

Experimental Investigation and Development of Sustainable Green Pavement Materials for Eco-Friendly Road Infrastructure

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Abstract

Rapid expansion of road infrastructure increases the demand for natural aggregates and bituminous binders while generating substantial quantities of reclaimed asphalt pavement (RAP) and construction and demolition (C&D) waste. This study experimentally evaluates the feasibility of using RAP and processed construction and demolition (PCD) aggregates in Dense Bituminous Macadam (DBM) mixtures prepared with VG-30 and Crumb Rubber Modified Bitumen (CRMB-55). The experimental programme included conventional and rheological characterization of the binders, physical and mechanical characterization of natural aggregate (NA), RAP and PCD, Marshall mix design, and performance evaluation using indirect tensile strength (ITS), retained stability (RS), and tensile strength ratio (TSR). VG-30 and CRMB-55 satisfied the relevant binder requirements. CRMB-55 showed higher stiffness, softening point and elastic recovery, indicating better resistance to high-temperature deformation, whereas VG-30 showed better low-temperature flexibility and compatibility with RAP. Aggregate characterization showed that RAP had favourable toughness and abrasion resistance, while PCD exhibited higher water absorption because of porous mortar and brick constituents. For VG-30, 30% RAP produced the maximum Marshall Stability of 19.88 kN. A sustainable VG-30 mixture containing 30% RAP and 41% PCD achieved 14.75 kN stability and satisfied the reported performance requirements. The corresponding high-recycled-content CRMB-55 mixture showed inferior moisture resistance. The results demonstrate that appropriately processed RAP and PCD can substantially replace virgin aggregates in bituminous pavements, reducing waste disposal and conservation pressure on natural resources while maintaining satisfactory engineering performance.

Keywords: Sustainable pavement, Reclaimed Asphalt Pavement, Construction and Demolition Waste, RAP, PCD, VG-30, CRMB-55, Marshall Stability, DBM.

I. INTRODUCTION

Road infrastructure is essential for economic activity, social connectivity and regional development, but conventional pavement construction consumes large quantities of natural aggregates and petroleum-derived binders. Continuous quarrying and extraction increase environmental pressure, while road rehabilitation and building demolition generate large streams of recyclable materials. A sustainable pavement strategy should therefore reduce virgin material demand without sacrificing strength, durability and serviceability.

Reclaimed Asphalt Pavement (RAP) is obtained by milling or removing existing asphalt layers. It contains aggregate coated with aged bitumen and therefore represents both a material resource and an opportunity to reduce fresh binder consumption. Processed Construction and Demolition (PCD) waste contains concrete, masonry, brick, mortar and stone fractions that can be crushed, screened and graded for engineering use. Their properties differ from natural aggregate, particularly in water absorption, specific gravity and resistance to mechanical degradation, so controlled processing and laboratory verification are necessary.

The present work investigates the combined use of RAP and PCD in DBM Grade-II mixtures using two binders:

conventional VG-30 and Crumb Rubber Modified Bitumen (CRMB-55). The study is intended to identify practical recycled-material contents that satisfy the reported MoRTH requirements and to compare the influence of binder type on mechanical and moisture-related performance.

A. Problem Statement

Large-scale road construction requires continuous supply of quality aggregates, whereas usable RAP and C&D materials are often disposed of or underutilized. The engineering challenge is to determine whether these materials can be incorporated at meaningful replacement levels while controlling stiffness, binder demand, tensile performance and moisture susceptibility.

B. Objectives

- Characterize VG-30 and CRMB-55 using conventional and advanced rheological tests.
- Determine the physical and mechanical properties of natural aggregate, RAP and PCD aggregates.
- Develop DBM Grade-II mixtures with different RAP and PCD proportions using Marshall mix design.
- Determine optimum binder content and compare Marshall Stability and Flow Value.
- Evaluate ITS, Retained Stability and TSR to assess mechanical and moisture-related performance.

- Identify a sustainable mixture with a high recycled-material content and satisfactory reported performance.

II. LITERATURE REVIEW

Previous research has established that recycled materials can be used in asphalt mixtures when their physical properties, gradation and interaction with the binder are properly controlled. Studies on RAP have reported that residual aged binder can increase mixture stiffness and reduce the requirement for virgin binder. Research on recycled concrete and demolition aggregates has shown that the attached mortar can increase porosity and water absorption, making aggregate blending and quality control important.

