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To cite this article: Yavuz Abut and Salih Taner Yildirim 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **245** 022064

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Structural Design and Economic Evaluation of Roller Compacted Concrete Pavement with Recycled Aggregates

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Abstract. Using recycled aggregates in the concrete offers advantages in many areas such as waste management, energy save and natural resources, conservation of ecological balance, low CO₂ emissions, and users are encouraged in this regard to use these materials. In this study, the profit / loss account arising in the structural design phase was investigated when Reclaimed Asphalt Pavement (RAP), which is limited to use in Roller Compacted Concrete (RCC) pavements, was used as coarse aggregate. RAP materials were used as coarse aggregates by the levels of 0%, 15% and 20% and mechanical properties such as compressive strength, flexural strength, splitting tensile strength and modulus of elasticity were investigated. In the last stage, the mechanical properties obtained from these experimental studies were entered into KENSLABS software as input, and the slab layer thicknesses were determined according to three different subgrade conditions and a certain fatigue criterion. According to the results, it has been determined that the use of RAP at a level of 20% is a serious reducing effect on mechanical properties and the use of RAP at a level of 15% does not bring a great economic benefit but it is reasonable to use it as coarse aggregate in RCC mixes in consideration of environmental effects.

1. Introduction

RCC technology is being used in the construction of dam on a large scale, but its use in road construction is increasing day by day. It has become an important construction technology alternative for local governments' transport policies because it provides about 10-40% of economic efficiency [1,2] due to reasons such as low binder content, non-reinforced application, longer cuts for jointing distance, paved without molding, convenience for early traffic service, and it can be paved and compacted by asphalt equipment. Because it has lower water and cement content than conventional concrete, it has zero slump concrete properties. Methods such as the soil compaction method, the consistency test method, the solid suspension model and the optimal paste volume method are used in the optimization of RCC. In these methods, some regulations are made by trial and error method according to the desired physical results [3-9]. Thanks to low hydration heat of cement, early traffic opening, quick and easy applicability, these coatings provide affordability for dams, airstrips, road and banquet applications [10]. Some researchers have studied long-term mechanical and transportation properties, sulfate and freeze-thaw resistance on RCC mixtures. As a result of these investigations, it has been seen that good results are obtained at a similar level to traditional concrete results [11-19].

The use of recycled aggregate in concrete offers advantages in many areas such as waste management, energy and natural resource savings, conservation of ecological balance, low CO₂ emissions, and



many authorities offer incentives for contractors to use these materials. The use of recycled aggregate in concrete has been studied by researchers in two ways:

Aggregates arising after construction debris are called Recycled Concrete Aggregate (RCA) and have generally been used in base and sub-base layers in several studies [20-25]. It has been found that in a study where RCA is used at the level of 50% and 100% instead of virgin coarse aggregate [26], RCA can be used in the base or sub-base layers with appropriate optimizations according to the cement level and traffic intensity.

The excavation of old or damaged Hot Mix Asphalt results in waste as Reclaimed Asphalt Pavement (RAP) material, which has been studied in many studies [27-34]. In a study [35] of examining the fracture properties of RCC with RAP at the level of 16%, although the compressive strengths were different, the fracture energy properties of RCC with 16% RAP samples were found to be similar.

In this study, when RAP was used as coarse aggregate in RCC content, the profit/loss account investigated as a result of structural design. RAP materials were used as coarse aggregates by the ratios of 0%, 15% and 20% and mechanical properties such as compressive, flexural, splitting tensile strength and modulus of elasticity were examined. In the last stage, KENSLABS software was performed to determine the thickness of the slab layer according to three different subgrade conditions and a specific performance criterion with the economical and environmental evaluation.

2. Material and Method

2.1. Material

Two different aggregate groups, sandstone (2No, 1No, K1) and limestone (K2) were used in the experimental study. RAP material was obtained from Kocaeli Metropolitan Municipality (KMM) Asphalt Construction Site stock area (Figure 1). The specific gravity and water absorption tests of aggregates and RAP materials were determined in accordance with EN 1097-6 and as given in Table 1, the grain size distributions were determined in accordance with AASHTO T 27 and shown in Table 2.

