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TECHNICAL PAPER

Using Reclaimed Asphalt Pavement in Backfilling Works Beneath the Structures

Ahmed Mahmoud A. Mostafa[1] · Ahmed Gamal M. Morsi[1] · Alnos Aly E. Hegazy[1]

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Abstract

Reclaimed asphalt pavement (RAP) is produced in significant amounts. Nevertheless, the use of RAP is limited due to the absence of laboratory and field performance data. This research addresses laboratory and field tests to evaluate the use of RAP and various adapted mixtures in constructions such as road-bed layers and substitution layers. Modified proctor compaction, California bearing ratio, unconfined compression test, and static plate loading tests have been conducted on RAP, a mixture of RAP and crushed stone aggregates (CSA), and RAP stabilized with cement to satisfy the objective. Results have shown that 100% RAP material is suitable for use as a sub-base material. The ability of RAP material to be utilized as a cement-treated base layer is more pronounced when it is stabilized with cement (100% RAP + 8% and 10% cement). Utilization of 100% RAP stabilized with cement has been demonstrated to be economical in comparison with 100% CSA without cement. Finally, RAP material has shown good performance as a substitution layer.

Keywords Reclaimed asphalt pavement (RAP) · California bearing ratio (CBR) · Unconfined compressive strength (UCS) · Cement stabilization · Cement-treated base (CTB)

✉ Ahmed Mahmoud A. Mostafa
a.mostafa37443@beng.bu.edu.eg

Ahmed Gamal M. Morsi
AHMED.MORSY@bhit.bu.edu.eg

Alnos Aly E. Hegazy
alnnos.hegazy@bhit.bu.edu.eg

[1] Civil Engineering Department, Benha Faculty of Engineering, Benha University, Benha, Egypt

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1 Introduction

RAP is defined as deteriorated asphalt obtained as a result of rehabilitation and maintenance of roads. On the other side, RAP contains beneficial materials (asphalt and aggregate) (Al-Shujairi et al. 2021; Han et al. 2011). In terms of RAP generation, road maintenance and road demolition processes generate several million tons of RAP annually. Table 1 indicates the data as per Chyne et al. (Chyne et al. 2019) and Abdel-Wahed et al. (Abdel-Wahed et al. 2020).

In diverse projects across the world, different RAP percentages have been used. Despite that, there is no specific optimal value across studies. Accordingly, there is no definite ideal percentage of RAP recommended for different purposes (Tiza et al. 2020). In consequence, further studies are needed to narrow the broad scope of RAP for various purposes.

Taha et al. (Taha et al. 1999) evaluated the mixture of RAP and natural aggregate as road base and sub-base layers. Compaction and CBR tests were conducted on the mixture of RAP and aggregate with percentages of 0%, 20%, 40%, 60%, 80%, and 100%. The results indicated that the 100% RAP had the lowest strength, with a CBR value of 11.0%. Regarding CBR evaluation, mixtures containing 60% or less RAP were recommended as suitable as sub-base layers. However, only 10% of RAP blends can be used as base materials. A study by Taha et al. (Taha et al. 2002) was aimed at a laboratory evaluation of RAP stabilized with cement and a mixture of RAP and natural aggregate as base materials. Results suggested that 100% RAP aggregate should not be recommended for use as a base material unless stabilized with cement. Guthrie et al. (2007a) investigated the effects of RAP content and cement content on the strength and durability of recycled aggregate base materials. The results indicated that the optimum moisture content (OMC) and maximum dry density ($\gamma_{\mathbf{dmax}}$) of the mixture decreased with increasing RAP contents. Also, the results obtained from unconfined compressive strength (UCS) data showed that UCS decreases as RAP content increases and increases as cement content increases.

In another study, it was found that adding RAP to an aggregate of a base material produces a mixture with lower dry density and strength. Besides, the

Table 1 RAP production per year

Country	Million tons of RAP	Reference
United States (US)	100	Chyne et al. (Chyne et al. 2019)
India	Approx. 100	
European countries	50	
Japan	12	
United Kingdom (UK)	11	
Egypt	Approx. 5	Abdel-wahed et al. (Abdel-Wahed et al. 2020)

CBR of the mixture decreases significantly with increasing RAP content in the mixtures. In addition, results from strength tests (CBR tests) show that the blends containing RAP are only suitable to function as sub-base materials if no stabilizer is added (Alotaibi et al. 2011). Hoppe et al. (Hoppe et al. 2015) stated that the utilization of RAP in road base and sub-base materials is viable and has been implemented by various transportation agencies. On the other hand, it is noted that there is a general trend towards utilizing up to 50% RAP content by weight in aggregate base and sub-base layers. With regard to other investigations, Saha and Mandal (Saha and Mandal 2017) showed that RAP can be used as the sub-base and base material of flexible pavement when RAP is blended with CSA in different proportions and treated with small percentages of cement.

The typical common range from lowest to highest and average values of RAP properties are suggested as follows: specific gravity 2.25 to 2.53 and 2.40, $\boldsymbol{\gamma}_{\mathbf{dmax}}$ 15 to 22.20 kN/m^3 and 18.41 kN/m^3, OMC 3 to 8% and 5.7%, CBR 5 to 25%, and 15%, bitumen content 2.9 to 7.5% and 5%. The maximum RAP percentage in the sub-grade, sub-base, and base layers is 50% (Al-Shujairi et al. 2021). Suebsuk et al. (Suebsuk et al. 2014) studied soil and RAP mixtures treated with cement. The UCS tests were performed on cylindrical specimens that were compacted on the OMC of untreated materials. They demonstrated the potential use of the treated mixtures in the construction of pavement base and sub-base layers.

In the last decade, increased traffic volume in Egypt triggered the development of the transport sector, resulting in the rehabilitation or reconstruction of all deteriorated pavements. In Egypt, approximately five million tons of RAP are produced annually. Nevertheless, less than 10% of RAP is utilized in limited works such as parking lots, temporary road diversions, and so forth (Abdel-Wahed et al. 2020; Mousa and Mousa 2019).

This research addresses laboratory and field tests to evaluate the use of RAP, a mixture of RAP and crushed stone aggregates (CSA), and also RAP stabilized with cement in constructions such as road-bed layers and substitution layers. The primary focus is on preserving the environment, conserving natural resources (aggregates), reducing waste accumulated in landfills, decreasing costs, and using RAP materials again in construction as an alternative to natural aggregates.

2 Materials Used

Reclaimed asphalt pavement (RAP) was sampled from an old pavement in the 6th of October City, Giza, where milling operations were in progress before road maintenance and rehabilitation. Crushed stone aggregates (CSA) were sampled from a site in the 6th of October City, Giza. Ordinary Portland cement (OPC) type I (42.5N) was obtained from the Arabian Cement Company.

3 Experimental Testing Program

Three specific tasks include the following:

1. Physical characterization of both RAP and CSA.
2. Conduct modified proctor, CBR, and UCS tests.
3. Determination of the ultimate bearing capacity of RAP material using a plate loading test.

The modified proctor test and California bearing ratio (CBR) test were conducted on the following mixtures: (i) a mixture of RAP and crushed stone aggregates (CSA) and (ii) a mixture of RAP and cement. The unconfined compressive strength (UCS) test was performed on the mixture of RAP and cement. The static plate loading test was performed on RAP material. The various proportions of mixed materials are presented in Table 2. The flow chart of the experimental study is presented in Fig. 1.

4 Material Characterization

To characterize both RAP and CSA, a variety of tests were performed, including specific gravity tests, loose bulk density tests, absorption tests, asphalt content tests, and Los Angeles abrasion tests.

