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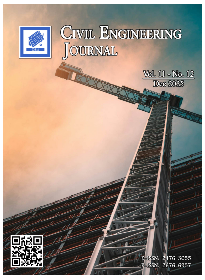

Strength Characteristics and Material Design of Recycled Flexible Pavement Materials

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Abstract

This study develops a strength-based mix-design framework for rehabilitating flexible pavements using reclaimed asphalt pavement (RAP) blended with crushed rock (CR) and cement. Objectives were to quantify 7-day unconfined compressive strength (UCS) as a function of mixture variables and to provide field-ready proportioning equations. Methods comprised laboratory testing of RAP–CR blends (RAP = 0–100%) with 2–5% cement, Modified Proctor compaction, and 7-day UCS; regression related UCS to a modified parameter (w/c)(1−k·AS), where asphalt content (AS) is obtained from AS = 0.04·RAP. Findings show that increasing RAP lowers dry density (2.31→2.11 g/cm³) and raises optimum moisture (5.03→7.17%). The 7-day prediction is $q_{u,7} = 23.44/[(w/c)(1-0.22 \cdot AS)]^{0.677}$ ($R^2 = 0.863$). A worked example (4-cm asphalt over a 20-cm base; 20-cm milling) gives RAP = 20%, AS = 0.80, recommended w/c = 1.31, and cement = 4.03% at OMC = 5.28% and dry density = 2.276 g/cm³, satisfying 1.72 MPa (17.5 kg/cm²) at 7 days. Novelty/Improvement: the framework consolidates RAP content and binder effects into a single modified w/c parameter, enabling rapid, transparent proportioning for construction control. Broader impacts include reduced demand for virgin aggregate and haul-off of demolition debris, fewer truck movements and landfill burdens, and potential life-cycle cost savings in network-level rehabilitation.

Keywords: Cement Stabilization; Crushed Rock (CR); Reclaimed Asphalt Pavement (RAP); Unconfined Compressive Strength (UCS).

1. Introduction

Currently, every country is experiencing rapid growth, and the inevitable aspects of that growth include transportation demands and increasing traffic volumes. For Thailand, the majority of transportation and logistics are still road-based. Several related agencies are actively working to develop transportation systems, including a shift toward rail systems. However, if roadways remain the primary means of travel and freight transport, road infrastructure and

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pavement structures will continue to be extensively used. Road distresses such as potholes and cracking are common. These distresses can be grouped into two categories: surface damage and structural damage to the pavement layers. Surface damage is typically repaired by resurfacing. However, when the damage extends to the structural layers of pavement, excavation and removal of the damaged layers, followed by recompaction of the new surface, are required [1-4].

In pavement rehabilitation, cost and speed, along with minimizing disruptions to traffic and public mobility, should be considered. The expense of pavement rebuilding can be reduced by 25-50% through full-depth reclamation (FDR), since it reduces the need for new materials and hauling away the compromised structural components from the site [5-7]. However, mixtures of reclaimed asphalt pavement (RAP) and virgin aggregate exhibit behavior different from conventional asphalt mixtures due to the relatively low strength of the RAP–aggregate blends [8-13]. Several studies have shown that the performance of cement-stabilized RAP meets the criteria for use as a pavement base and subbase [14-16]. This has led researchers to investigate the reuse of reclaimed pavement materials to reduce waste from road repairs. These materials are mixed with commonly used road-improvement materials such as crushed rock (CR). Recent contributions also document cement-stabilized RAP and FDR practice with updated strength–moisture trends and proportioning guidance, reinforcing field constructability and quality control [17, 18].

Soil–cement mix design typically uses unconfined compressive strength (UCS) as the primary quality-control parameter [19]. In traditional mix-design methods, the cement content per unit dry weight of material **is** varied. The selection of cement content depends on the desired engineering properties and type of soil. The cement content commonly used in soil-cement applications ranges from 2% to 16% by the dry weight of the material [20].

The pavement in-place recycling technique used by Thailand's Department of Rural Roads involves the reuse of existing pavement materials after on-site quality improvement. Cement is commonly used as an additive to enhance the quality of the existing pavement structure [21-23]. The cement content used for the in-place recycling of reclaimed pavement material typically ranges from 2% to 5% of the dry weight of material. The optimal cement content is selected based on the correlation between UCS and the cement content required to achieve 1.72 MPa (17.5 kg/cm²) for the soil–cement sample in accordance with the standard for soil–cement base [24-25].