As a binder in accordance with EN 197-1, CEM I 42.5 R type cement obtained from Nuh Cement was utilized. Physical and chemical properties of the cement are also given in Table 3.

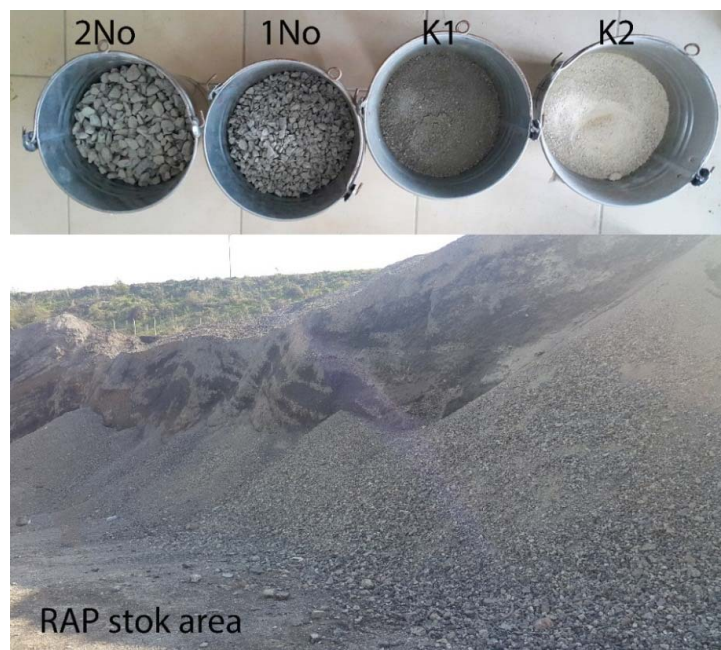


Figure 1. Aggregate groups and RAP materials

Table 1. Physical properties of aggregate and RAP

Code	Size Fractions (mm)	Aggregate Formation	Saturated-Surface-Dry (SSD) Specific Gravity	Water Absorption (%)	Loose Bulk Density kg/m ³
2No	9.5-25	Sandstone	2.72	0.8	1421
1No	4.75-19	Sandstone	2.70	0.8	1445
K1	0-4.75	Sandstone	2.63	1.1	1614
K2	0-4.75	Limestone	2.65	1.2	1689
RAP	4.75-19	Bituminous Materials	2.53	0.5	1323

Table 2. Sieve analysis of aggregate and RAP

Seives size (mm/in)		2No	1No	K1	K2	RAP
25	1	100.0	100.0	100.0	100.0	100.0
19	3/4	87.4	100.0	100.0	100.0	100.0
12.5	1/2	20.4	91.9	100.0	100.0	81.8
9.5	3/8	8.2	68.3	100.0	100.0	64.0
4.75	No. 4	1.4	0.9	99.7	99.5	1.3
1.18	No. 16	0.0	0.0	54.0	49.8	0.8
0.15	No. 100	0.0	0.0	22.0	16.3	0.5
0.075	No. 200	0.0	0.0	18.0	12.7	0.3

Table 3. Physical and chemical properties of cement

Chemical properties		Physical and mechanical properties	
Constituent (%)			
SiO ₂	20.5	Specific gravity (g/cm ³)	3.14
Al ₂ O ₃	4.65	Blaine (cm ² /g)	4015
Fe ₂ O ₃	3.4	Le Chatelier Expansion (mm)	1
CaO	62.7	Setting period start (min)	158
Free CaO	1.71	Setting period stop (min)	222
MgO	1.65	90 μ sieve (%)	0.3
SO ₃	2.94	45 μ sieve (%)	14.5
Na ₂ O	0.18	2 day-strength (MPa)	27.8
K ₂ O	0.41	7-day strength (MPa)	49.2
Cl-	0.01	28-day strength (MPa)	57.6
Insoluble residue	0.5		
Ignition loss	3.36		

2.2. Method

Mix-design has been carried out with reference to "Guide for Roller Compacted Concrete Pavements (GRCCP), National Concrete Pavement Technology Center, 2010" [4]. For this purpose, mixing ratios of the materials are prepared as 25% 2No, 25% 1No, 25% K1, 25% K2 and are plotted in Figure 2. During the first stage of the experimental work, optimal cement level and w/c ratio were determined for CONTROL (C) mixtures. In the second stage, by using the same cement level and w/c ratio values, RAP15 and RAP20 mixtures were obtained by replacing 15% and %20 with 1No aggregate.