4.1 Gradation

Sieve analyses were performed on RAP and CSA according to ASTM C136; see Fig. 2. Additionally, Table 3 shows a summary of the gradation parameters, D_{10}, D_{30}, and D_{60}. The coefficient of uniformity (C_u) and coefficient of curvature (C_c) are also mentioned.

Table 2 Mix proportions and their nomenclature

Sample no	Nomenclature	Sample no	Nomenclature
(1)	0% RAP + 100% CSA	(8)	100% RAP + 2% cement
(2)	100% RAP + 0% CSA	(9)	100% RAP + 4% cement
(3)	90% RAP + 10% CSA	(10)	100% RAP + 6% cement
(4)	80% RAP + 20% CSA	(11)	100% RAP + 8% cement
(5)	70% RAP + 30% CSA	(12)	100% RAP + 10% cement
(6)	60% RAP + 40% CSA		
(7)	50% RAP + 50% CSA		

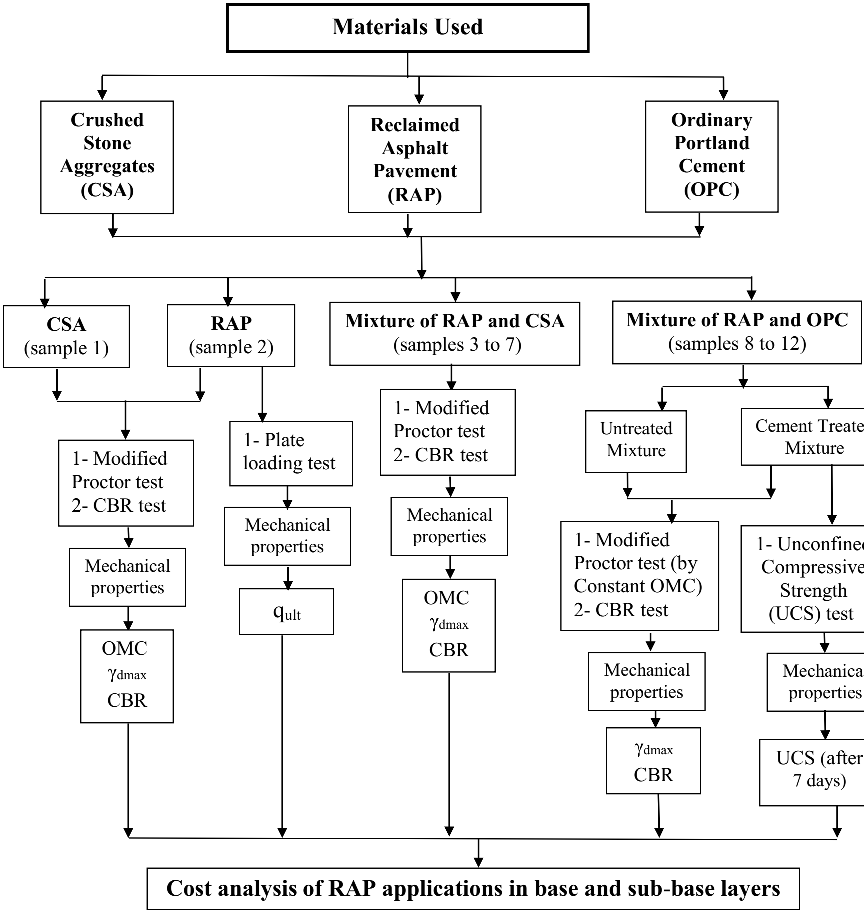

Fig. 1 Flow chart of the experimental plan

4.2 Physical Properties

Table 4 provides a summary of the specific gravity, loose bulk density, sieve analyses, water absorption, soil classification, internal friction angle, asphalt content, and Los Angeles abrasion data obtained on RAP and CSA. The properties of the cement used are given in Table 5.

5 Compaction Testing

Compaction testing with a modified proctor followed the guidelines established in ASTM D1557 method B (ASTM D1557 2012). Figure 3 indicates the correlation between dry density and moisture content for the mixture of RAP and CSA. A

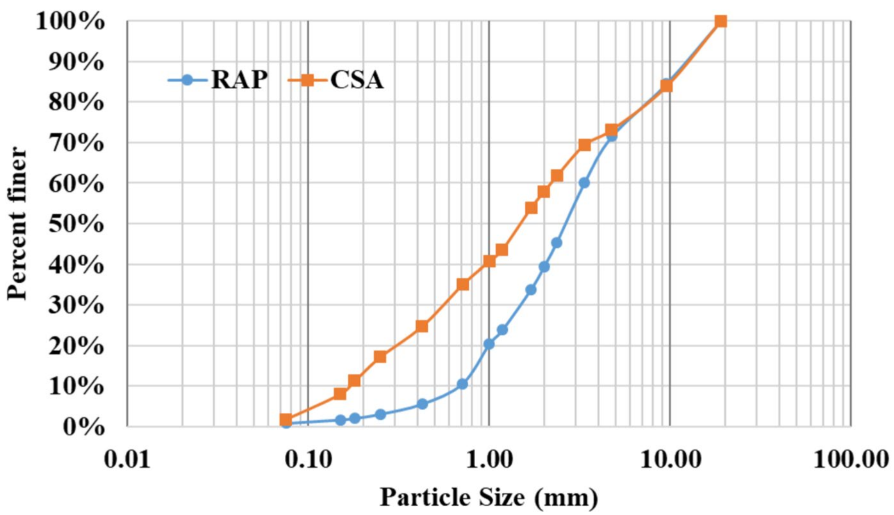

Fig. 2 Particle-size distributions for RAP and CSA

Table 3 Gradation parameters for RAP and CSA

Gradation parameters	RAP	CSA
D_{10} (mm)	0.70	0.18
D_{30} (mm)	1.50	0.55
D_{60} (mm)	3.35	2.15
Coefficient of uniformity (C_u)	4.78	11.94
Coefficient of curvature (C_c)	0.96	0.79

Table 4 Physical properties of RAP and CSA

Property	RAP	CSA	References
Specific gravity	2.413	2.858	ASTM D 854
Loose bulk density (kN/m^3)	13.7	16.4	ASTM C 29
Voids (%)	43.22	42.62	
Water absorption (%)	3.57	5.59	ASTM C 128
Los Angles abrasion (%)	25.37	18.50	ASTM C 131
Internal friction angle (φ°)	33°	34°	Al-Hashemi and Al-Amoudi 2018; ASTM D6393 2014)
Asphalt content (%)	5.22	Indeterminate	ASTM D 2172 method A
Classification	A-1-a	A-1-a	AASHTO

Table 5 The mechanical, physical, and chemical properties of the cement used

Property		Value
Specific gravity		3.15
Sulfate content (%)		3
Chloride content (%)		0.04
Volume expansion (mm)		1
Initial setting time (min)		155
Compressive strength (MPa)	2 days	20.5
	28 days	51.9