Studies have been conducted on the improvement of the existing pavement structure via cement stabilization using RAP as an aggregate [26-30]. Additionally, the engineering properties of varying contents of reclaimed pavement material in full-depth reclamation (FDR) mixes have also been studied [31]. Ghanizadeh et al. [9] reported that increasing the amount of RAP in the mix of sandy clay (SP-SC) and gravelly clay (GW-GC) samples stabilized with cement resulted in reduced bearing capacity, swelling, and UCS. Suddeepong et al. [32] found that increasing the RAP content raised the optimum moisture content (OMC), while the maximum dry unit weight and UCS decreased. Suebsuk et al. [33] identified that in RAP, the asphalt binder content controls the material strength. Furthermore, the modified soil–water–cement (SWC) ratio has been used to describe the strength behavior of cement-stabilized materials. A study by Kampala et al. [34] revealed that full-depth recycled materials with milling depths of 20, 25, and 30 cm exhibited a decrease in UCS because of the increase in RAP content. The compaction behavior, represented by the maximum dry unit weight, also decreased with increasing RAP content, while the optimum moisture content increased. However, the properties of all mixes are related to SWC. Complementary recent studies highlight mix-design/strength models for FDR with Portland cement and expanded sustainability evidence from LCA/LCCA, supporting recycled aggregates in pavement bases [34–37]. Building on this line of work, recent contributions have examined strength evolution and proportioning when RAP replaces conventional aggregates and reported sustainability and life-cycle advantages that motivate recycling at the network scale.

Despite these advances [26-34], a concise, field-ready mix-design framework that integrates RAP effects via an asphalt-adjusted water-to-cement parameter and provides an explicit predictive equation for 7-day UCS together with a worked proportioning example under in-place recycling conditions remains limited, particularly for Thailand. To address this gap, this study develops and validates a strength-based approach that relates UCS to a modified parameter $(w/c)(1-k\cdot AS)$ and demonstrates its practical use for both central-plant and in-place recycling.

This study focuses on the influence of cement content, water content, and the RAP-to-aggregate ratio on UCS and durability at different curing ages. In addition to the complexities in the mix design of recycling materials mentioned above, the durations of mix design, construction, and road opening are also important considerations. The theoretical basis follows an Abrams-type relationship in which hydration-controlled strength is governed by the effective water-to-cement ratio; the proposed form introduces $(1-k\cdot AS)$ to reflect asphalt-binder effects on effective water/cement availability and observed density–moisture trends in RAP–CR blends.

This research aims to estimate the appropriate cement content for the reuse of reclaimed pavement materials by examining the relationship between UCS and SWC, with varying proportions of RAP, CR, cement, and water content. The results enable the development of predictive equations for UCS and cement content as functions of asphalt content, curing age, and water-to-cement ratio (w/c). These equations can be used in the mix designs for both central-plant recycling and in-place recycling, thereby enhancing the efficiency of road rehabilitation and construction control. Finally, the remainder of the paper is organized as follows: Section 2 describes materials; Section 3 details sample preparation and testing; Section 4 presents results and discussion; Section 5 provides a worked mix-design example; and Section 6 concludes.

2. Materials

The construction route for the Rural Roads Maintenance Project, Section Pak 4020 from Highway No. 3168 to Ban Bo Nok in Kui Buri District, Prachuap Khiri Khan Province, in southern Thailand, was selected (Figure 1). The RAP and CR were obtained from road demolition (Figure 2). Sample preparation assumed a milling depth of 20 cm, with pavement layer thicknesses of 4, 5, 8, and 10 cm (Figure 3). The cement used in the study was Portland cement Type I with a specific gravity of 3.15, tested in accordance with ASTM C188-17 [38].

Figure 1. Location of the study road

(A) RAP (B) CR

Figure 2. Reclaimed asphalt pavement (RAP) and crushed rock (CR)

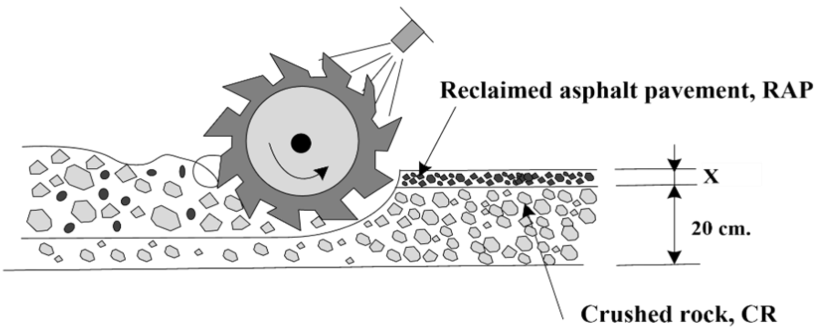

Figure 3. Milling depth of 20 cm for 4, 5, 8, and 10 cm pavement layers

Regarding in-place pavement recycling, the Department of Highways Standard No. DH-S 213/2000 (Pavement Recycling) [22] provides specifications for material selection, proportioning, and performance requirements to ensure the structural integrity and longevity of rehabilitated pavements. Unconfined compressive strength (UCS) is used as the controlling parameter for material quality. The traditional mix design method varies the cement content at 2%, 3%, 4%, and 5% by dry weight. The appropriate cement content is selected based on a minimum UCS of 1.72 MPa (17.5 kg/cm²) as specified by the standard [24].