Research has also investigated waste-derived binder modifiers. Bio-oils have been studied as rejuvenators for aged binders, while crumb rubber and recycled plastics have been used to improve high-temperature performance. Waste oils, rice husk ash, recycled glass powder and other additives have similarly been examined for sustainable asphalt applications. The literature review in the project indicates that recycled-material performance depends strongly on dosage, particle characteristics, binder chemistry and service temperature.

A key research gap is the combined evaluation of RAP and PCD in the same bituminous mixture together with comparison of conventional VG-30 and CRMB-55 binders. The present investigation addresses this gap through a sequential experimental programme in which the optimum RAP level is established first and PCD is subsequently introduced in different sizes and proportions.

A. Research Gap

Although RAP recycling is increasingly established, simultaneous utilization of substantial RAP and processed C&D aggregate requires careful control because the two recycled materials affect the mix differently. RAP contributes aged binder and stiffness, whereas PCD generally increases absorption and may reduce mechanical resistance. The interaction between these materials and a highly elastic CRMB-55 binder also requires experimental verification.

III. MATERIALS AND METHODOLOGY

A. Materials

Natural aggregate (NA), reclaimed asphalt pavement (RAP), processed construction and demolition (PCD) aggregate, VG-30 bitumen and CRMB-55 were used. The aggregate programme included gradation, impact, abrasion, flakiness and elongation, water absorption and specific gravity tests. Binder characterization included penetration, softening point, ductility, elastic recovery, specific gravity and viscosity, followed by BBR and DSR investigations.

TABLE I. BASIC PROPERTIES OF VG-30 AND CRMB-55 BINDERS

Binder property	VG-30	CRMB-55	Reported requirement
Penetration at 25°C (0.1 mm)	68	50	45 / 30–60
Softening point (°C)	50.2	60.3	47 / 55
Ductility at 25°C (cm)	>75	—	40 / —
Elastic recovery at 15°C (%)	—	67	— / 60
Specific gravity	1.01	1.10	0.99 / —
Absolute viscosity at 60°C (Poise)	2984	—	2400–3600 / —
Kinematic viscosity at 135°C (cSt)	438	—	350 / —
Viscosity at 150°C (Poise)	—	5	— / 4–8

VG-30 showed a penetration of 68 (0.1 mm), softening point of 50.2°C and ductility greater than 75 cm. CRMB-55 showed lower penetration (50), higher softening point (60.3°C) and elastic recovery of 67%. The project results therefore indicate that CRMB-55 is stiffer and more resistant to elevated-temperature deformation, while VG-30 provides greater flexibility.

B. Aggregate Characterization

TABLE II. PHYSICAL PROPERTIES OF NATURAL, RAP AND PCD AGGREGATES

Property	NA	RAP	PCD	MoRTH limit
Aggregate Impact Value (%)	22	12	28	≤27
Los Angeles Abrasion (%)	30	21	34	≤35
Combined Flakiness + Elongation (%)	27	28	30	≤35
Water absorption, 10 mm (%)	1.0	8.42	—	≤2*
Specific gravity, 10 mm	2.58	2.10	—	—
Specific gravity, 20 mm	2.65	2.31	—	—
Specific gravity, 40 mm	2.78	2.40	—	—

The aggregate results show clear differences among the three sources. RAP exhibited the lowest impact and abrasion values, indicating good resistance to mechanical degradation. PCD showed comparatively higher impact and abrasion values and higher water absorption because of porous mortar and brick fragments. The combined flakiness and elongation indices remained within the reported limit. Blending PCD with natural aggregate and

RAP was therefore used to compensate for the weaker characteristics of the demolition-derived fraction.

C. Aggregate Gradation

The aggregate fractions were graded before mix preparation to obtain the required DBM Grade-II blend. The project data show that the individual fractions could be combined without significantly disturbing the overall particle-size distribution. Proper gradation improves particle interlock, reduces segregation and provides a stable aggregate skeleton.