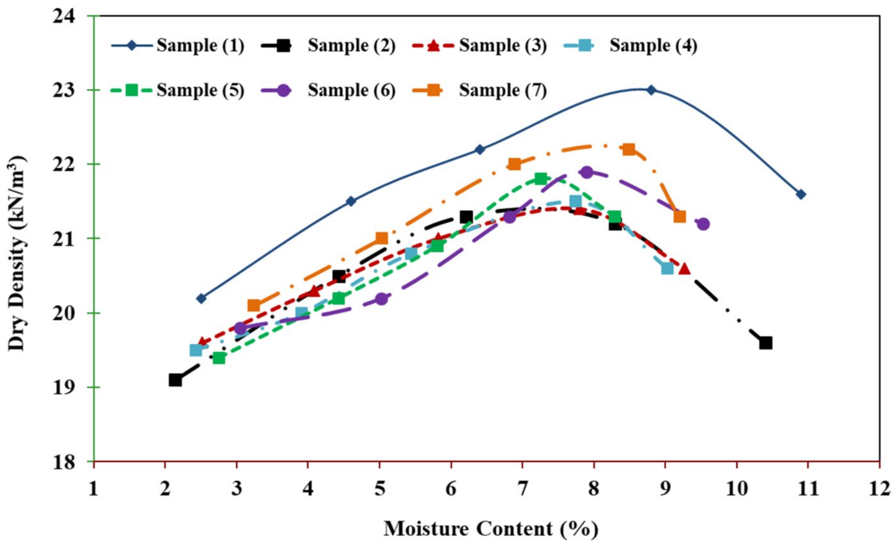

Fig. 3 Compaction test curve results for the mixture of RAP and CSA

summary of the OMC and γ_{dmax} values for the mixture of RAP and CSA and also the mixture of RAP and cement are presented in Tables 6 and 7, respectively.

According to the compaction results as shown in Fig. 3 and Table 6, it is clear that inverse relationships exist between RAP percentages and both OMC and γ_{dmax}. In addition, with an increase in CSA content, the OMC and γ_{dmax} of RAP increased by 11.26% and 3.73%, respectively. Regarding OMC, since water is less absorbed by particles encased with asphalt cement, less water is needed to achieve optimum particle lubrication at higher RAP percentages. The decrease in γ_{dmax} with increasing RAP percentages is related to a lower specific gravity of RAP than CSA.

Considering these test results shown in Table 7, it is remarkable that increasing the cement content led to corresponding reductions in γ_{dmax} of RAP by 0 to 4.20%, with cement content varying from 0 to 10% at constant OMC. This is because cement absorbs little of the OMC needed to achieve the γ_{dmax} of RAP.

Table 6 Compaction parameters for the mixture of RAP and CSA

Sample no	Mixture	γ_{dmax} (kN/m^3)	OMC (%)	Incrementation percentage in γ_{dmax} for RAP (%)	Incrementation percentage in OMC for RAP (%)
(1)	0% RAP + 100% CSA	23.00	8.70	Not applicable	Not applicable
(2)	100% RAP + 0% CSA	21.40	7.10	0.00	0.00
(3)	90% RAP + 10% CSA	21.40	7.50	0.00	5.63
(4)	80% RAP + 20% CSA	21.50	7.60	0.46	7.04
(5)	70% RAP + 30% CSA	21.80	7.50	1.86	5.63
(6)	60% RAP + 40% CSA	21.90	7.70	2.33	8.45
(7)	50% RAP + 50% CSA	22.20	7.90	3.73	11.26

Table 7 Effect of cement content on maximum dry density of RAP

Sample no	Mixture	γ_{dmax} (kN/m^3)	OMC (%) constant	Percent of reduction in γ_{dmax} (%)
(2)	100% RAP + 0% cement	21.40	7.10	0.00
(8)	100% RAP + 2% cement	21.40	7.10	0.00
(9)	100% RAP + 4% cement	21.30	7.10	0.47
(10)	100% RAP + 6% cement	21.10	7.10	1.40
(11)	100% RAP + 8% cement	20.80	7.10	2.80
(12)	100% RAP + 10% cement	20.50	7.10	4.20

The linear relationship between the percentage RAP in the mixture of RAP and CSA and the OMC and also $\boldsymbol{\gamma}_{\mathbf{dmax}}$ is depicted in Figs. 4 and 5, respectively. These empirical formulas are as follows:

$$OMC = 8.66 - 0.015 \times RAP \tag{1}$$

$$\gamma_{dmax} = 23 - 0.017 \times RAP \tag{2}$$

where OMC is the optimum moisture content (%), $\boldsymbol{\gamma}_{\mathbf{dmax}}$ is the maximum dry density (kN/m^3), and RAP is the RAP in the mixture of RAP and CSA (%) (absolute value).

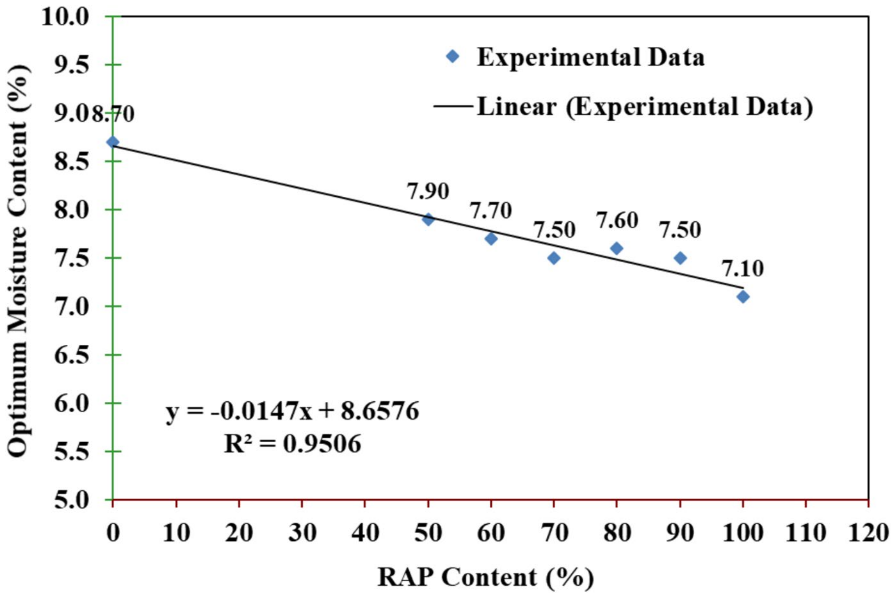

Fig. 4 Correlation between percentages of RAP in the mixture of RAP and CSA and the optimum moisture content

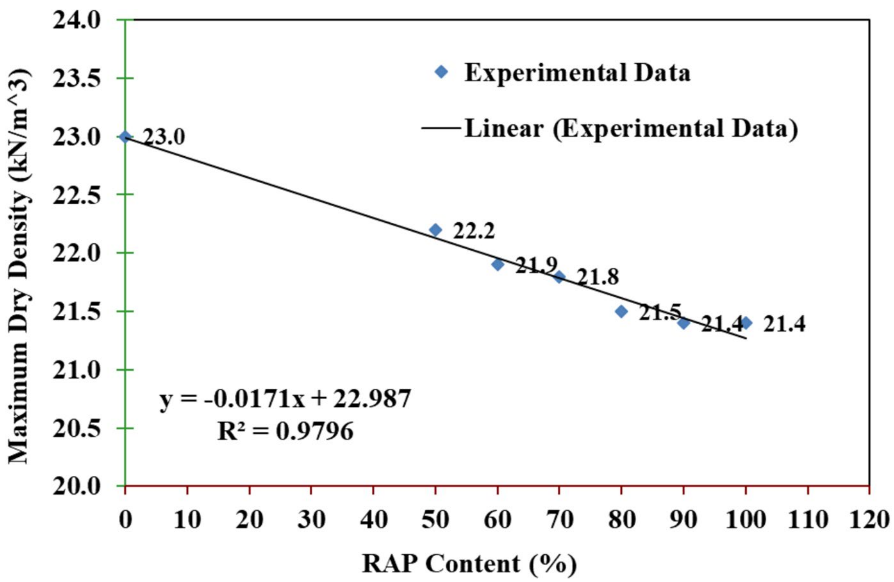

Fig. 5 Correlation between percentages of RAP in the mixture of RAP and CSA and the maximum dry density