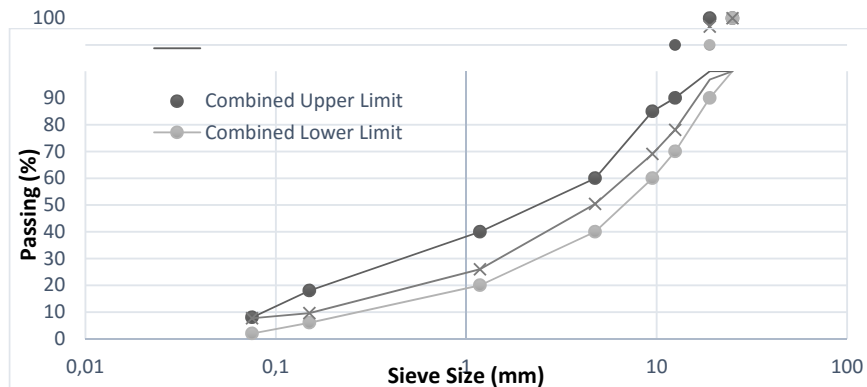


Figure 2. Sieve analysis of Control mixture

Within the scope of the study, a strength of concrete about 35 MPa [36] is targeted. To achieve this, we can apply an experimental study consisting 5 steps:

1. Cement level of 300 kg/m^3 was taken as constant and samples were prepared with w/c ratios of 0.30, 0.35, 0.40 and 0.45. A total of 12 specimens were produced with 3 samples per w/c to ensure optimum water content. Maximum dry unit weight and optimum water content of the C mixtures were employed using the vibrating hammer method (ASTM C1435-99) [37]. For the compaction process; a device (with a capacity of 11 kg, 900 W, with 2000 blows/min) was used (Figure 3-a). A circular tamping plate with a diameter of $140 \pm 3 \text{ mm}$ and a weight of 3.2 kg, which can be mounted on the top of the device shaft, is used as an auxiliary apparatus. A laboratory-type pan-mixer with an effective mixing capacity of 56 liters was used to homogeneously mix the materials. Mixture order was chosen as aggregate, cement, water and the mixing time of each was specified to be 75 s. Mixed samples were casted in 3 lifts of molds ($\text{Ø}150\text{mm}$, $h=300\text{mm}$) and compacted by vibrating hammer for 20 seconds. A tamping rod was used on each lift 15 times to pass to the next lift. In the case of circular mortar around the tamping plate, the compaction process is terminated before 20 s. For the determination of the flexural strength, 9 prismatic specimens with dimensions of $150 \times 150 \times 600 \text{ mm}$ were prepared. A vibratory soil plate compactor was used to compact these samples (Figure 3-b). These procedures were repeated for each sample and the amounts of material for 1 m^3 hardened concrete are given in Table 4.
2. Mixtures of RAP15 and RAP20 were prepared using the same cement level and water content and their mechanical properties such as compressive strength, flexural strength, splitting tensile strength and modulus of elasticity were investigated.



Figure 3. The Vibrating hammer (a), The Vibratory soil plate compactor (b)

Table 4. Quantities of materials for 1 m³ C mixes

	Cement (kg)	2No (kg)	1No (kg)	K1 (kg)	K2 (kg)	Water (kg)	Total (kg)	w/c
1	300	553.8	549.8	535.5	539.6	90.0	2569	0.30
2	300	543.6	539.6	525.6	529.6	105.0	2544	0.35
3	300	533.4	529.5	515.8	519.7	120.0	2518	0.40
4	300	523.2	519.4	505.9	509.8	135.0	2493	0.45