The Pak 4020 corridor was selected as representative because its layer configuration (4–10 cm AC over a 20 cm recycled base) and in-place recycling practice reflect common rural-road rehabilitation in Thailand. To ensure broader applicability and internal validity, the test matrix spans RAP:CR from 0:100 to 100:0 with cement = 2–5% by dry mass, explicitly including two baselines: CR100 (no RAP) and RAP100 (no CR). These controls bound the mixture space and allow the proposed parameter w/c(1−k·AS) to be validated against mixes without reclaimed asphalt or without virgin aggregate, while design compliance is checked against the 7-day requirement of 1.72 MPa (17.5 kg/cm²).

3. Sample Preparation and Testing Program

Each mix was prepared and tested in triplicate (n = 3) to ensure repeatability; gradation envelopes are given in Figure 4. The RAP was mixed with CR in six combinations: RAP0:CR100, RAP20:CR80, RAP25:CR75, RAP40:CR60, RAP50:CR50, and RAP100:CR0 (RAP and CR indicate percentage contents). The cement was mixed at levels of 2%, 3%, 4%, and 5% by dry weight of the mix, and the samples were tested for their properties to ensure that the unconfined compressive strength met the minimum requirement of 1.72 MPa (17.5 kg/cm²).

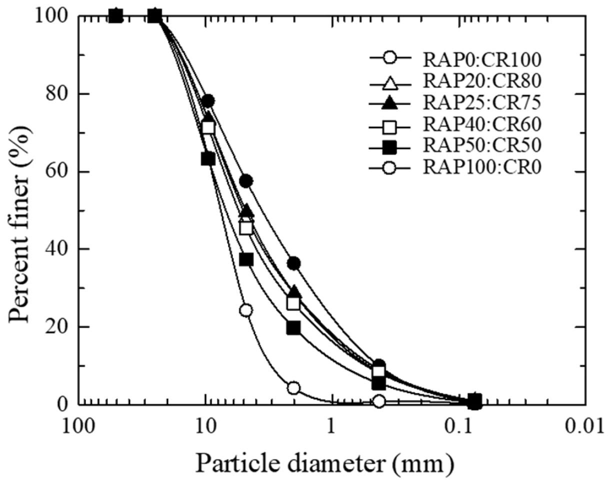

Figure 4. Particle-size distribution of recycled pavement materials

As shown in Figure 4, the fraction of coarse particles increased with increasing RAP content. For all samples, the fraction passing the 2.00 mm (No. 10) sieve was less than 70%, and the fraction passing the 0.075 mm (No. 200) sieve was less than 25%, in accordance with the standard [22].

The unconfined compressive strength test was conducted in accordance with ASTM D2166/D2166M-24 [39] using a standard specimen of 10.16 cm (4 inches) in diameter and compacted with modified compaction energy. Compaction used a Modified Proctor procedure with a 101.6 mm mold (≈ 2,700 kN·m/m³); resulting curves and OMC/dry densities appear in Figure 5 and Table 1. The samples were prepared with three moisture conditions: 2% below OMC (OMC−2), at OMC, and 2% above OMC (OMC+2). Prior to testing, the specimens were soaked in water for 2 h to minimize the influence of matric suction and then air-dried until they reached a saturated surface-dry (SSD) condition. The samples were then tested for compressive strength as shown in Figure 6, with a testing rate of 1.0% of specimen height per minute.

Table 1. Dry density (g/cm³) and OMC (%) from the modified compaction test

Mix ID	Mix Proportions		Dry Density(g/cm³)	OMC %
	RAP (%)	CR (%)		
RAP0:CR100	0	100	2.31	5.03
RAP20:CR80	20	80	2.30	5.22
RAP25:CR75	25	75	2.28	5.13
RAP40:CR60	40	60	2.26	5.24
RAP50:CR50	50	50	2.25	6.01
RAP100:CR0	100	0	2.11	7.17