TABLE III. GRADING OF INDIVIDUAL AGGREGATE FRACTIONS

Sieve (mm)	26.5 mm NA	20 mm NA	10 mm NA	6 mm NA	Stone dust	40 mm PCD	20 mm PCD	10 mm PCD	RAP
37.5	100	100	100	100	100	100	100	100	100
26.5	86.5	100	100	100	100	95.9	100	100	100
19	9.9	93.6	100	100	100	1.04	98.5	100	97.2
13.2	0.9	9.5	95.9	100	100	1.04	33.60	100	90.0
4.75	0.2	0.6	4.7	76.35	94.6	0.79	0.95	0.6	43.3
2.36	0.2	0.6	1.3	22.24	80.7	0.79	0.90	0.55	30.8
0.300	0.1	0.6	1.2	0.4	30.7	0.79	0.70	0.5	5.7
0.075	0	0.4	0.5	0.2	10.2	0.79	0.25	0.1	0.2

D. Experimental Programme

The experimental programme followed five sequential stages. Stage 1 involved binder characterization. Stage 2 involved physical, mechanical, mineralogical and microstructural characterization of NA, RAP and PCD. Stage 3 consisted of DBM-II mix development using the Marshall procedure. Stage 4 compared VG-30 and CRMB-55 at the selected recycled aggregate combinations. Stage 5 evaluated the developed mixtures through Marshall Stability, Flow Value, ITS, RS and TSR.

Marshall specimens were prepared using the standard procedure, and optimum binder content was selected at 4% design air voids as adopted in the project. A control mix containing natural aggregate was followed by RAP replacement levels and then combined RAP-PCD mixtures. The same aggregate combinations were examined with both binders to facilitate a direct comparison.

E. Marshall Mix Design

Marshall Stability represents the maximum load carried by a compacted specimen before failure, while Flow Value represents the deformation corresponding to the maximum load. Optimum binder content is selected to achieve the target volumetric condition while maintaining acceptable stability and flow. In the present study, the principal parameters were optimum bitumen content, Marshall Stability and Flow Value.

IV. RESULTS AND DISCUSSION

A. Binder Performance

The conventional tests established that both binders met the applicable requirements reported in the project. The BBR investigation showed that VG-30 had lower creep stiffness and higher m-values at -6°C and -12°C , indicating better stress relaxation and low-temperature flexibility. The DSR investigation showed higher complex shear modulus and rutting parameter for CRMB-55, together with lower phase angle, indicating superior high-temperature rutting resistance.

The two binders therefore have complementary performance characteristics. VG-30 is more compatible with mixtures containing RAP because of its comparatively lower viscosity and greater flexibility. CRMB-55 is beneficial where elevated-temperature stiffness and elastic recovery are priorities. Binder selection should consequently consider traffic loading, climate and the desired balance between flexibility and rutting resistance.

B. Marshall Characteristics with VG-30

TABLE IV. MARSHALL PARAMETERS OF VG-30 MIXES

Mix	Composition	OBC (%)	Stability (kN)	Flow (mm)
V1	NA control	4.70	13.14	3.10
V2	NA + 25% RAP	4.10	16.95	2.95
V3	NA + 30% RAP	3.95	19.88	2.90
V4	NA + 35% RAP	3.80	17.69	2.78
V5	30% RAP + 16% PCD40	4.40	18.59	3.35
V6	30% RAP + 12.5% PCD40	4.25	18.81	3.27
V7	30% RAP + 10% PCD40	4.25	18.97	3.20
V8	30% RAP + 15% PCD20	4.40	16.44	3.38
V9	30% RAP + 12.5% PCD20	4.25	17.49	3.30
V10	30% RAP + 10% PCD20	4.25	18.02	3.25
V11	30% RAP + 10% PCD10	4.40	17.04	3.30
V12	30% RAP + 16% PCD40 + 15% PCD20 + 10% PCD10	5.00	14.75	3.65

The control VG-30 mixture produced 13.14 kN stability at 4.70% optimum binder content. Increasing RAP to 25% and 30% raised stability to 16.95 and 19.88 kN, respectively, while reducing optimum binder content to 4.10 and 3.95%. This behaviour is consistent with the presence of aged binder on RAP particles, which contributes to stiffness and reduces the requirement for fresh binder. At 35% RAP, stability decreased to 17.69 kN, indicating that excessive RAP replacement was not beneficial.