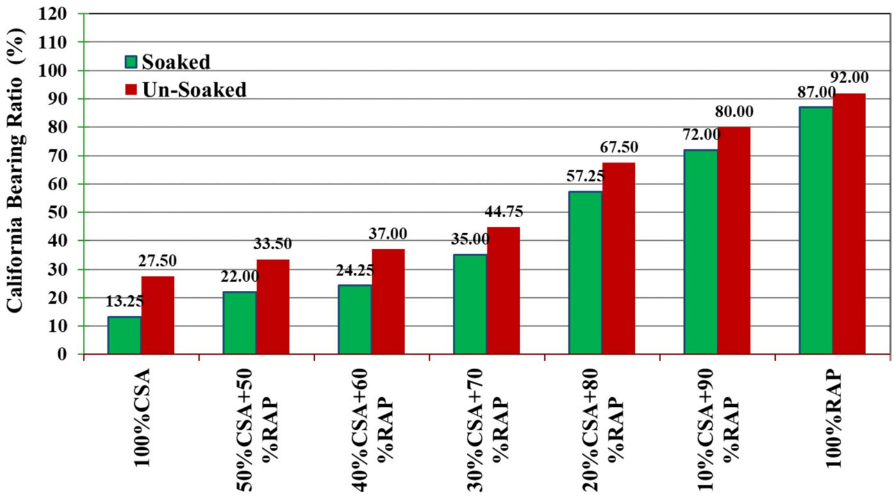

Fig. 6 CBR before and after soaking versus a mixture of RAP and CSA

Table 8 A summary of CBR values for the mixture of RAP and CSA

Sample no	Mixture	Unsoaked CBR (%)	4 days of soaked CBR (%)	Reduction percentage in CBR (%)
(2)	100% RAP + 0% CSA	92.00	87.00	5.43
(3)	90% RAP + 10% CSA	80.00	72.00	10.00
(4)	80% RAP + 20% CSA	67.50	57.25	15.18
(5)	70% RAP + 30% CSA	44.75	35.00	21.78
(6)	60% RAP + 40% CSA	37.00	24.25	34.46
(7)	50% RAP + 50% CSA	33.50	22.00	34.33
(1)	0% RAP + 100% CSA	27.50	13.25	51.82

6 California Bearing Ratio (CBR) Tests

6.1 Mixture of RAP and CSA Results

The California bearing ratio test followed the guidelines established in ASTM D 1883–99 (ASTM D1883 1999). Figure 6 shows the results of unsoaked and four-day-soaked CBR tests performed on the mixture of RAP and CSA. A summary of CBR values for the mixture of RAP and CSA is presented in Table 8.

From Table 8, it was observed that 100% RAP showed an extremely high soaked and unsoaked CBR value. Additionally, as the percentage of CSA in the mixture of RAP and CSA increases, the soaked and unsoaked CBR values of the mixture decrease significantly. This effect is attributed to the lower value of CBR for both soaked and unsoaked specimens of CSA material.

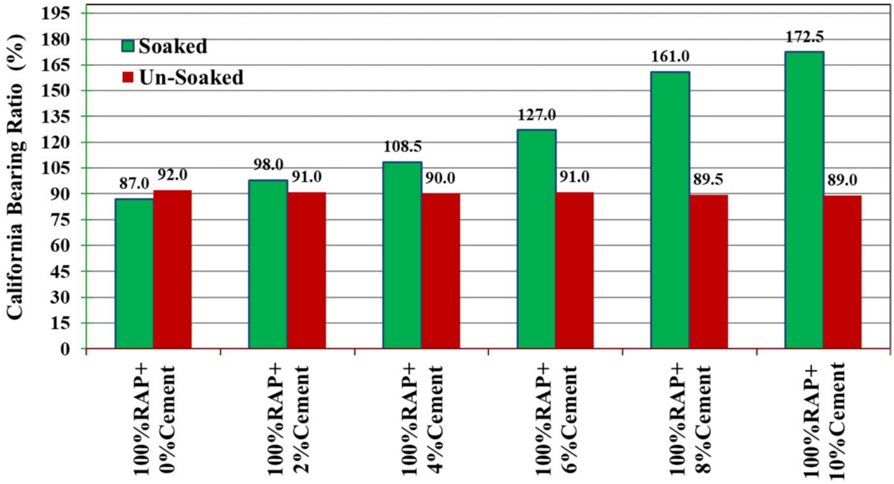

Fig. 7 CBR before and after soaking versus a mixture of RAP and cement

Table 9 A summary of CBR values for the mixture of RAP and cement

Sample no	Mixture	Unsoaked CBR (%)	7 days soaked CBR (%)	Incrementation percentage in CBR (%)
(2)	100% RAP + 0% cement	92.00	87.00	5.43
(8)	100% RAP + 2% cement	91.00	98.00	7.70
(9)	100% RAP + 4% cement	90.00	108.50	20.55
(10)	100% RAP + 6% cement	91.00	127.00	39.56
(11)	100% RAP + 8% cement	89.50	161.00	79.88
(12)	100% RAP + 10% cement	89.00	172.50	93.82

The large-scale reduction in the CBR value of CSA under soaked conditions is related to the higher water absorption of CSA than RAP; the water absorption of CSA and RAP is 5.59% and 3.57%, respectively, which is 56% higher than RAP. This is because most RAP particles are coated with bitumen; thus, less water is absorbed by the particles. Conversely, CSA is composed of non-coated particles, and therefore, high water absorption is achieved by the particles.

6.2 Mixture of RAP and Cement Results

The results of unsoaked and 7-day-soaked CBR tests performed on the mixture of RAP and cement are shown in Fig. 7. A summary of CBR values for the mixture of RAP and cement is presented in Table 9.

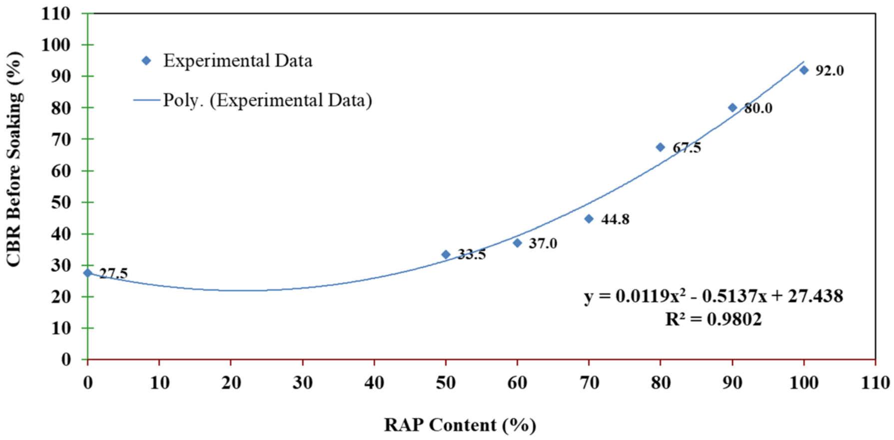

Fig. 8 Correlation between CBR before soaking and percentages of RAP in the mixture of RAP and CSA