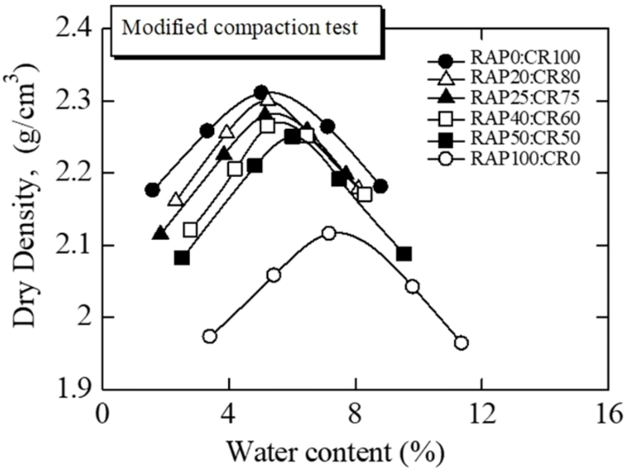

Figure 5. Compaction curve of recycled pavement materials

Figure 6. Unconfined compressive strength (UCS) test

The RAP asphalt-binder content test was conducted in accordance with DH-S 213-2000 Pavement Recycling [22]. Since asphalt content (AS) is a critical parameter in designing the strength of a new mix, it is essential to perform the test each time RAP is reused. The asphalt binder content was measured using the Troxler NTO machine, as shown in Figure 7. The procedure to determine the asphalt content from the original pavement surface follows ASTM D6307-16 [40] and the standard procedures for asphalt concrete [41]

Figure 7. Determination of asphalt content

4. Results and Discussion

Figure 5 and Table 1 show that the dry unit weights from the compaction tests of all samples were above the standard for reclaimed pavement material. The maximum dry unit weight of CR100 was the highest at 2.31 g/cm³ and decreased with increasing RAP content due to the lower specific gravity of RAP compared with CR. The optimum moisture content (OMC), however, increased with increasing RAP content, with the OMC of CR100 at 5.03% and RAP100 at 7.17%. These compaction trends imply that tighter moisture control around OMC is needed at higher RAP to achieve the 7-day UCS target.

These compaction trends are consistent with previous findings: mixes with higher RAP show lower maximum dry unit weight and higher OMC because RAP has lower specific gravity and asphalt-coated particles that retain water and hinder densification [33, 34]. Our measured decrease from 2.31 to 2.11 g/cm³ and OMC increase from 5.03% to 7.17% across CR100→RAP100 align with the ranges reported in earlier RAP–cement studies [26-30, 32].

The unconfined compressive strength correlated well with the water-to-cement ratio (w/c) of soil according to Abrams' theory [25], in line with previously reported work [27, 28]. Accordingly, UCS can be predicted from the w/c ratio, as indicated by Equation 1:

$$q_u = \frac{A}{(W/C)^B} \quad (1)$$

Equation 1 reflects hydration-controlled (Abrams-type) behavior: for a given aggregate skeleton, lowering w/c by reducing W toward OMC or by increasing cement content increases q_u, whereas moving far below OMC risks under-compaction and loss of density. Where A and B are constants that depend on curing age and soil type; A increases with curing age, and B governs the rate of strength reduction with increasing w/c. The value of B is taken as independent of the RAP:CR proportion. However, for recycled pavement material, the tested samples contained various ratios of RAP to CR. Therefore, following previous work, the w/c ratio was modified to eliminate the influence of asphalt content [32, 33]. The relationship between UCS and the modified w/c ratio is represented in Equation 2.

$$q_{uD} = \frac{A}{[W/C(1-k\cdot AS)]^B} \quad (2)$$

The observed reduction in strength with increasing RAP mirrors prior reports that attribute UCS loss to asphalt films limiting aggregate interlock and diluting the effective paste fraction [30, 31]. Our explicit use of AS in the modified parameter w/c(1−k·AS) operationalizes the "binder-effect" concept noted by Suebsuk et al. [33], while the linear relation AS=0.04·RAP (Figure 8) provides a field-ready bridge from RAP percentage to the effective strength descriptor.

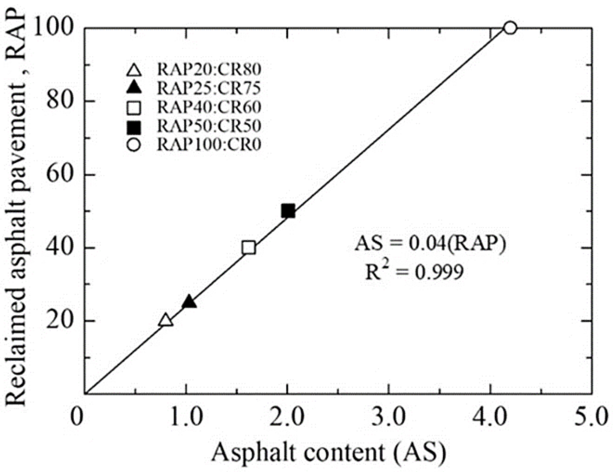

Figure 8. Relationship between asphalt content (AS) and RAP content

The modified term w/c (1−k·AS) captures the asphalt–binder effect that reduces effective water/cement availability; consequently, at the same w/c, mixes with higher RAP (larger AS) are expected to develop lower UCS. Where A, B, and k are empirical material constants; w/c is the water-to-cement ratio; and AS is the asphalt-binder content. The relationship between AS and RAP content was then established. The results show a linear relationship between AS and RAP, as represented by Equation 3.

$$AS = 0.04(RAP) \quad (3)$$

Although A and B depend on soil type and curing age, the rate of strength gain over time was similar for full-depth reclaimed materials stabilized with cement and compacted, because cement hydration is the main factor controlling the rate of increase in strength [27]. Therefore, the relationship in Equation 2 was used to develop a 7-day predictive equation for UCS for full-depth recycled pavement mixed with cement (see Table 2 and Figure 9).