With 30% RAP held constant, the addition of PCD changed the trend. PCD increased binder demand because of its porous nature and adhered mortar. Stability remained satisfactory for several combinations, but the final multi-size PCD blend produced 14.75 kN stability at 5.00% binder. This value remained above the control mixture and represents a substantial recycled-material content.

C. Marshall Characteristics with CRMB-55

TABLE V. MARSHALL PARAMETERS OF CRMB-55 MIXES

Mix	Composition	OBC (%)	Stability (kN)	Flow (mm)
C1	NA control	4.85	15.78	3.30
C2	NA + 30% RAP	4.25	15.68	3.05
C3	30% RAP + 16% PCD40	4.70	14.02	3.50
C4	30% RAP + 12.5% PCD40	4.55	14.36	3.42
C5	30% RAP + 10% PCD40	4.55	14.88	3.32
C6	30% RAP + 15% PCD20	4.70	13.76	3.56
C7	30% RAP + 12.5% PCD20	4.55	14.08	3.46
C8	30% RAP + 10% PCD20	4.55	14.32	3.35
C9	30% RAP + 10% PCD10	4.70	13.57	3.40
C10	30% RAP + 16% PCD40 + 15% PCD20 + 10% PCD10	5.30	10.01	4.20
C11	30% RAP + 16% PCD40 + 12.5% PCD20 + 10% PCD10	5.30	10.67	4.05
C12	30% RAP + 16% PCD40 + 10% PCD20 + 10% PCD10	5.15	11.43	3.95
C13	30% RAP + 16% PCD40 + 10% PCD20 + 7.5% PCD10	5.15	12.08	3.80

The CRMB-55 control mixture exhibited 15.78 kN stability at 4.85% optimum binder content. Incorporation of 30% RAP gave 15.68 kN, showing only a marginal change. With increasing PCD, optimum binder content generally increased, while stability declined. The high-recycled-content combinations C10–C13 had stability values between 10.01 and 12.08 kN and higher flow values. These results show that the stiff CRMB-55 binder did not interact with RAP and PCD as favourably as VG-30 at the highest recycled-material contents.

D. Performance Evaluation

The project evaluated the developed mixtures using indirect tensile strength, retained stability and tensile strength ratio. RAP generally improved the moisture-related performance of VG-30 mixtures. Its lower effective water absorption compared with PCD and the residual binder coating around RAP particles helped limit

moisture penetration and improve aggregate-binder adhesion.

PCD addition caused a progressive reduction in indirect tensile strength and moisture resistance. The porous structure, adhered mortar and lower mechanical strength of PCD contributed to this reduction. Larger PCD particles performed better in ITS than smaller particles, showing that aggregate size influences tensile behaviour.

All control and modified mixtures reported in the project satisfied the minimum TSR requirement of 80%, except the final CRMB-55 mixture with the highest recycled content. The final sustainable VG-30 mixture containing 30% RAP and 41% PCD satisfied the reported ITS, RS and TSR requirements, while the corresponding CRMB-55 mixture containing 30% RAP and 33.5% PCD did not satisfy the minimum TSR requirement.

E. Sustainability Implications

The use of RAP directly reduces the demand for virgin aggregates and can reduce the requirement for fresh bitumen because RAP contains residual aged binder. PCD recycling diverts demolition materials from disposal and creates an alternative source of aggregate. Together, these measures can reduce quarrying, landfill demand, material transportation and associated energy consumption. The engineering results indicate that these environmental benefits can be achieved without unacceptable performance loss when recycled-material proportions are controlled.

V. CONCLUSIONS

- VG-30 and CRMB-55 satisfied the conventional binder requirements reported in the project and were technically suitable for flexible pavement mix development.
- CRMB-55 exhibited lower penetration, higher softening point, higher elastic recovery and higher high-temperature stiffness, indicating improved rutting resistance.
- VG-30 exhibited better low-temperature flexibility and stress relaxation characteristics and showed better compatibility with RAP-containing mixtures.
- RAP showed favourable impact and abrasion resistance and reduced optimum binder content when introduced into VG-30 mixtures.
- PCD exhibited higher water absorption and comparatively lower mechanical resistance because of porous mortar and brick constituents.
- 30% RAP was identified as the optimum RAP replacement level for the VG-30 series, producing the maximum Marshall Stability of 19.88 kN.
- The sustainable VG-30 mixture containing 30% RAP and 41% PCD achieved 14.75 kN Marshall Stability and satisfied the reported performance requirements.
- CRMB-55 mixtures with high PCD contents showed lower stability and poorer moisture resistance than the corresponding VG-30 mixtures.
- The study demonstrates that substantial quantities of RAP and PCD can be incorporated into DBM mixtures when aggregate grading, binder type and recycled-material proportions are properly controlled.

