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EFFECT OF RECLAIMED ASPHALT PAVEMENT ON LCC-BASED ROLLER-COMPACTED CONCRETE PAVEMENTS

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Abstract

The incorporation of reclaimed asphalt pavement (RAP) in roller-compacted concrete pavements (RCCP) offers significant potential for sustainable material utilisation. This study investigates the incorporation of RAP as a coarse aggregate in RCCP produced with a limestone–calcined clay (LCC) based binder comprising 50% of the total binder content, with RAP replacing natural coarse aggregates in the range of 25-100%. Within the LCC-based system, progressive RAP incorporation reduced moisture demand by approximately 2–11%, indicating a moisture-modifying effect associated with the asphalt-coated aggregate surface that partially offsets dilution associated with the elevated effective water-to-binder (w/b) ratio in the LCC-based system. Compressive strength results showed that all levels of RAP incorporation led to strength reductions at all ages; however, at early ages, the rate of strength loss relative to the LCC reference was comparatively lower, which is attributed to the reduction in effective w/b ratio counteracting part of the binder dilution effect. With advancing curing age, reduced mechanical interlock associated with RAP governed the response, leading to pronounced and sustained strength losses at higher replacement levels. At 28 days, cumulative strength losses ranged from approximately 20% to over 80% across RAP replacement levels, and only the mixture incorporating 25% RAP satisfied the commonly cited 27.6 MPa minimum compressive strength requirement for RCCP. The results show that RAP can be incorporated into LCC-based RCCP at limited replacement levels, where its moisture-reducing behaviour complements the LCC binder without compromising structural performance, while higher RAP contents remain constrained by aggregate skeleton degradation.

Keywords: roller-compacted concrete pavement, reclaimed asphalt pavement, limestone – calcined clay blend, sustainable concrete materials, green pavement

1 Introduction

Asphalt pavements dominate road infrastructure worldwide and undergo progressive deterioration under increasing traffic loads and environmental exposure, necessitating periodic rehabilitation and reconstruction. These activities generate more than 300 million tonnes of RAP annually, consisting primarily of mineral aggregates coated with aged asphalt binder, making its reuse a critical challenge in pavement engineering [1]. Although RAP is routinely reused in asphalt mixtures, its utilisation is governed by its behaviour as a reclaimed composite aggregate rather than as a fresh mineral resource [2]. Repeated recycling accelerates ageing of the asphalt coating and degradation of the underlying aggregate, producing stiffer particles with reduced bonding efficiency. Consequently, RAP contents in new asphalt layers are restricted, leading to surplus material and highlighting the need for alternative pavement applications capable of accommodating RAP at higher replacement levels without compromising structural performance. RCCP offers a promising rigid-pavement application for RAP utilisation.

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RCCP is characterised by zero-slump consistency and high aggregate content, with structural performance governed by a dense aggregate framework formed through mechanical compaction [3, 4]. Owing to this compaction-controlled behaviour, strength and stiffness development in RCCP are primarily dictated by aggregate interlock and matrix densification, rendering the system inherently suited for incorporating reclaimed aggregates whose performance is governed by particle-level interactions rather than binder flexibility [5].
In parallel, efforts to reduce the carbon footprint of RCCP have led to the adoption of LCC blends as partial replacements for ordinary Portland cement (OPC) [6, 7]. Previous studies have shown that LCC-based RCCP achieves satisfactory later-age strength; however, the finer particle characteristics of LCC increase moisture demand and raise the optimum moisture content required for compaction [6]. At a 50% OPC replacement level, LCC incorporation has been reported to increase optimum moisture content by approximately 13.5%, effectively elevating the w/b ratio under RCCP's compaction-controlled regime and contributing to reduced early-age performance [7]. In contrast to this binder-induced increase in moisture demand, RAP exhibits fundamentally different moisture-related behaviour when introduced as a coarse aggregate in RCCP. The aged asphalt coating reduces effective water absorption and inter-particle friction under vibration, enhancing lubrication within the aggregate skeleton and lowering the optimum moisture content required to achieve target density [2, 5].
Despite growing interest in RAP incorporation and LCC binders for sustainable pavement construction, their combined influence within RCCP has not been systematically examined. Existing studies typically address aggregate replacement or binder modification in isolation, although RCCP performance is governed by their coupled effects on moisture–density relationships and aggregate skeleton formation [5, 6]. When RAP and LCC are incorporated simultaneously, the reduction in moisture demand associated with RAP may partially counterbalance the effective increase in w/b ratio induced by the LCC binder, altering compaction efficiency and strength development in a non-additive manner. Accordingly, the present study investigates the combined use of RAP as a coarse aggregate replacement at levels of 25%, 50%, 75%, and 100% in an RCCP system employing a 50% LCC binder replacement and the binder content established by Butle et al. [7], with emphasis on moisture–dry density relationships and strength development.