Table 2. Recommended water-to-cement ratio (w/c) and predicted 7-day UCS for recycled material samples at a milling depth of 20 cm (inputs: RAP:CR, W (%), Cement (%), AS; effective term w/c (1 − k·AS) uses k = 0.22)

Sample	RAP:CR	W (%)	Cement (%)	w/c	AS	$q_{u,7}$ (MPa)	w/c (1-k·AS)
1	20:80	3.3	2	1.65	0.80	0.94	1.94
2		3.3	3	1.10	0.80	1.48	1.29
3		3.3	4	0.83	0.80	1.89	0.97
4		3.3	5	0.66	0.80	2.63	0.78
5		5.3	2	2.65	0.80	0.97	3.12
6		5.3	3	1.77	0.80	1.55	2.08
7		5.3	4	1.33	0.80	2.01	1.56
8		5.3	5	1.06	0.80	2.84	1.25
9		7.3	2	3.65	0.80	0.82	4.29
10		7.3	3	2.43	0.80	0.99	2.86
11		7.3	4	1.83	0.80	1.37	2.15
12		7.3	5	1.46	0.80	1.76	1.72
13	25:75	3.4	2	1.70	1.03	0.86	2.09
14		3.4	3	1.13	1.03	1.40	1.39
15		3.4	4	0.85	1.03	1.66	1.04
16		3.4	5	0.68	1.03	2.43	0.83
17		5.4	2	2.70	1.03	0.96	3.31
18		5.4	3	1.80	1.03	1.44	2.21
19		5.4	4	1.35	1.03	1.88	1.66
20		5.4	5	1.08	1.03	2.47	1.32
21		7.4	2	3.70	1.03	0.81	4.54
22		7.4	3	2.47	1.03	0.94	3.03
23		7.4	4	1.85	1.03	1.31	2.27
24		7.4	5	1.48	1.03	1.65	1.82
25	40:60	3.9	2	1.95	1.62	0.81	2.64
26		3.9	3	1.30	1.62	1.35	1.76
27		3.9	4	0.98	1.62	1.61	1.32
28		3.9	5	0.78	1.62	2.38	1.06
29		5.9	2	2.95	1.62	0.77	4.00
30		5.9	3	1.97	1.62	1.39	2.67
31		5.9	4	1.48	1.62	1.83	2.00
32		5.9	5	1.18	1.62	2.44	1.60
33		7.9	2	3.95	1.62	0.75	5.36
34		7.9	3	2.63	1.62	0.92	3.57
35		7.9	4	1.98	1.62	1.28	2.68
36		7.9	5	1.58	1.62	1.55	2.14
37	50:50	4.02	2	2.01	2.01	0.76	2.90
38		4.02	3	1.34	2.01	1.30	1.93
39		4.02	4	1.01	2.01	1.57	1.45
40		4.02	5	0.80	2.01	2.33	1.16
41		6.02	2	3.01	2.01	0.86	4.34
42		6.02	3	2.01	2.01	1.34	2.89
43		6.02	4	1.51	2.01	1.79	2.17
44		6.02	5	1.20	2.01	2.37	1.74
45		8.02	2	4.01	2.01	0.71	5.78
46		8.02	3	2.67	2.01	0.84	3.86
47		8.02	4	2.01	2.01	1.21	2.89
48		8.02	5	1.60	2.01	1.56	2.31
49	0:100	3.2	2	1.60	0	1.24	1.60
50		3.2	3	1.07	0	1.63	1.07
51		3.2	4	0.80	0	2.17	0.80
52		3.2	5	0.64	0	2.70	0.64
53		5.2	2	2.60	0	1.43	2.60
54		5.2	3	1.73	0	1.83	1.73
55		5.2	4	1.30	0	2.37	1.30
56		5.2	5	1.04	0	2.89	1.04
57		7.2	2	3.60	0	1.06	3.60
58		7.2	3	2.40	0	1.22	2.40
59		7.2	4	1.80	0	2.25	1.80
60		7.2	5	1.44	0	2.69	1.44

Notes: (1) $q_{u,7}$ values are predicted from Equation 4 under the shown inputs (not direct test results). (2) The primary unit for UCS in this paper is MPa; values in kg/cm² are provided in brackets for reference. Convert by 1 kg/cm² = 0.0981 MPa; the agency threshold is 1.72 MPa (17.5 kg/cm²). (3) AS is computed from RAP via AS = 0.04·RAP (see Figure 8).