- Use of recycled pavement and demolition materials provides a practical route toward resource conservation, waste reduction and more sustainable highway construction.

A. Practical Recommendations

- Process and screen RAP and PCD before use and maintain source-wise quality control.
- Determine gradation, water absorption and mechanical properties for each recycled-material source before mix design.
- Prefer VG-30 for high recycled aggregate contents where flexibility and RAP compatibility are important.
- Consider CRMB-55 where high-temperature rutting resistance is the primary requirement, but verify moisture resistance for high recycled-material contents.
- Do not transfer the reported optimum percentages directly to field projects without source-specific laboratory validation and trial sections.
- Use moisture conditioning and performance testing as part of quality assurance for recycled bituminous mixtures.

B. Limitations and Future Scope

The investigation is laboratory based and uses materials from the sources characterized in the project. RAP properties can vary with pavement age, traffic history, milling method and residual binder condition, while PCD properties vary with the proportion of concrete, brick and mortar. Long-term field validation, full-scale wheel tracking, fatigue testing, life-cycle assessment, and detailed economic analysis are therefore recommended before large-scale implementation.

Future research should examine rejuvenators for high-RAP mixtures, alternative gradations, warm-mix technologies, longer-term ageing, fatigue and rutting performance, and mechanistic-empirical pavement design. Field trials should be monitored for rutting, cracking, moisture damage and maintenance requirements over multiple seasons.

F. Literature Synthesis and Research Position

Studies on recycled pavement materials consistently show that the engineering behaviour of recycled aggregates is controlled by source, processing method, residual binder condition and particle-size distribution. RAP is particularly attractive because it contains both aggregate and aged bitumen. When RAP is properly fractionated and blended, the residual binder can contribute to mixture stiffness and can reduce the quantity of virgin binder required. However, excessive RAP may produce a mixture that is too stiff or may require rejuvenation, particularly when the recovered binder has undergone substantial ageing.

Construction and demolition waste behaves differently. Recycled concrete and masonry particles frequently contain adhered cement mortar, which increases porosity and water absorption and can reduce specific gravity. These characteristics can increase binder demand and moisture susceptibility. The project results support this general behaviour: PCD had higher water absorption than

the natural aggregate and caused a progressive increase in optimum binder content when added to the recycled mixtures.

Research on modified binders indicates that crumb rubber can increase elastic recovery and high-temperature stiffness. This is useful for heavily trafficked pavements exposed to elevated temperatures. At the same time, a very stiff binder can reduce the benefit of RAP when the combined recycled system becomes excessively stiff. The present comparison of VG-30 and CRMB-55 is therefore important because it demonstrates that binder selection cannot be separated from recycled aggregate selection.

The present research differs from a simple RAP replacement study because it considers two recycled sources together and compares two binders under the same aggregate gradation framework. The sequential approach—first optimizing RAP and then introducing PCD—helps distinguish the beneficial contribution of RAP from the adverse effects that may occur when excessive porous PCD is added.

G. Calculation and Mix-Design Considerations

The Marshall procedure uses the measured specimen mass, dimensions and stability-flow response to determine the volumetric and mechanical characteristics of each mixture. Bulk density is obtained from the specimen mass and bulk volume. Air voids are determined from the difference between theoretical maximum specific gravity and bulk density, while VMA represents the volume of intergranular void space in the compacted aggregate structure. VFB expresses the proportion of VMA occupied by effective bitumen. In the present work, optimum binder content was selected at the reported 4% design air-void condition, after which stability and flow were used to assess the suitability of the mix.

For recycled mixtures, the calculation process requires particular care because RAP carries residual binder and PCD may have significantly different specific gravity and absorption characteristics. Treating RAP as ordinary virgin aggregate without accounting for residual binder can overestimate the fresh binder requirement. Similarly, using a single generic absorption value for all PCD fractions may underrepresent the actual binder demand. Source-specific testing is therefore essential for reliable mix design.