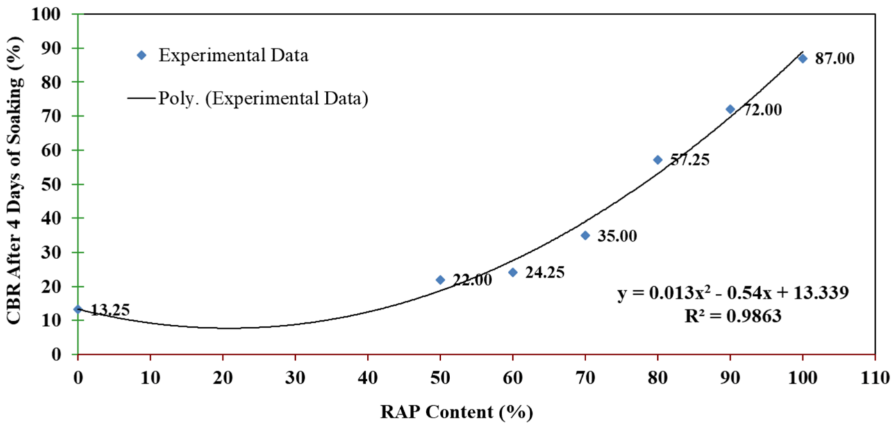

Fig. 9 Correlation between CBR after 4 days of soaking and percentages of RAP in the mixture of RAP and CSA

As seen in Table 9, the RAP treatment with small percentages of cement results in a slight decrease in unsoaked CBR values but a substantial increase in 7-day soaked CBR values. In all cases, it has been observed that the values of soaked CBR are much higher than those of unsoaked CBR because of the curing effect.

The nonlinear relationship between the percentage RAP in the mixture of RAP and CSA and CBR before and after soaking is depicted in Figs. 8 and 9, respectively. These empirical formulas are as follows:

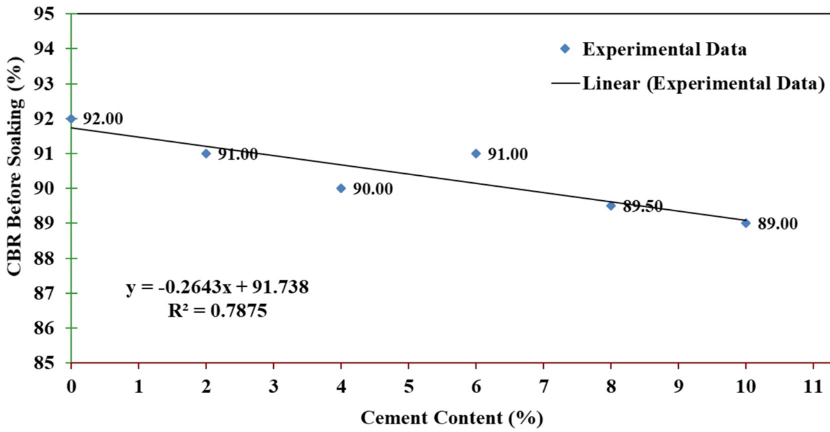

Fig. 10 Correlation between percentages of cement and the CBR before soaking in the mixture of RAP and cement

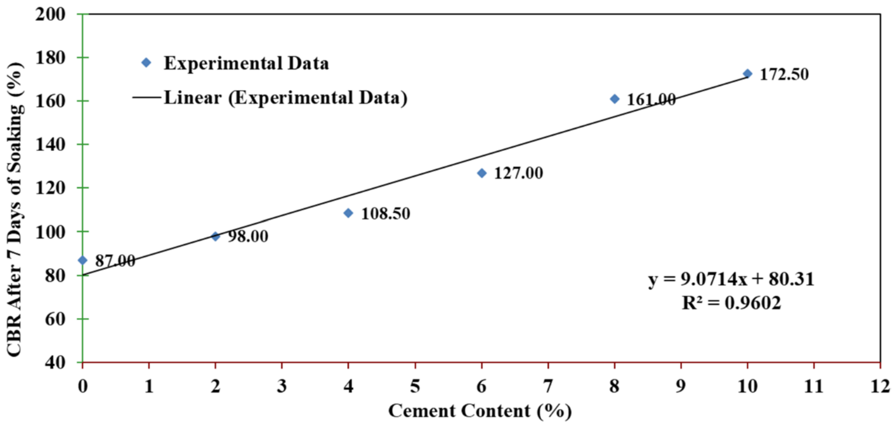

Fig. 11 Correlation between percentages of cement and the CBR after 7 days of soaking in the mixture of RAP and cement

$$CBR = 0.012 \times RAP^2 - 0.51 \times RAP + 27.44 \tag{3}$$

$$CBR = 0.013 \times RAP^2 - 0.54 \times RAP + 13.34 \tag{4}$$

where CBR is the California bearing ratio (%) and RAP is the RAP in the mixture of RAP and CSA (%) (absolute value).

The linear relationship between the percentage RAP in the mixture of RAP and cement and CBR before and after soaking is depicted in Figs. 10 and 11, respectively. These empirical formulas are as follows:

$$CBR = 91.74 - 0.26 \times Cement \tag{5}$$

Table 10 Unconfined compressive strength (UCS) results

Sample no	Mixture	Unconfined compressive strength (N/mm^2)
(2)	100% RAP + 0% cement	0.22
(8)	100% RAP + 2% cement	1.65
(9)	100% RAP + 4% cement	2.22
(10)	100% RAP + 6% cement	3.81
(11)	100% RAP + 8% cement	5.10
(12)	100% RAP + 10% cement	6.03

$$CBR = 80.31 + 9.07 \times Cement \tag{6}$$

where CBR is the California bearing ratio (%) and RAP is the RAP in the mixture of RAP and CSA (%) (absolute value).

7 Unconfined Compressive Strength (UCS) Tests

The unconfined compressive strength test followed the guidelines established in ASTM D1633-17 method B (ASTM D1633 2017). The specimens prepared for UCS testing were compacted on the optimum moisture content (OMC) of

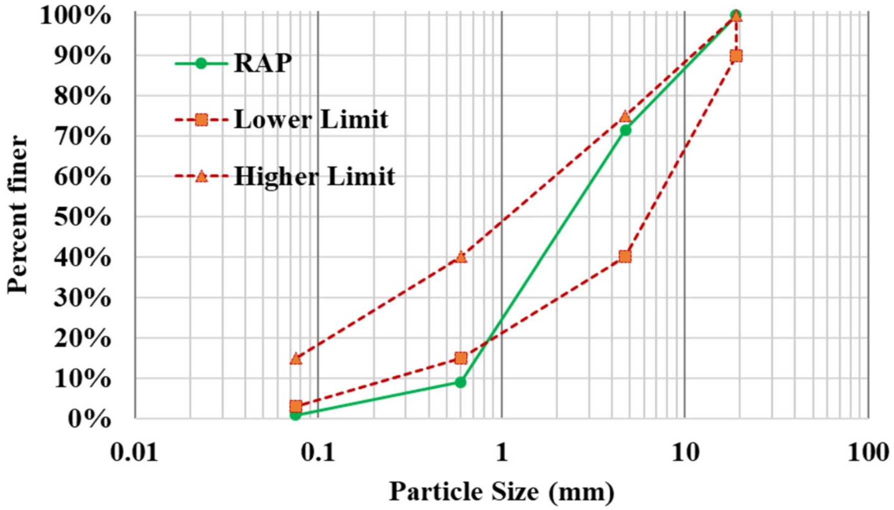

Fig. 12 Comparison of RAP gradation with Egyptian code standards requirements for cement-treated base (CTB) materials