3. Test Procedures

3.1. Dry unit weight and optimum water content

Dry unit weight for optimum water contents of the samples were performed as follows; 28-days samples which prepared with vibrating hammer, were dried at 105 °C until their weights were not changed by %0.5 for 24 hours. After determining the moisture content of the samples, dry unit weight values were determined by using *Equation (1)* [38]. The values determined are the average values of 3 samples.

$$\gamma_{dry} = \frac{\gamma_{wet}}{1 + w} * 100 \quad (1)$$

γ_{dry} : Dry Unit Weight (kg/m³)

γ_{wet} : Wet Unit Weight (kg/m³)

w : Water Content (%)

In order to find the maximum dry unit weight, the first derivative of the polynomial equation is equated to zero so that is useful to find x value that makes the maximum y. Maximum dry unit weight and optimum water content values have been calculated as 2402 kg/m³ and 4.06% respectively (Figure4).

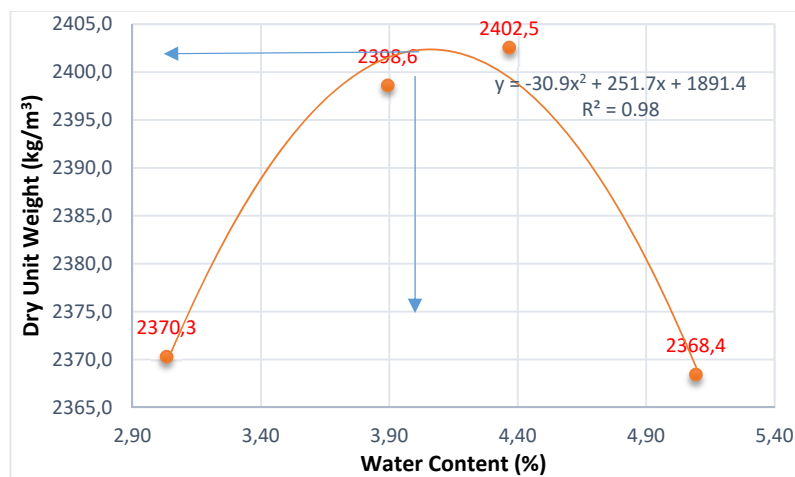


Figure 4. Relation Between dry unit weight and optimum water content

According to the determined optimum water content; C, RAP15 and RAP20 were prepared. The amounts of materials for 1 m³ concrete are given in Table 5.

Table 5. Materials ratio for C, RAP15 and RAP20 mixtures (1m)

Type	Cement (kg)	2 No (kg)	1 No (kg)	K1 (kg)	K2 (kg)	RAP (kg)	Water (kg)	Total kg/m ³	w/c
C	300	540.0	536.0	522.1	526.1	0	110.4	2535	0.368
RAP15	300	540.0	214.4	522.1	526.1	301.3	110.4	2514	0.368
RAP20	300	540.0	107.2	522.1	526.1	401.8	110.4	2508	0.368

3.2. Mechanical experiments

According to the optimum water content and maximum dry density, a total of 27 cylindrical specimens ($\varnothing 150$ mm h = 300 mm) were prepared for the determination of compressive strength according to EN 12390-3 and splitting tensile strength in accordance with EN 12390-6 and tested at the end of 7 and 28-days of cure periods.

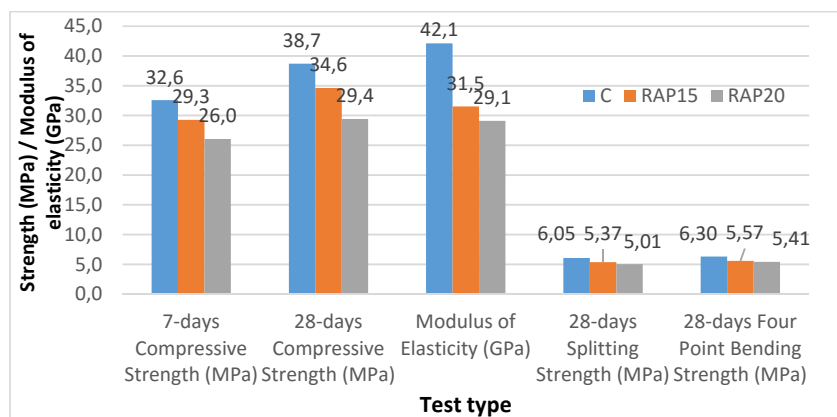
Modulus of elasticity and poisson's ratio were determined in accordance with ASTM C 469 in the Construction Materials Laboratory of Civil Engineering at the University of Kocaeli. Circular frames mounted on cylindrical samples and two analog dial indicators were utilized to measure the vertical and horizontal of deformation. Loading was carried out on a compression press whose capacity 2000 kN with a speed close to approximately 241 ± 34 kPa/s as specified in ASTM C 469. Before testing, peak load values were determined by compressive strength of the counterpart specimens. During the modulus of elasticity test, after reaching 40% of the peak load that was specified in these co-samples, loading was terminated and reloaded again. Two cycles were performed for all groups.