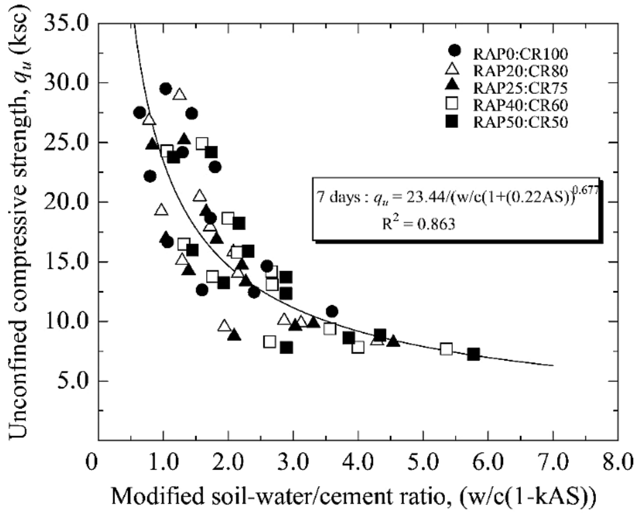

Figure 9. Relationship between UCS and SWC

Derivation outline (transparency). Starting from an Abrams-type relation $q_u = A/(w/c)^B$, we introduce an asphalt adjustment to reflect the binder's reduction of effective water/cement, giving the working parameter $z=(w/c)(1-k\cdot AS)$. The derivation proceeded in three steps: (i) compute asphalt content from RAP via AS=0.04·RAP (Figure 8); (ii) form z for each specimen at 7 days; and (iii) fit the log–log linearized model $\ln q_{u,7}=\ln A-B \ln z$. Parameter k was obtained by optimizing goodness-of-fit (grid/nonlinear search), followed by regression for A and B. The final 7-day model yields k=0.22, A=23.44, and B=0.677 with R^2=0.863; residuals showed no systematic bias across RAP groups. This procedure makes explicit how RAP (via AS) enters the modified w/c term and why the datasets collapse to a single predictive trend

$$q_{u,7} = \frac{23.44}{[W/C(1-0.22\cdot AS)]^{0.677}} \tag{4}$$

where, A = 23.44, B = 0.677, and k = 0.22.

To guide practical proportioning, Table 2 summarizes the recommended water-to-cement ratios (w/c) for recycled materials at a milling depth of 20 cm, together with the input variables used in the prediction (compaction water W, cement content, RAP:CR, asphalt content AS) and the predicted 7-day unconfined compressive strength (UCS) obtained from Equation 4.

Table 2 is a quick lookup: choose RAP:CR, pick W near Modified Proctor OMC, then increase Cement (%) until $q_{u,7}\geq 1.72$ MPa (17.5 kg/cm²); the companion column w/c(1−k·AS) is the field control target.

Consistent with prior studies, higher RAP contents reduce maximum dry density, increase OMC, and depress UCS [14–16, 26–30, 32–34]. By introducing the asphalt-adjusted parameter w/c (1−k·AS), the present datasets with varying RAP, cement, and moisture collapse onto a single monotonic trend (Figure 9), clarifying the mechanism whereby asphalt binder reduces the effective water/cement available for hydration. The 7-day prediction (Equation 4) attains R^2=0.863, comparable to or exceeding reported correlations for cement-stabilized RAP bases, and it provides a transparent basis to select Cement (%) that satisfies the 1.72 MPa (17.5 kg/cm²) specification.

Across all RAP:CR groups, increasing Cement (%) lowers w/c and increases the predicted 7-day UCS; at fixed cement, a higher W raises w/c and reduces strength. The factor (1−k·AS) diminishes with RAP, so strength gain per 1% cement increment becomes smaller at high RAP—underscoring the value of moisture optimization near OMC.

In practice, the designer selects RAP:CR from the existing layer, reads AS from Figure 8, chooses W near the Modified Proctor OMC, and then scans Table 2 to identify the Cement (%) achieving $q_{u,7} \geq 1.72$ MPa (17.5 kg/cm²). The selection can be verified by substituting into Equation 4 via the effective term w/c (1− k·AS); field control then targets the corresponding w/c and compaction settings.

The linear relation AS=0.04·RAP enables direct translation from field RAP percentage to the effective strength parameter in equations 2 and 4, streamlining preliminary proportioning.