Performance testing complements the Marshall procedure. Indirect tensile strength provides an indication of tensile resistance and susceptibility to cracking-related damage. Retained stability compares conditioned and unconditioned strength and provides an indication of moisture sensitivity. Tensile Strength Ratio is calculated from conditioned and unconditioned indirect tensile strengths and is used in the project to judge moisture resistance against the reported MoRTH criterion.

H. Key Performance Relationships

Marshall stability assessment: maximum load carried by the compacted specimen before failure.

Flow value: deformation of the Marshall specimen corresponding to the maximum load.

Air voids, V_a (%) = $[(G_{mm} - G_{mb}) / G_{mm}] \times 100$.

Voids filled with bitumen, VFB (%) = $[(VMA - V_a) / VMA] \times 100$.

Tensile Strength Ratio, TSR (%) = (Conditioned ITS / Unconditioned ITS) $\times 100$.

I. Comparative Discussion of Optimum Mixtures

The VG-30 series provides the clearest evidence of the structural benefit of RAP. The control mixture had a stability of 13.14 kN, whereas the 30% RAP mixture reached 19.88 kN, an increase of approximately 51%. At the same time, optimum binder content decreased from 4.70% to 3.95%. The improvement is attributed in the project to the stiffness contribution of aged RAP binder and the mechanical contribution of the RAP aggregate skeleton. Increasing RAP further to 35% reduced stability to 17.69 kN, indicating that an optimum rather than a maximum replacement level exists.

Once 30% RAP was fixed, PCD was introduced in different sizes. The 40 mm PCD combinations retained relatively high stability, while smaller or combined PCD fractions generally reduced stability as the recycled content increased. The final VG-30 mixture contained 30% RAP together with a multi-size PCD blend and achieved 14.75 kN stability at 5.00% binder. Although its stability was lower than the 30% RAP-only mixture, it remained above the control mixture and provided a much greater recycled-material contribution.

The CRMB-55 results reveal a different interaction. The control mixture already achieved 15.78 kN stability, higher than the VG-30 control, demonstrating the high-temperature stiffness contribution of the modified binder. However, the addition of 30% RAP resulted in 15.68 kN, almost unchanged. As PCD content increased, stability fell and optimum binder content increased. The final high-recycled-content CRMB-55 mixtures therefore became less attractive from both mechanical and moisture-resistance perspectives.

These results highlight an important design principle: sustainability is not achieved simply by maximizing waste content. The optimum solution is a balanced mixture in which recycled materials replace a meaningful proportion of virgin resources while maintaining the required engineering properties. The present study identifies such a balance for the VG-30 system.

J. Environmental and Economic Significance

Recycling RAP conserves the aggregate fraction already present in the old pavement and also retains the value of residual bitumen. This reduces the need for quarrying, crushing and transporting new aggregate. Recycling PCD similarly converts demolition debris into a useful construction input and reduces the quantity requiring landfill or uncontrolled disposal. The combined approach therefore addresses both resource depletion and waste management.

The economic benefit is expected to arise from reduced consumption of virgin aggregates and, in RAP mixtures, reduced demand for fresh binder. However, economic performance depends on haul distance, processing cost, source quality, screening requirements and plant configuration. A recycled material located far from the asphalt plant may not provide the same economic benefit

as a locally available material. Consequently, life-cycle cost and life-cycle environmental assessment should accompany future field trials.

From a sustainability perspective, the most important finding is that recycled-content optimization can be based on engineering performance rather than on an arbitrary percentage target. The 30% RAP and 41% PCD VG-30 mixture provides a project-specific example of how a high recycled-material content can be achieved while retaining satisfactory reported tensile and moisture performance.

K. Quality-Control Requirements for Field Application

Field adoption should begin with systematic source characterization. RAP should be stockpiled by source and, where possible, fractionated to improve consistency. PCD should be screened to remove undesirable materials such as wood, plastic, glass and organic matter. Aggregate moisture, absorption and gradation should be monitored because changes in these parameters can alter binder demand and compaction behaviour.