For flexural strength, 9 beam specimens (150 x 150 x 600 mm) were prepared in accordance with EN 12390-6 Part 4. In order to compact the beam specimens, a vibratory soil plate compactor was used and a four-point flexural procedure was applied to determine the flexural strength.

4. Results and Discussion

4.1 Test results

The test results of the samples are shown in Figure 5. It has been observed that RAP materials have a reducing effect on mechanical properties. For RAP15-mixes and RAP20-mixes respectively, this reduction effect on modulus of elasticity is at most 25-31%. RAP mixes reduces 28-days compressive strength, splitting tensile strength and flexural strength by 11-24%, 11-17% and 12-14% respectively. It has been found that RAP15-mixes have suitable mechanical properties for a concrete of about 35 MPa but the same conditions are not valid for RAP20-mixes.

**Figure 5.** The experimental test results

4.2. Structural Design: Numerical example by KENSLABS

A number of design procedures are used for the structural design of RCC slab thickness. Depending on axle loads by the mechanistic properties of the pavement layers and a number of empirical relationships based on fatigue life, slab thicknesses can be determined. The KENSLABS is a pavement design software Huang, that uses the finite element method in dividing into finite rectangle elements [39]. In this system, the wheel loads and subgrade reaction are vertically effected on the generated nodes. The subgrade layer can be defined as liquid or solid model and the forces can be solved as interior, edge or corner concentrating on the slab according to Westergaard (1926, 1933, 1948), Goldbeck and Older’s (1919, 1924) analyzes. The slab is divided into finite elements and the following data is entered as input in KENSLABS;

- The number of layers and thicknesses
- Flexural strength, modulus of elasticity and poisson's ratio
- Equivalent single axle loads (ESALs)
- Wheel position and contact radius, force or pressure
- Desired coordinates for stress or strain values
- Performance criteria (rutting, fatigue, etc.).

The following equations are recommended by the PCA (Packard and Tayabji, 1985) [40] for the fatigue design.

$$\text{For } \frac{\sigma}{S_c} \geq 0.55 : \log N_f = 11.737 - 12.077 \left(\frac{\sigma}{S_c} \right)^{3.268} \tag{2}$$

$$\text{For } 0.45 < \frac{\sigma}{S_c} < 0.55 : N_f = \left(\frac{4.2577}{\frac{\sigma}{S_c} - 0.4325} \right) \tag{3}$$

$$\text{For } \frac{\sigma}{S_c} \leq 0.45 : N_f = \text{unlimited} \tag{4}$$

N_f : the allowable number of repetitions

σ : the flexural stress in slab

S_c : the modulus of rupture of concrete(flexural strength)