2 Materials and methods

2.1 Materials

The materials used in this study comprised a binary binder system and natural and reclaimed aggregates. The binder consisted of OPC (53 grade, conforming to IS 12269 [8]) and a LCC composite blended in a 1:1 mass ratio. The LCC blend was prepared by intergrinding 31.67% limestone powder, 63.33% calcined clay, and 5% gypsum. The limestone exhibited a carbonate content of 91.49%, while the raw clay contained 43.47% kaolinite, satisfying the requirements of IS 18189 [9]. Detailed physical characteristics of the constituent materials and the resulting LCC system are reported by Butle et al [7]. All aggregates used in this study complied with IS 383 [10]. Crushed basalt with nominal sizes of 10 mm and 20 mm, sourced from a quarry in the Umred region of Maharashtra, was used as the natural coarse aggregate. RAP, employed as a coarse aggregate replacement, was obtained from milled and demolished flexible pavement sections generated during routine pavement rehabilitation [11]. The RAP was manually broken to remove oversized fragments and extraneous materials, followed by crushing and sieving to obtain 10 mm and 20 mm fractions, and was used in an untreated condition. The asphalt binder content of the RAP, determined in accordance with ASTM D2172 [12], was 4.83% by mass.

The physical properties of the aggregates are summarised in Table 1. Compared with basalt, RAP exhibited a lower specific gravity, reflecting its composite aggregate–binder nature and indicating that its parent aggregate source differed from the natural basalt used in this study.

Table 1 Physical properties of Aggregates

Parameters	River Sand	Basalt		RAP	
		10-mm	20-mm	10-mm	20-mm
Specific gravity	2.64	2.91	2.92	2.29	2.31
Water absorption [%]	1.11	1.19	1.20	0.54	0.51
Impact value [%]	-	5.64	8.15	12.22	11.38
Crushing value [%]	-	9.97	11.03	18.64	17.29
Abrasion value [%]	-	19.26	21.27	27.01	25.68

2.2 Mixture design

The mixture proportions were developed in accordance with IRC SP 68 [3]. Two benchmark mixtures established by Butle et al. [7] were adopted to provide reference performance. The first benchmark, BASE, employed an OPC-only binder system and represented conventional RCCP, while the second incorporated a 50% LCC replacement with 100% natural aggregates and served as the reference for evaluating aggregate substitution under identical binder chemistry. For all mixtures, the binder content was fixed at 12% by mass of total aggregates, and aggregate gradation was kept constant to satisfy the RCCP grading envelope, comprising 45% fine aggregate, 25% 10 mm coarse aggregate, and 30% 20 mm coarse aggregate. RAP was introduced as a replacement for natural basalt coarse aggregates at levels of 25%, 50%, 75%, and 100%, designated as RAP-25, RAP-50, RAP-75, and RAP-100, respectively. These replacement levels were selected to examine the progressive influence of RAP incorporation on moisture–dry density behaviour and strength development of LCC-based RCCP under partial and full replacement conditions. The detailed mixture proportions are presented in Table 2.

Table 2 Mix design

Mix	OPC	LCC	River Sand	Basalt		RAP		Water
				10-mm	20-mm	10-mm	20-mm	
BASE	300	0	990	550	660	0	0	129.8
RAP-00	150	150	990	550	660	0	0	147.3
RAP-25	150	150	990	412.5	495	137.5	165	145.0
RAP-50	150	150	990	275	330	275	330	141.5
RAP-75	150	150	990	137.5	165	412.5	495	138.0
RAP-100	150	150	990	0	0	550	660	131.8

* All values are in kg/m^3

*The BASE and RAP-00 mixtures correspond to the C-100 and LCC-50 mixes reported by Butle et al. [7] and are used here as reference benchmarks

2.3 Experimental research

The experimental programme involved determining the optimum moisture content and maximum dry density for each mixture using the modified Proctor compaction method in accordance with IS 2720 (Part 8) [13], with moisture content varied to establish complete moisture–dry density relationships. Based on the identified optimum moisture content, mixtures were compacted using a vibrating hammer in accordance with ASTM C1435 [14] to simulate field-scale RCCP compaction and cast into 150 mm cube moulds. Specimens were demoulded after 24 h, water-cured at 27 ± 2 °C, and tested for compressive strength at 3, 7, 28, and 90 days in accordance with IS 516 (Part 1) [15], with reported values representing the average of three specimens per mixture and curing age.