Plant production should control mixing temperature, storage time, moisture content and feed proportions. Trial batches should be prepared before routine production, followed by laboratory verification of binder content, gradation, density, air voids and stability. Recycled aggregate proportions should be adjusted when source properties change. These controls are particularly important for PCD because its heterogeneous composition can produce larger variation than natural aggregate.

Construction quality should also include field density measurement, surface regularity and drainage checks. Because recycled mixtures can respond differently to moisture and temperature, early monitoring of rutting, cracking and stripping is recommended. The laboratory optimum reported in this study should therefore be treated as a starting point for field validation rather than as a universal specification.

L. Overall Research Contribution

The principal contribution of the investigation is the integrated evaluation of recycled aggregate combinations and binder type. The work demonstrates that RAP and PCD should not be evaluated independently when the intended application is a high-recycled-content bituminous mixture. RAP can provide a beneficial stiffness and binder contribution, whereas PCD requires tighter control because of its absorption and mechanical characteristics. VG-30 offered the better overall balance for the recycled mixtures studied, while CRMB-55 retained an advantage for high-temperature stiffness and rutting resistance.

The findings provide a laboratory basis for sustainable DBM construction using locally processed waste materials. They also show why performance-based optimization is essential: a mixture with a slightly lower recycled percentage may be preferable if it provides significantly better moisture resistance and long-term durability. Future field trials can build on these results by

incorporating traffic loading, climatic exposure, ageing and life-cycle assessment.

M. Detailed Interpretation of Recycled Aggregate Behaviour

RAP and PCD influence a bituminous mixture through different mechanisms. RAP is a composite recycled material in which aggregate particles remain coated with aged asphalt binder. During heating and mixing, part of this aged binder can participate in the new binder system. Consequently, increasing RAP content may reduce the fresh binder requirement and increase mixture stiffness. This mechanism is visible in the VG-30 results, where optimum binder content decreased from 4.70% for the control mix to 3.95% at 30% RAP.

The response at 35% RAP is equally important because it demonstrates that higher replacement does not automatically produce higher performance. Stability decreased from 19.88 kN at 30% RAP to 17.69 kN at 35% RAP. This suggests that an optimum recycled-content level exists at which the combined aggregate structure, residual binder and fresh binder achieve a favourable balance. Such behaviour is consistent with the need for source-specific optimization rather than adopting a single national replacement percentage for every RAP source.

PCD, in contrast, is primarily a recycled aggregate resource. Its particles may contain adhered mortar, brick and other masonry components. These constituents increase internal porosity and water absorption. Higher absorption can increase the amount of binder required to achieve adequate coating and can also increase moisture susceptibility if the mixture is not properly designed. The reported results show this trend clearly: as PCD was introduced into the 30% RAP VG-30 system, optimum binder content generally increased.

Particle size also affected the results. The project evaluated 40 mm, 20 mm and 10 mm PCD fractions. Larger PCD particles generally provided better tensile performance than smaller particles. A possible engineering interpretation is that larger, more durable particles participate more effectively in the load-bearing skeleton, while a greater proportion of fine porous particles can increase surface area and binder demand. This observation supports fraction-specific processing of C&D waste before asphalt production.

N. Binder–Aggregate Interaction

The comparison between the two binders shows that the performance of a recycled mixture is not governed by aggregate properties alone. VG-30 has comparatively lower viscosity and greater flexibility, allowing it to accommodate the stiffness introduced by RAP. The final VG-30 recycled mixture maintained satisfactory ITS, RS and TSR even with a high combined recycled content. CRMB-55, although stronger against high-temperature deformation, produced less favourable results when large quantities of RAP and PCD were combined.

The CRMB-55 control mix had a stability of 15.78 kN, confirming the beneficial effect of the modified binder in a conventional aggregate system. However, when 30%

RAP was introduced, stability changed only slightly to 15.68 kN. Further PCD addition caused a steady decline in stability and an increase in optimum binder content. The result suggests that the high stiffness of CRMB-55 and the aged binder in RAP can create a mixture that has limited flexibility for effective stress redistribution.

This interaction is especially relevant for field pavement design. A binder that is excellent under high-temperature rutting conditions may not automatically be the best choice for a high-recycled-content mixture. Climate, traffic, RAP stiffness, PCD absorption and moisture exposure should be considered together. The project therefore supports a performance-based selection approach rather than a binder-only or aggregate-only selection approach.