Interpretation and use of Table 2. For a selected RAP:CR and compaction water W, increasing Cement (%) lowers w/c, which in turn increases the predicted 7-day UCS; conversely, at a fixed cement content, increasing W raises w/c and reduces strength, consistent with hydration-controlled (Abrams-type) behavior. The effective term w/c (1 − k·AS) captures the influence of asphalt binder: higher RAP → higher AS → a smaller factor (1 − k·AS) → lower effective cementing efficiency and lower predicted UCS. For example, within RAP20:CR80, increasing cement from 2% → 5% reduces w/c from ~1.65 → 0.66 and raises $q_{u,7}$ from ~9.6 → 26.8 kg/cm² (~0.94 → 2.63 MPa), exceeding the 7-day specification of 1.72 MPa (17.5 kg/cm²). At higher RAP contents (e.g., RAP50:CR50), the same cement increment yields a smaller strength gain because (1−k·AS) is lower; this aligns with observed density–moisture trends and supports selecting cement via the table/equation rather than a single fixed dosage.

Figure 9 shows that q_u collapses monotonically against w/c(1−k·AS) over all mixes, indicating that the single modified parameter governs strength; the fitted 7-day model (Equation 4) explains most of the variance (R^2 = 0.863) without systematic bias across RAP groups.

As defined by Thai Soil–Cement Base specifications from the Department of Highways and the Department of Rural Roads [22, 24], the 7-day UCS must be ≥ 1.72 MPa (17.5 kg/cm²). Therefore, by substituting this value into Equation (4), the required water-to-cement ratio can be estimated, as shown in Table 3.

Table 3. Estimated w/c based on a milling depth of 20 cm (AC thickness = 4, 5, 8, and 10 cm)

RAP Ratio	RAP20:CR80 (AC = 4 cm)	RAP25:CR75 (AC = 5 cm)	RAP40:CR60 (AC = 8 cm)	RAP50:CR50 (AC = 10 cm)
w/c	1.31	1.26	1.14	1.07

By inserting the agency threshold $q_{u,7}$=1.72 MPa (17.5 kg/cm^2) into Equation 4, the required w/c can be back-calculated for each milling/AC-thickness scenario (Table 3) and then mapped to Cement (%) at the selected W.

Sensitivity checks indicate that a +1% absolute increase in W typically lifts w/c by ~0.2–0.3 and can lower $q_{u,7}$ by ~10–20% depending on RAP, while a +10% absolute increase in RAP (≈ +0.4 in AS) reduces (1−k·AS) sufficiently to require either ~0.5–0.7% more cement or tighter moisture control to recover strength.

5. Mix Design from Equation

The mixture design for the construction project, which used the in-place recycling method with a pavement thickness of 4 cm and a milling depth of 20 cm, is shown in Figure 10. The results of the modified compaction test were as follows: the maximum dry unit weight was 2.276 g/cm³ and the optimum moisture content was 5.28%. The required unconfined compressive strength (UCS) for the cement-treated material after 7 days of curing was 1.72 MPa (17.5 kg/cm²).

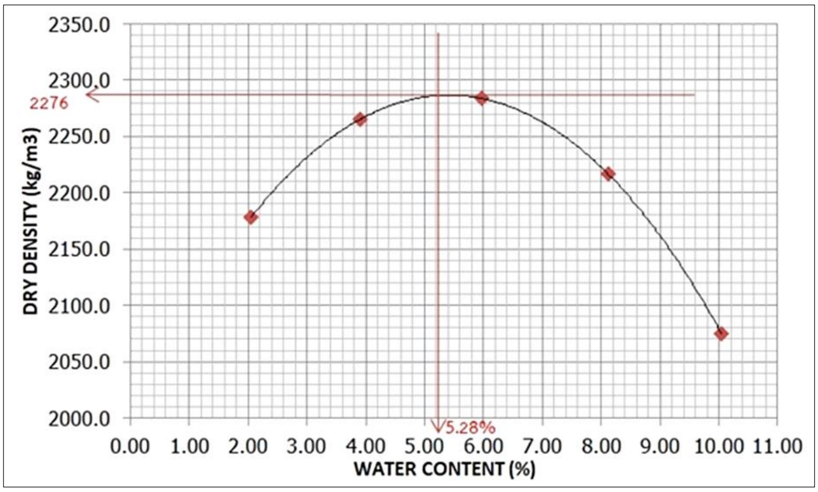

Figure 10. Compaction curve of reclaimed pavement materials

6. Steps in Mix Proportioning

The mix proportion of reclaimed pavement materials can now be designed using the proposed equations. In this exercise, the pavement thickness is 4 cm, the thickness of crushed rock is 20 cm, and the milling depth is 20 cm.