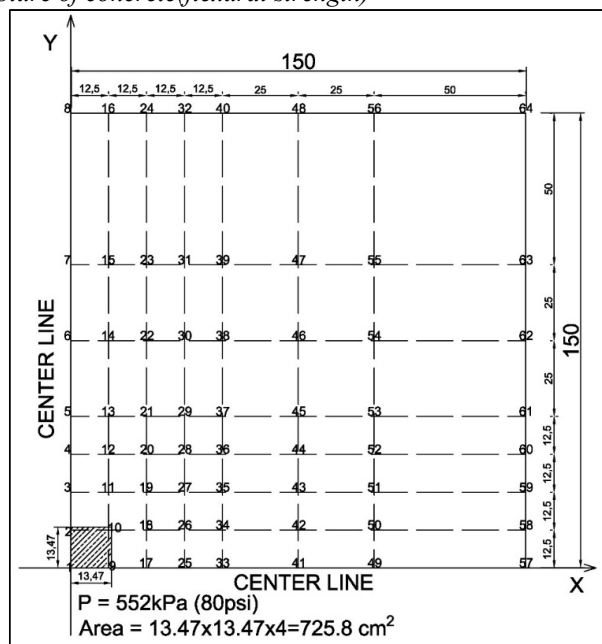


Figure6. Finite element model (measured in cm)

The slab is designed as a coating that residing on an elastic subgrade layer and force densities are distributed across the pavement by divided into finite elements. It can be defined to the system as a whole or by its symmetry with respect to x and y axes. In order to determine the slab thickness, the rigid plate has been defined to KENSLABS by dividing it into 64 nodes and 49 rectangles as shown in Figure6, with symmetry to x - y axis. For three different subgrade layers, poisson's ratio was fixed by 0.4 and the “subgrade resilient modulus” were entered as 5,000 psi (34.5 MPa) for low strength level soil, 10,000 psi (69 MPa) for medium strength level soil and 20,000 psi (138 MPa) for high strength level soil. The wheel pressure and concentrated area were taken to 552 kPa (80 psi) and 725.8 cm² (square) respectively, in accordance with FHWA (1978). The performance criterion is based on Equation 4 and the values of Concrete Modulus of Elasticity (E_c), Poisson's ratio (ν) and Modulus of Rupture of Concrete (S_c) are entered as input which is shown in Table 6, and the operation algorithm to be monitored is shown in Figure 7.

Table 6. KENSLABS input variables

Run	Type	Subgrade Resilient Modulus (M _R), MPa	Concrete Modulus of Elasticity (E _c), GPa	Poisson's Ratio (PR), ν	Modulus of Rupture of Concrete (S _c), MPa
1	C	34.5	42.1	0.202	6.23
2	C	69	42.1	0.202	6.23
3	C	138	42.1	0.202	6.23
4	RAP15	34.5	31.5	0.240	5.57
5	RAP15	69	31.5	0.240	5.57
6	RAP15	138	31.5	0.240	5.57
7	RAP20	34.5	29.1	0.241	5.41
8	RAP20	69	29.1	0.241	5.41
9	RAP20	138	29.1	0.241	5.41

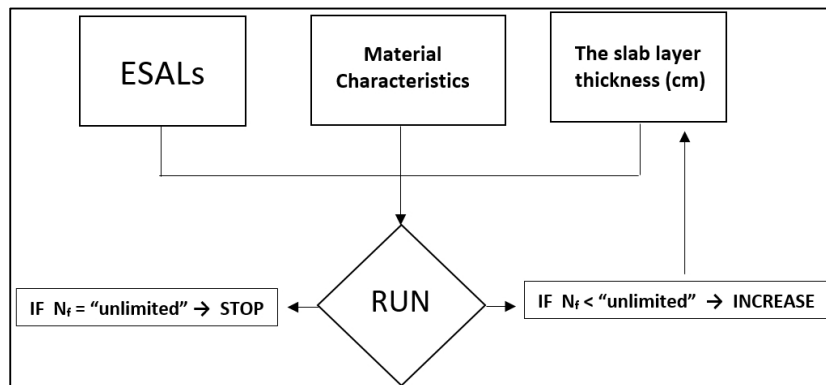


Figure 7. KENSLABS algorithm

The results are shown in Figure 8. If the RAP15 slab thickness is increased by about 1 cm for each subgrade level, the service life becomes "unlimited" as in C mix. In order to ensure the same design life, RAP15 slab thickness should be increased by 6.6%, 7.1% and 6.9% for low, medium and high-strength subgrade type respectively. Instead of a low-strength subgrade, using medium-strength gives an economical efficiency of 8% for slab thickness. This ratio is around 16% by the transition from low-strength to high-strength subgrade type.