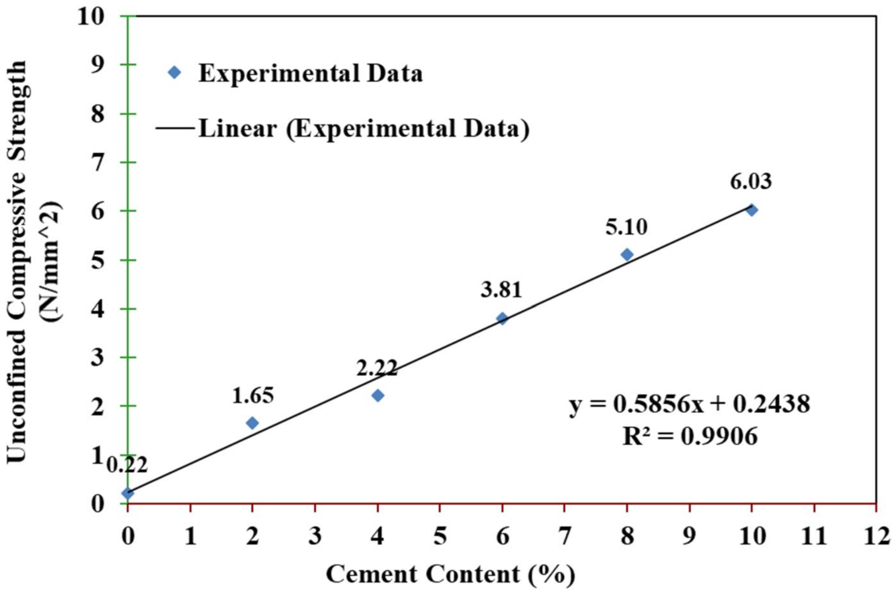

Fig. 13 Correlation between percentages of cement in the mixture of RAP and cement and the unconfined compressive strength (UCS)

untreated materials; see Table 7. After extrusion, all specimens were covered with wet fabric for a 7-day curing period and placed in plastic buckets. According to PCA guidelines (Soil-Cement Laboratory Handbook 1992), the specimens were then subjected to soaking under water for 4 h immediately before the compression test. A summary of UCS values for the mixture of RAP and cement is presented in Table 10. A comparison of RAP gradation with the gradation of cement-treated base material (Egyptian Code 2016) is evident in Fig. 12. The presence of cement increases bonding between RAP particles. Moreover, as the cement content in the mixture increases, the strength value increases. The 7-day UCS value of cement-treated base material must be 50 kg/cm^2 (4.9 N/mm^2) or more according to Egyptian code standards requirements for cement-treated base material (Egyptian Code 2016). Based on Fig. 12 and Table 10, it has been observed that the gradation of the RAP material was approximately inside the specification limits. In addition, acceptable mechanical properties for cement-treated RAP material at a cement content of 8% and 10% were achieved.

The linear relationship between the percentage of cement in the mixture of RAP and cement and the UCS is depicted in Fig. 13. These empirical formulas are as follows:

$$UCS = 0.58 \times Cement + 0.24 \tag{7}$$

where UCS is the unconfined compressive strength (N/mm^2) and Cement is the cement in the mixture of RAP and cement (%) (absolute value).

Table 11 Comparison of RAP physical and mechanical properties with Egyptian code standards requirements for subgrade, sub-base, and cement-treated base (CTB) materials

Property	RAP material	Subgrade material	Sub-base material	Cement-treated base (CTB) materials
		Egyptian code standards (Egyptian Code 2016)		
Water absorption	3.57%	Not available	$\leq$ 10%	Not available
CBR swelling	0.01%	$\leq$ 1.50%	$\leq$ 3%	Not available
Group index	0	0–20	Not Available	Not available
California bearing ratio (CBR)	87%	$\geq$ 15%	$\geq$ 30%	Not available
Unconfined compressive strength (UCS)	5.10 N/mm^2 (at 8% cement) 6.03 N/mm^2 (at 10% cement)	Not available	Not available	$\geq$ 4.90 N/mm^2

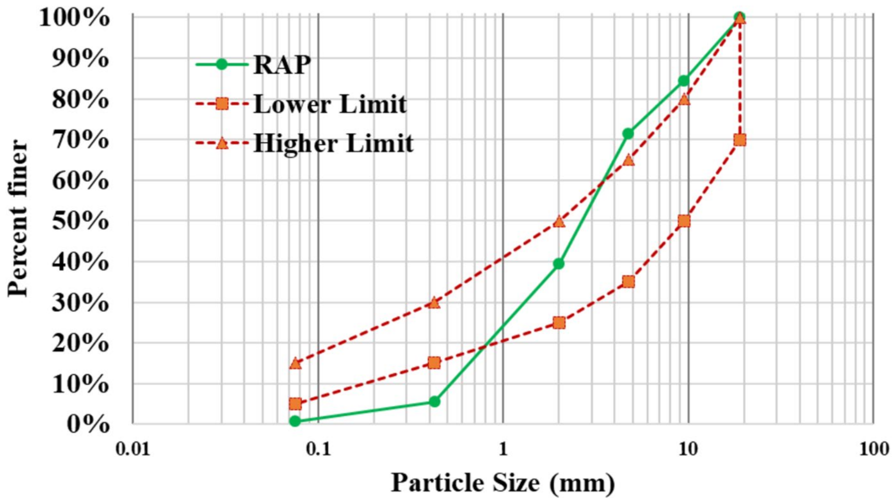

Fig. 14 Comparison of RAP gradation with Egyptian code standard requirements for granular base materials

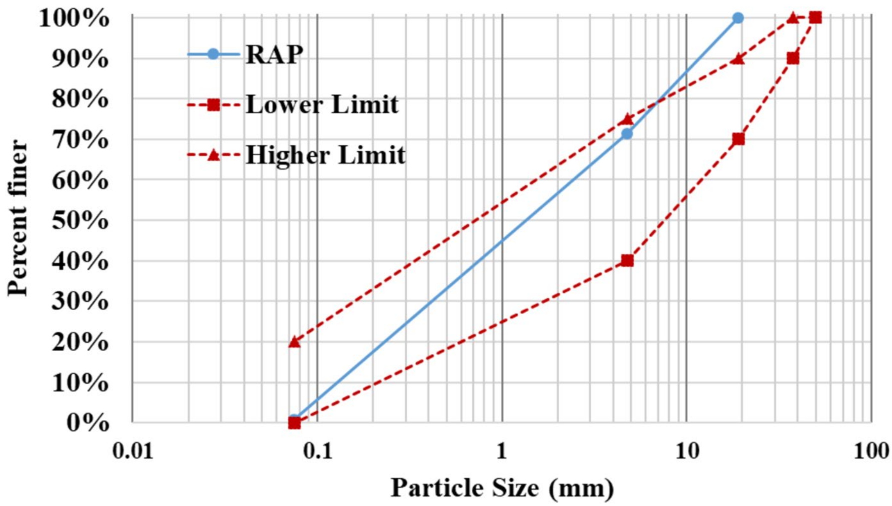

Fig. 15 Comparison of RAP gradation with Egyptian code standard requirements for granular sub-base materials

8 Properties of RAP Materials as Subgrade, Sub-base, and Cement-Treated Base (CTB) Materials

The physical and mechanical properties of subgrade, sub-base, and cement-treated base (CTB) materials according to Egyptian code standards (Egyptian Code 2016) are given in Table 11. A comparison of RAP gradation with Egyptian code standards