Step 1. Calculate the amount of RAP for pavement thickness of 4 cm, and thickness of base layer (crushed rock) of 20 cm, using the following equation:

$$\text{RAP}(\%) = \frac{4}{20} \times 100 = 20\%$$

Step 2. Find the asphalt content (AS) using Equation 3 for an original pavement thickness of 4 cm and RAP of 20%.

$$AS = 0.04 \times 20 = 0.80$$

Step 3. Calculate the w/c ratio for the designed RAP of 20% (with 4 cm original pavement thickness) by selecting the recommended value from Table 3 (alternatively, use Equation 4).

$$W/C = 1.31$$

Step 4. Determine the amount of cement using w = 5.28% and w/c = 1.31.

$$C = 4.03\%$$

Step 5. Calculate the dry weight of the recycled base-layer sample using a maximum dry unit weight of 2,276 kg/m³, and a volume per square meter of 0.20 m³.

$$Ws = 2276 \times 0.20 = 455.2\ kg/m^2$$

Step 6. Find the weight of water and cement as follows:

Water:

$$W_w = 455.2 \times \frac{5.28}{100} = 24.03\ kg/m^2$$

Cement:

$$W_c = 455.2 \times \frac{4.03}{100} = 18.34\ kg/m^2$$

It has been shown that the improvement of asphalt concrete pavement structures by recycling existing pavement materials with crushed rock and cement for reuse is a viable option. The UCS of the improved material was tested in the laboratory, and the obtained data were used to develop an equation for predicting the 7-day UCS based on the test relationships. The proposed equation can be utilized by researchers and engineers to predict UCS and design mix proportions for asphalt concrete pavement rehabilitation in compliance with the Department of Highways' standards. Additionally, this approach contributes to reducing construction waste generated from road demolition.

Field implementation considerations. This study is laboratory-focused; key on-site challenges not covered include maintaining moisture near OMC under weather/time constraints, achieving uniform cement dispersion and rapid mixing, compaction timing to avoid moisture drift, and managing RAP/AS variability (gradation, contaminants, and gauge calibration). These items will be addressed in future field validation and QC procedures.

7. Conclusions

Improving road infrastructure is crucial for enhancing transportation efficiency and providing convenient travel. This study focused on improving the design of recycled pavement mixtures by testing six mixture types: CR100, RAP20:CR80, RAP25:CR75, RAP40:CR60, RAP50:CR50, and RAP100, with cement contents of 2%, 3%, 4%, and 5%. The results are summarized as follows:

- The maximum dry unit weight of the crushed rock sample (CR100) was the highest at 2.31 g/cm³. The maximum dry unit weight decreased as the amount of RAP increased, with the lowest dry unit weight observed in the RAP100 sample. This indicates that the amount of asphalt binder affects compaction and water content, which in turn influences the density of the mix.
- The value of AS from Equation (3), when the existing pavement thickness is 4 cm, results in RAP = 20%. The optimal cement content for stabilizing the base structure is calculated to be 18.34 kg/m².
- One of the key factors influencing the strength of base-structure stabilization using cement is the water content. Based on compaction tests using the Modified Proctor method, the optimum moisture content is 5.28%. This value is used in calculating the appropriate cement content for base improvement.
- The predictive model for the strength of recycled, stabilized base structures is developed based on the relationship between UCS (q_u) and SWC. The prediction equation for q_u at a curing age of 7 days yields a coefficient of determination $R^2 = 0.863$, demonstrating its effectiveness in evaluating the stabilization of recycled base structures.

It has been shown that the recycling of existing pavement materials with crushed rock and cement for improving the existing road is a viable option. The developed equation for predicting the 7-day UCS based on the test relationships can be utilized to predict UCS and mix proportions for asphalt concrete pavement rehabilitation, contributing to the reuse of material generated from road demolition. Admittedly, the $R^2 = 0.863$ of the predictive model needs additional verification. Additional tests and data are needed to verify the model with independent field sections and explore uncertainty factors (e.g., AS variability and moisture drift) to further support network-level applications.

8. Declarations

8.1. Author Contributions

Conceptualization, A.B., A.A., P.A., and Y.S.; methodology, A.B., P.A., and Y.S.; software, A.B., A.A., and Y.S.; validation, P.A., A.K., P.P., and P.C.; formal analysis, A.B., P.A., and Y.S.; investigation, A.B., A.A., P.A., Y.S., T.T., S.S., P.S., and P.P.; resources, A.B., A.A., P.A., and Y.S.; data curation, A.B., P.A., and Y.S.; writing—original draft preparation, A.B.; writing—review and editing, P.A., Y.S., and P.C.; visualization, A.B., P.A., and Y.S.; supervision, A.B., P.A., Y.S., and P.C.; project administration, A.B., P.A., and Y.S.; funding acquisition, A.B., P.A., and Y.S. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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8.4. Conflicts of Interest

The authors declare no conflict of interest.

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