O. Moisture Susceptibility and Tensile Performance

Moisture is one of the most important causes of premature deterioration in flexible pavements. Water can weaken the aggregate-binder interface, promote stripping and reduce tensile strength. Recycled aggregates require particular attention because their surface texture and absorption characteristics may differ from those of virgin aggregate. In this study, RAP improved the reported moisture performance of VG-30 mixtures, while PCD generally reduced it.

The beneficial behaviour of RAP is associated with its relatively low effective water penetration after aggregate particles are coated by aged bitumen. The retained binder can also improve adhesion between the recycled aggregate and the new binder system. In contrast, PCD contains porous mortar and brick fractions that can absorb water and increase the likelihood of moisture-related damage. The results therefore show that increasing PCD content should be accompanied by careful moisture testing.

Indirect tensile strength provides a useful measure of resistance to tensile failure. The project observed that PCD addition generally reduced ITS for both binders, while VG-30 mixtures consistently showed higher ITS than the corresponding CRMB-55 mixtures. Retained Stability and TSR further confirmed the importance of moisture conditioning. The final VG-30 mixture with 30% RAP and 41% PCD satisfied the reported performance requirements, whereas the corresponding high-recycled-content CRMB-55 mixture did not satisfy the minimum TSR requirement.

P. Comparison of Key Results

Parameter | VG-30 outcome | CRMB-55 outcome

Control stability | 13.14 kN | 15.78 kN

Best RAP result | 30% RAP: 19.88 kN | 30% RAP: 15.68 kN

Final sustainable mix | 30% RAP + 41% PCD; 14.75 kN | 30% RAP + 33.5% PCD; lower moisture performance

Binder advantage | Flexibility and RAP compatibility | High-temperature stiffness and elastic recovery

Main limitation | Lower high-temperature stiffness than CRMB-55 | High recycled-content moisture compatibility

Q. Implications for Sustainable Highway Engineering

The engineering significance of the study extends beyond the laboratory strength values. Conventional pavement construction follows a largely linear material pathway in

which natural rock is extracted, processed, transported, incorporated into pavement, and ultimately discarded during rehabilitation. RAP recycling interrupts this pathway by returning pavement-derived materials to productive use. C&D recycling similarly converts demolition waste into a secondary construction resource.

A sustainable pavement should be evaluated using multiple criteria: structural performance, durability, constructability, material availability, cost and environmental impact. The present study addresses the first three criteria through laboratory testing and provides a material basis for the remaining economic and environmental assessments. Because RAP and PCD can be sourced from maintenance and demolition activities, local recycling networks could reduce the transport distance associated with virgin aggregate supply.

At the same time, sustainability should not be interpreted as maximum waste incorporation at any cost. The results show that excessive PCD can reduce tensile and moisture performance. The preferred mixture is therefore the one that maximizes useful recycled content within the limits of required pavement performance. The 30% RAP and 41% PCD VG-30 mixture represents the optimum reported in this project for that balance.

The approach can also support circular-economy objectives in road construction. Existing pavements become sources of new aggregate, demolition materials become engineered aggregate, and waste rubber incorporated in CRMB-55 can contribute to binder modification. Such material loops can reduce dependence on virgin resources and create a more resilient supply chain for pavement construction.

R. Reproducibility and Suggested Field Validation

For reproducibility, future investigations should document the source and age of RAP, milling depth, residual binder content, fractionation procedure, PCD composition, washing or cleaning procedure, aggregate moisture condition, mixing temperature and compaction energy. These variables can materially influence the measured optimum binder content and performance. A recycled mixture reported without these details is difficult to transfer reliably to another project.

Field validation should begin with a controlled trial section using the selected VG-30 recycled mixture. The trial should compare laboratory predicted density and binder content with plant production results. During construction, temperature, mixing time, laydown temperature and roller passes should be recorded. After opening to traffic, periodic surveys should measure rut depth, cracking, surface defects and drainage performance.

Longer-term monitoring should ideally cover at least one complete seasonal cycle and should be extended for multiple years where possible. The field observations can then be compared with laboratory ITS, TSR, stability and rheological indicators. Such correlation would help establish whether the laboratory optimum identified in this project translates into durable pavement performance under actual traffic and climate conditions.

VI. REFERENCES

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