Table 12 Results of plate load test

Pressure in N/mm^2	0.01	3.0	6.0	9.0	12.0	15.0
Deformation in mm	0.01	0.52	1.46	2.36	3.26	4.86

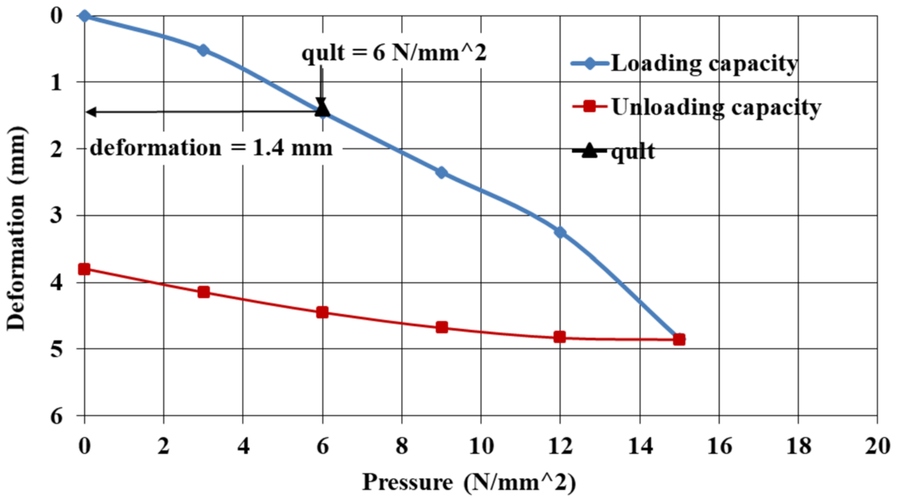

Fig. 16 Pressure-deformation diagram of RAP material

requirements for granular base and sub-base materials (Egyptian Code 2016) is illustrated graphically in Figs. 14 and 15, respectively.

Based on Table 11, it is shown that the physical and mechanical properties of RAP materials achieve the Egyptian code standards requirements for subgrade, sub-base, and cement-treated base (CTB) materials. Nevertheless, the gradation of RAP does not meet the requirements as base course material; see Fig. 14. On the other hand, it has been observed that the gradation of the RAP material was approximately inside the specification limits, see Fig. 15. Consequently, RAP materials can be used as sub-grade, sub-base, and cement-treated base (CTB) materials, and hence, the crust thickness of roads will be reduced, resulting in a reduction in the cost of construction.

9 Field Test for Validation and to Obtain the Ultimate Bearing Capacity of RAP Material

A plate loading test was performed according to ASTM D1194 (ASTM D1194 1994). The field test consisted of a circular steel bearing plate 1 inch (25 mm) in thickness and 30 inch (762 mm) in diameter, a replacement layer with dimensions of 1.0 × 1.0 m and a thickness of 1.0 m. The RAP material is spread in four

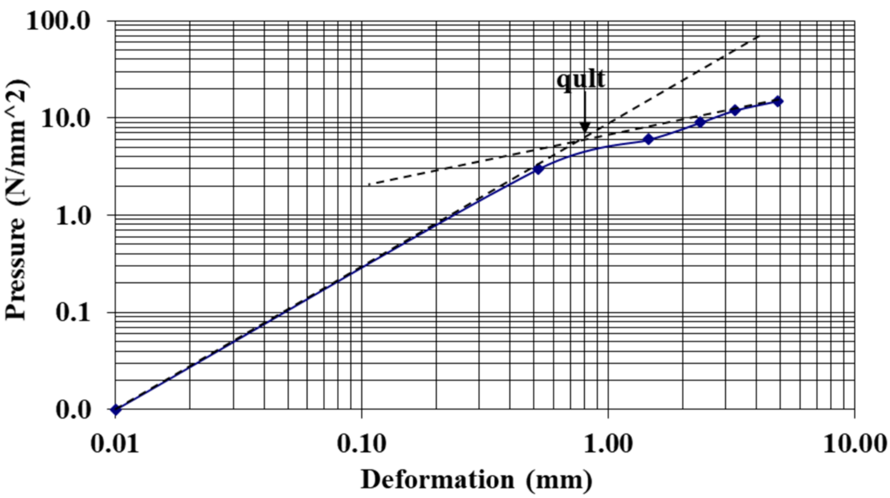

Fig. 17 Plot of plate load test results

layers with a thickness of 25 cm and compacted mechanically by a plate compactor under the optimum moisture content of the RAP material. The surface of the final layer is leveled, and then, the circular steel plate is centered. The results of the test are summarized in Table 12. The same results are plotted on a graph, as evident in Fig. 16. A logarithmic pressure deformation graph, as stipulated by ECP 202 (ECP 202 2007), shows the ultimate bearing capacity (q_{ult}) of RAP material; see Fig. 17. Considering these test results shown in Figs. 16 and 17, it is remarkable that there is a sudden change in deformation after the fourth increment of pressure; thus, the ultimate bearing capacity (q_{ult}) can be taken to correspond to 1.4 mm of deformation of the bearing plate, which is 6 N/mm^2.

10 Discussion of the Obtained Results and the Results of the Previous Studies

Table 13 provides a summary of the maximum percentage of RAP (by weight) allowed. According to Table 13, different RAP percentages have been used in different projects across the world. Nevertheless, there is no specific optimal value across researches, this is because the properties of RAP are influenced by the moisture content, gradation, type of aggregate material, bitumen content, and the crushing (milling) technique; thus, not all RAP is the same. According to the comparison of the present study with the results of other studies, it is evident that the percentages of the RAP allowed were higher than the previous studies' values.

Table 13 Summary of the maximum percentage of RAP (by weight) allowed

Reference	Mixture	Testing	RAP allowed
This study	%RAP + %CSA[(1)]	CBR[(3)]	Up to 100% in the sub-base layer
	%RAP + %CSA	CBR	Up to 100% in the sub-grade layer
	%RAP + %C[(2)]	UCS[(4)]	Up to 100% in the CTB[(6)] layer at 8% C
	%RAP + %C	UCS	Up to 100% in the CTB layer at 10% C
	100%RAP	PLT[(5)]	Up to 100% in the substitution layer
	100%RAP	PLT	Up to 100% in backfilling works
Taha et al. (1999)	%RAP + %Agg.[(7)]	CBR	Up to 60% in the sub-base layer
			Up to 10% in the base layer
Guthrie et al. (2007a)	%RAP + %Agg. + %C	UCS	Up to 50% in the base layer at 1%C
Guthrie et al. (2007b)	%RAP + %Agg	CBR	Up to 60% in the base layer
Alotaibi et al. (2011)	%RAP + %Agg	CBR	Up to 50% in the sub-base layer
Ansori and Radam (2015)	%RAP + %Agg	CBR	Up to 9% in the sub-base layer
			Up to 3% in the base layer

Table 13 (continued)

Reference	Mixture	Testing	RAP allowed
Mousa (2017)	%RAP + %Agg	CBR	Up to 60% in the sub-base layer
			Up to 20% in the base layer
Saha and Mandal (2017)	%RAP + %Agg. + %C	CBR	Up to 25% in the base layer at 1% C
			Up to 50% in the base layer at 2% C
			Up to 75% in the base layer at 3% C
Al-Shujairi et al. (2021)	Not applicable[(8)]		30% to 50% in the sub-grade layer
			50% to 60% in the base and sub-base layers