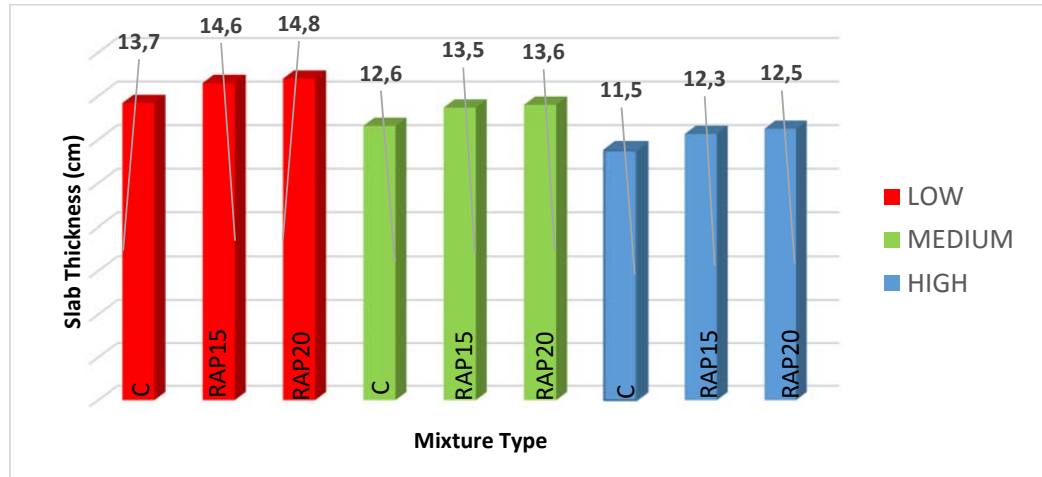


Figure 8. Slab thickness according to different subgrade conditions (cm)

According to these analyzes, if the slab thickness is determined by 15 cm according to a certain fatigue life for C-mixes, approximately 16 cm of slab thickness is required to achieve the same fatigue life when RAP is used. The cost of the aggregate in concrete mix is around 5.1 €/ton in the construction sector of Turkey. When an economical comparison is made between the two mixes, it is understood that for 1 km RCC construction, if RAP is used by %15 in the mix, a profit of 994.4 € will be obtained. The economic assessment to be made when 15% RAP is substituted is shown in Table 7. Since RAP 20-mixes have not suitable mechanical properties for a concrete of about 35 MPa, there is no need for an economic evaluation of this mixes.

Table 7. Economic assessment

	CONTROL	RAP15		
2No (ton/m ³)	0.540	0.540		
1No (ton/m ³)	0.536	0.214		
K1 (ton/m ³)	0.522	0.522		
K2 (ton/m ³)	0.526	0.526		
Total Aggregate (ton/m ³)	2.124	1.802		
Cost of The Aggregate (€/ton)	5.1	5.1	Cost & Benefit (€)	
Cost of The Aggregate In Concrete (€/m ³)	10.6	9.1	1.5	
1 m ² Volume of The Road (m ³)	0.15	0.16		Cost & Benefit For The Road (6.5 m x 1 km) (€)
1 m ² Cost of The Road (€)	1.6	1.5	0.1	994.4

Equation 5 can be obtained when an equation from is generated by input and output data ($R^2 = 0.95$).
 Slab Thickness = $21.49 - 0.05*(M_R) + 0.20*(E_C) + 25.82*(PR) - 3.22*(S_C) + 0.000151*(M_R)^2 - 0.00035*(M_R)*(E_C) - 0.0517*(MR)*(PR) + 0.00507*(M_R)*(S_C)$ (5)

The graphs in Figure 9 are obtained by Equation 5. With these graphics, the slab thickness can be determined according to different M_R , E_C and S_C values. For example, the physical conditions required for a slab thickness of 12-13 cm are indicated by arrows on the graphs. As E_C decreases or S_C increases, the slab thickness decreases. Thanks to Figure 9, different slab thicknesses can be obtained for the different M_R , E_C and S_C values.

