. Accordingly, the observed similarity pertains principally to the direction of changes in mechanical and volumetric indicators, rather than establishing that disparate binding agents necessarily share identical maturation kinetics, constituent interactions or long-term field behaviour. The converging results therefore support the contribution of a denser granular skeleton to compaction-associated mechanical enhancement, while reaffirming that binder chemistry and constituent selection influence the overall material response.

5. Conclusion

Firstly, the investigation established that compaction energy exerts a direct, consequential influence upon the mechanical attributes and functional service response of pre-mixed cold asphalt. Incremental increases in consolidation intensity produced favourable changes in load-bearing resistance, abrasive deterioration and susceptibility to irreversible deformation, consonant with the formulated hypothesis and the empirical results of Marshall, Cantabrian and Hamburg wheel-tracking procedures. The collective evidence consequently demonstrates that conventional cold-mix asphalt may attain advantageous technical performance provided that the compaction process is conducted under appropriately controlled conditions.

Secondly, the lowest compaction energy regime, employed as a light-traffic reference, enabled the investigated material to satisfy the minimum service criterion. Its comparatively open constituent framework, however, was more susceptible to the cumulative effects of repeated loading. Reduced density constrained the interlocking efficiency of the aggregate skeleton and attenuated stress transmission within the bituminous matrix. Accordingly, this consolidation level is primarily defensible for pavements with limited structural exigencies, particularly low-volume roads where prompt reinstatement of traffic circulation is an important practical consideration. Thirdly, specimens consolidated at the medium-traffic reference intensity exhibited a more equitable combination of load resistance and regulated deformability. Intermediate compaction energy promoted closer aggregate accommodation and more efficacious interactions between mineral particles and bituminous binder, without imparting an unduly rigid mechanical response. This condition can therefore be considered potentially appropriate for urban carriageways and other routes experiencing moderate vehicular loading, where sufficient structural capacity must coexist with the ability to tolerate controlled displacement without premature material deterioration.

Fourthly, the heavy-traffic reference setting exhibited the most advantageous response within the limits of the experimental programme, yielding greater Marshall stability, less constituent attrition and reduced vulnerability to permanent wheel-path deformation. These improvements are attributable to a more securely interlocked aggregate framework and more effective transmission of repeatedly imposed stresses between adjacent particles. Within the three consolidation intensities actually investigated, 75 blows per face accordingly represented the optimum compaction energy because it afforded the most favourable measured combination of Marshall stability, resistance to wear, mitigation of rutting and flow confined to the accepted reference limits.

Finally, compaction merits recognition as a fundamental determinant of structural efficacy and prospective longevity in commercially pre-mixed cold asphalt, rather than merely an ancillary operation during pavement construction. Nevertheless, the principal experimental constraint is the exclusive reliance on laboratory-controlled conditions and manually applied compaction, both of which may engender departures from the behaviour ultimately encountered in field installations. Future investigations should therefore corroborate the findings through full-scale pavement trials, implement more rigorous consolidation quality-control protocols and delineate thresholds beyond which additional compaction becomes detrimental, particularly through excessive brittleness or the eventual emergence of cracking during prolonged service.

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