3 Results and discussion

3.1 Optimum moisture content and maximum dry density

The optimum moisture content and maximum dry density values derived from the moisture–density relationships are summarised in table 3. The BASE mixture exhibited an optimum moisture content of 5.19% and a maximum dry density of 2496.8 kg/m³. Replacement of OPC with the LCC binder (RAP-00) increased the optimum moisture content to 5.89% while reducing the maximum dry density to 2450.7 kg/m³. The increase in moisture demand reflects the finer particle characteristics and higher specific surface area of the LCC binder, whereas the reduction in dry density is attributable to the lower specific gravity of the limestone and calcined clay constituents [6, 7]. Within the LCC-based RCCP system, progressive replacement of natural basalt aggregates with RAP produced systematic changes in moisture – density behaviour. Relative to RAP-00, the optimum moisture content decreased consistently with increasing RAP content, with reductions ranging from 1.53% to 10.53% across replacement levels of 25% to 100%. When referenced to BASE, the RAP-modified mixtures continued to exhibit higher moisture requirements; however, the magnitude of increase diminished steadily from 11.75% at RAP-25 to 1.54% at RAP-100, indicating convergence towards the BASE moisture condition as RAP content increased. The reduction in moisture requirement with increasing RAP content is associated with the aged asphalt coating on RAP particles, which lowers effective water absorption and inter-particle friction, enhancing lubrication and facilitating particle rearrangement during compaction. As RAP content increases within the LCC-based matrix, this aggregate-level moisture-modifying effect progressively offsets the elevated moisture demand imposed by the finer LCC binder [2, 5].

Trends in maximum dry density mirrored changes in aggregate composition. Relative to RAP-00, incorporation of RAP resulted in progressive reductions in maximum dry density, ranging from 2.40% to 9.20% for replacement levels between 25% and 100%. When compared with BASE, cumulative reductions increased from 4.21% to 10.88% with increasing RAP content. These reductions are governed primarily by the lower specific gravity and composite nature of RAP particles, as the asphalt coating enhances lubrication during compaction but does not compensate for intrinsic density differences [5]. Overall, the results indicate that the moisture – density behaviour of RCCP incorporating RAP within an LCC-based binder system Is controlled by the balance between binder-driven moisture demand and RAP-induced moisture modification. This interaction produces systematic shifts in optimum moisture content and maximum dry density with increasing RAP content, while all mixtures remained within the constructability limits prescribed in IRC SP 68 [3], confirming their practical feasibility.

Table 3 Optimum moisture content and maximum dry density

Mix	BASE	RAP-00	RAP-25	RAP-50	RAP-75	RAP-100
Optimum moisture content [%]	5.19	5.89	5.80	5.66	5.52	5.27
Maximum dry density [kg/m^3]	2496.8	2450.7	2391.8	2336.6	2278.2	2225.2

3.2 Compressive strength

Figure 1 presents the compressive strength development of the RCCP mixtures. The BASE mixture exhibited compressive strengths of 23.73, 32.45, 42.22, and 52.76 MPa at 3, 7, 28, and 90 days, respectively, reflecting steady strength gain governed by cement hydration, matrix densification, and effective aggregate interlock. Replacement of OPC with the LCC binder (RAP-00) resulted in a consistent reduction in compressive strength across all curing ages, with strengths of 15.59, 24.33, 39.57, and 46.37 MPa at 3, 7, 28, and 90 days, respectively. This reduction was most pronounced at early ages and is attributed to slower initial hydration and increased water demand of the LCC binder, which lowers early matrix stiffness under RCCP's compaction-controlled regime. With advancing curing age, the strength deficit relative to BASE narrowed, reflecting the growing contribution of calcined clay pozzolanic reactions and limestone filler effects to matrix refinement and load transfer [6, 7]. Within the LCC-based system, incorporation of RAP as a coarse aggregate replacement produced additional strength reductions relative to RAP-00. At 3 days, RAP-25 exhibited a comparatively moderate reduction, whereas RAP-100 showed a substantial loss, with reductions relative to RAP-00 ranging from 6.84% to 59.41%. At early ages, compressive behaviour is governed predominantly by particle packing and aggregate skeleton formation rather than matrix maturity. Although the asphalt coating on RAP particles weakens mineral-to-mineral contact and reduces mechanical interlock, RAP also exhibits lower water absorption than natural basalt, reducing the effective w/b ratio within the LCC matrix and partially offsetting binder dilution, particularly at lower RAP contents [2, 5].