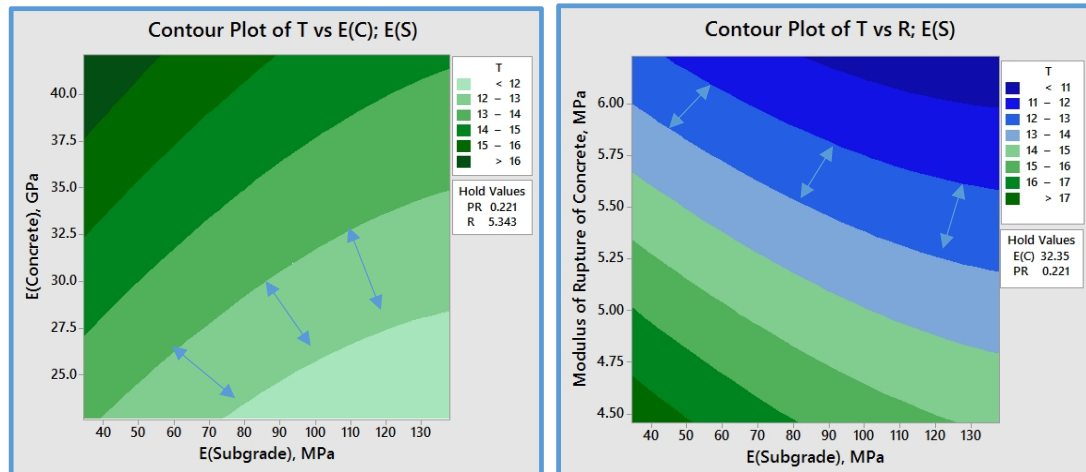


Figure 9. Relation between slab thickness and parameters

5. Conclusion

RCC pavement has recently become an alternative to road construction by many construction authorities, as it is more economical than conventional concrete and can be paved and compacted with asphalt equipment.

Using recycled aggregates for road construction with transportation policies is important for the conservation of energy and natural resources. Using recycled aggregates in RCC has been worked by many researchers. In this study, when RAP has been used as a coarse aggregate in the RCC content, the following findings have been obtained;

- Maximum density method has been applied for proper cement level and w/c determination. Desired strength and economic conditions for a concrete of about 35 MPa have been obtained when the cement level has 300 kg/m³. Maximum dry unit weight and optimum water content of the mixture are 2402 kg/m³ and 4.06% respectively. The cylindrical specimens compacted according to the vibrating hammer method used by this procedure, and the prismatic specimens compacted with a vibratory soil plate compactor showed similar strength properties.
- When 20% of RAP is used in the mixture content, severe decreases on compressive and flexural strength are observed. This proves that these mixes may be suitable for using of the low volume roads even if they are not suitable for concrete at a level of 35 MPa. If 15% of RAP is used in the mixture content, a concrete suitable for a level of 35 MPa is obtained even if mechanical properties decrease. Compressive strength of the RAP15 mixtures is 89% of the C-mixes. Reduction was seen on modulus of elasticity by 75%.
- Depending on the axle loads, rigid pavement thicknesses can be determined with a number of design guidelines using flexural strength of the slab layer and fatigue life based on the performance criteria. Mechanical properties obtained from the experiments in this study are applied as input to KENSLABS software and the slab thickness which should be in case of selecting "unlimited" fatigue life according to three different subgrade conditions are determined. If 15% of RAP is used, the slab thickness is increased by about 1 cm for each subgrade condition and the service life becomes "unlimited" as it is in the case of C-mixes. In order to ensure the same design life, the slab thickness of RAP15 mixtures should be increased by 6.6%, 7.1% and 6.9% for low, medium and, high-strength subgrades respectively. Instead of low-strength subgrade, using Medium-strength subgrade gives the economical efficiency at the rate of 8%. This rate is around 16% in the transition from Low-strength to High-strength subgrade conditions.
- The cost of the aggregate in concrete mix is around 5.1 €/ton in the construction sector of Turkey. When an economical comparison is made between the two coatings, it is understood that if RAP is used, for 1 km of RCC road, a profit of 994.4 € will be obtained.

- At the next stage of the work, mechanical data should be extended with different concrete strength and RAP contents. Durability properties such as freeze-thaw, shrinkage and transportation properties of the mixtures should be entered into the pattern to be established as data for the performance of the pavement design.

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