[1]Crushed stone aggregates

[2]Cement

[3]California bearing ratio

[4]Unconfined compression test

[5]Plate loading test

[6]Cement-treated base layer

[7]Natural aggregates

[8]Review article

Table 14 Flexible pavement design considerations

Category	Condition
Pavement type	Major city streets and thoroughfares and country highways
Equivalent single axle loads (ESALs)	10,000,000
Design period	20 years
Initial serviceability index (P_i)	4.2
Terminal serviceability index (P_t)	2.5
Reliability level (R)	90%
Overall standard deviation (S_0)	0.35
Δ (PSI)	1.7

Table 15 Materials properties used for pavement design

Material	CBR (%)	Resilient modulus (E), ksi	Layer coefficient (a)
HOT mix asphalt (HMA)	Not applicable	400	0.42
Conventional base	80	27.5	0.13
Conventional sub-base	30	15	0.11
Cement-treated base (100% RAP + 10% cement)	172.5	862	0.229
Cement-treated base (100% RAP + 8% cement)	161	770	0.209
Sub-base (100% RAP)	87	20	0.138
Subgrade soil	8	12	Not applicable

11 Cost Analysis

11.1 Design Parameters

A typical cross-section of a flexible pavement consists of a wearing surface layer (hot mix asphalt), a base layer, and a sub-base layer resting on subgrade soil. To investigate the cost analysis, the pavement thickness should be calculated, and the method in this research is the AASHTO guide for design of pavement structures (AASHTO 1993), with design considerations listed in Table 14. All CBR values are measured in the laboratory, except for the CBR values of conventional base layers, conventional sub-base layers, and subgrade soil. Both resilient modulus and layer coefficient are defined with respect to CBR values for different layers from the AASHTO design guide, as presented in Table 15. Five scenarios were considered and numbered from 1 to 5, as illustrated in Table 16, to quantify the benefits of utilizing RAP materials. Scenario 1 represents the traditional pavement section, whereas scenarios 2, 3, 4, and 5 are considered to evaluate the use of RAP as a cement-treated base and a sub-base layer.

Table 16 Results of calculated pavement thicknesses for different scenarios

Scenario	Pavement layer	Thickness (cm)
1	Hot mix asphalt (HMA)	10
	Conventional base	35
	Conventional sub-base	5
	Subgrade soil	Not applicable
2	Hot mix asphalt (HMA)	10
	Cement-treated base (100% RAP + 10% cement)	18
	Conventional sub-base	5
	Subgrade soil	Not applicable
3	Hot mix asphalt (HMA)	10
	Cement-treated base (100% RAP + 8% cement)	19
	Conventional sub-base	5
	Subgrade soil	Not applicable
4	Hot mix asphalt (HMA)	10
	Cement-treated base (100% RAP + 10% cement)	14
	Sub-base (100% RAP)	10
	Subgrade soil	Not applicable
5	Hot mix asphalt (HMA)	10
	Cement-treated base (100% RAP + 8% cement)	15
	Sub-base (100% RAP)	10
	Subgrade soil	Not applicable

Table 17 Unit prices used in cost–benefit analysis

Material	Unit rate
Conventional base	230 LE/m^3
Conventional sub-base	90 LE/m^3
Ordinary Portland cement (OPC)	1950 LE/ton
Reclaimed asphalt pavement (RAP)	Free of cost

11.2 Results

Table 16 shows the results of calculated pavement thicknesses for different scenarios. For all scenarios, at a constant wearing surface with a 10 cm thickness, using RAP as a cement-treated base layer (100% RAP + 8% and 10% cement) and sub-base layer (100% RAP) immediately below the asphalt layer (scenarios 4 and 5) reduces the overall pavement thickness by approximately 31% compared with the traditional pavement section for scenario 1.

The unit cost of the pavement layers was estimated based on the monthly bulletin of building materials prices (Monthly bulletin of building materials prices 2023), excluding transport costs, as shown in Table 17. The results of the cost estimation for pavement

Table 18 Cost analysis results of RAP applications in the base layer and sub-base layer

Scenario	Pavement layer	Thickness (cm)	Cost (LE/m^2)	Total cost (LE/m^2)
1	HOT mix asphalt (HMA)	10	Ignored	85
	Conventional base	35	80.5	
	Conventional sub-base	5	4.5	
2	HOT mix asphalt (HMA)	10	Ignored	51.5
	Cement-treated base (100% RAP + 10% cement)	18	47	
	Conventional sub-base	5	4.5	
3	HOT mix asphalt (HMA)	10	Ignored	43.5
	Cement-treated base (100% RAP + 8% cement)	19	39	
	Conventional sub-base	5	4.5	
4	HOT mix asphalt (HMA)	10	Ignored	37
	Cement-treated base (100% RAP + 10% cement)	14	37	
	Sub-base (100% RAP)	10	0	
5	HOT mix asphalt (HMA)	10	Ignored	31.5
	Cement-treated base (100% RAP + 8% cement)	15	31.5	
	Sub-base (100% RAP)	10	0	

layers are summarized in Table 18. This table illustrates that scenario 5 is the most efficient among all scenarios, with an average saving of 53.5 LE/m^2, which represents a 63% reduction in the cost of pavement, reflecting the effective use of the RAP material.

12 Conclusions

Based on the results of the research study, the following conclusions are drawn:

1. RAP material is a viable alternative to aggregate used in constructions such as road-bed layers, substitution layers, and backfilling works.
2. The OMC and γ_{dmax} of RAP increased by 11.26% and 3.73%, respectively, with the increase in CSA content in the mixture of RAP and CSA. On the other hand, there is a reduction of 4.20% in the γ_{dmax} value of RAP when RAP is blended with cement at constant OMC. In addition, there is a linear relationship between the percentage of RAP and the OMC, as well as γ_{dmax} in the mixture of RAP and CSA.
3. The increase in RAP content in the mixture of RAP and CSA from 0 to 100% showed that the soaked CBR value increased from 13.25 to 87%, respectively, and the unsoaked CBR value increased from 27.5 to 92%, respectively. On the other hand, the increase in cement content from 0 to 10% in the mixture of RAP and cement showed that the

soaked CBR value increased from 87 to 172.5%, respectively, and the unsoaked CBR value decreased from 92 to 89%, respectively. The relationship between the percentage of RAP and CBR before and after soaking in the mixture of RAP and CSA is found to be nonlinear. In addition, there is a linear relationship between the percentage of RAP in the mixture of RAP and cement and CBR before and after soaking.
4. 100% RAP material can be utilized as a sub-base material without adding CSA or cement.
5. 100% RAP material can be utilized as substitution layers beneath the structures and also used as backfilling material without adding CSA or cement.
6. The UCS value of the mixture of RAP and cement increased from 0.22 to 6.03 N/mm^2, with an increase in cement content from 0 to 10%, respectively. Consequently, 100% RAP material can be utilized as cement-treated base (CTB) materials at cement contents of 8% and 10% in the mixture of RAP and cement. There is a linear relationship between the percentage of cement and the UCS in the mixture of RAP and cement.
7. The average reduction in the overall pavement thickness is approximately 31% when a cement-treated base layer (100% RAP + 8% and 10% cement) and sub-base (100% RAP) are used (scenarios 4 and 5). Therefore, scenarios 4 and 5 provide the highest savings among the five scenarios. In particular, an average savings of 63% is achieved when using a cement-treated base layer (100% RAP + 8% cement) and a sub-base (100% RAP) (scenarios 5).

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Code Availability Not applicable.

Declarations

Consent for Publication All of the authors of the article agree to publish.

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Ethics Approval and Consent to Participate This research does not contain any studies with human participants or animals performed by any of the authors.

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