As curing progressed to 7 and 28 days, the influence of RAP became increasingly pronounced. At 7 days, strength reductions relative to RAP-00 ranged from 11.51% to 67.78%, while at 28 days the corresponding range increased to 15.12% to 79.33%. At 28 days, only RAP-25 exceeded the PCA [4] minimum requirement of 27.6 MPa for RCCP, whereas higher RAP replacement levels failed to meet this criterion. At these ages, increasing matrix stiffness reduced the binder-level penalty associated with LCC, while the weaker RAP aggregate skeleton increasingly governed compressive response, limiting the ability of the matured matrix to compensate for reduced interlock [5]. By 90 days, the strength difference between BASE and RAP-00 remained moderate, confirming satisfactory later-age performance of the LCC binder. However, RAP-modified mixtures continued to exhibit substantial strength losses, with reductions relative to RAP-00 ranging from 18.82% to 82.30%. As RAP is essentially inert within the cementitious matrix and does not participate in strength development, prolonged curing does not lead to meaningful recovery, and aggregate-controlled behaviour continues to dominate at higher RAP replacement levels [2, 5]. Overall, the compressive strength results demonstrate a curing-age-dependent transition in controlling mechanisms. At early ages, RAP moderates strength loss by reducing the effective w/b ratio within the LCC matrix, partially compensating for aggregate weakening. With advancing curing age, matrix development diminishes binder-related penalties, while the structural deficiency associated with the asphalt-coated RAP aggregate skeleton becomes dominant. This shift explains why strength reductions are comparatively less severe at 3 days but increase at later ages, highlighting the non-additive interaction between binder chemistry and aggregate structure in RAP-modified LCC-based RCCP systems.

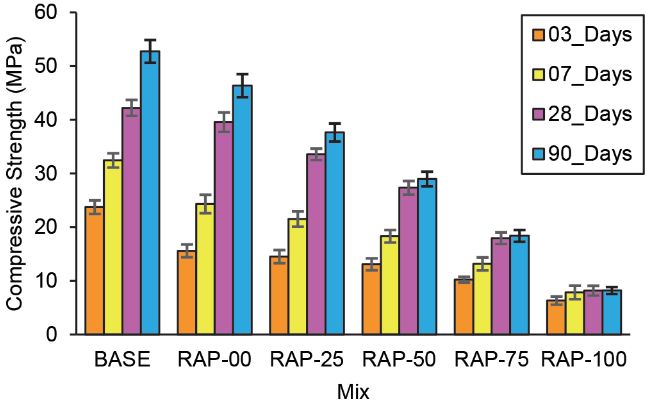

Figure 1 Compressive Strength

4 Conclusion

This study investigated RAP incorporation as a coarse aggregate replacement in LCC-based RCCP, focusing on moisture–density behaviour and compressive strength. The results show that RAP modifies the performance of LCC-based RCCP through a coupled interaction between moisture control and aggregate skeleton integrity, rather than behaving as a conventional mineral aggregate. Incorporation of RAP progressively reduced the effective moisture demand of the LCC-based system, leading to a reduction in the effective w/b ratio that counteracted the elevated water demand imposed by the finer LCC binder. This moisture-modifying effect improved compaction efficiency and moderated the severity of early-age strength reductions associated with binder dilution. With advancing curing age, the beneficial influence of RAP on the effective w/b ratio diminished as matrix stiffness developed. At later ages, compressive strength became increasingly governed by aggregate-level mechanisms, and the asphalt-coated nature of RAP weakened mechanical interlock and load transfer within the aggregate skeleton. Under the present mix design, RAP incorporation up to 25% satisfied the minimum compressive strength requirement for RCCP, whereas higher replacement levels resulted in pronounced strength losses. Overall, the findings confirm that RAP can be effectively incorporated into LCC-based RCCP at limited replacement levels (≈25%), where its ability to reduce the effective w/b ratio complements the LCC binder without compromising structural performance. Higher RAP contents, while beneficial for resource recovery, lead to aggregate-controlled strength degradation, highlighting the non-additive interaction between binder chemistry and aggregate structure in low-carbon RCCP systems.

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