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Assessment of mechanical properties of roller compacted concrete with reclaimed asphalt pavements

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Abstract. Reclaimed asphalt pavement (RAP) is a sustainable alternative to natural aggregates, addressing material shortages in construction and promoting eco-friendly practices. In this study, the effect of partial replacement of the RAP in roller compacted concrete (RCC) is investigated, whereas the mechanical properties of obtained concrete mixtures are quantified. The obtained RCC mixes are modified by partial replacement of 10% of cement with silica fume (SF) and an addition of 2% steel fiber (St.F) of the total mix as a reinforcement resulting in improvement of the mechanical properties of RCC. Replacement of natural aggregate (NA) by 100%, 70%, 50%, and 30% of RAP are tested for the altered RCC mix. A total of 129-cylinder RCC samples are prepared and evaluated for mechanical and physical properties for the obtained RCC mixes. The samples were evaluated for compressive strength, tensile splitting strength, the modulus of elasticity, the toughness, the water absorption, and the density. The results showed an increasing trend in compressive strength, and modulus of elasticity, and modulus of toughness with increasing RAP percentages. Contrarily, the RCC density and water absorption were reduced by increasing RAP percentage. While the tensile splitting test results did not show a clear trend by altering the RAP percentages. The obtained compressive strength (20.53 MPa) for 100% RAP is still a reasonable value for pavement with light traffic, sidewalks, or similar constructions using RCC mixes. The study showed that the RAP is recommended for potential utilization of numerous known waste materials in the RCC construction.

Keywords: natural aggregate; reclaimed asphalt pavement; rolled compacted concrete; silica fume; steel fiber

1. Introduction

Worldwide, the depletion of construction materials, notably the scarcity of essential resources such as sound aggregates, has prompted significant concern among construction authorities, decision-makers, and researchers, which situation causes urgent attention to identify solutions and alternatives. Pavement recycling appears as a practical approach, characterized by its environmentally friendly nature, to address the pressing issue of NA limited resources in construction. For asphalt pavements in the European-27 countries, in 2023, the total production of hot and warm mix asphalt was 202.7 million tons. It was estimated that a total of 37.5 million tons of reclaimed asphalt were available, out of which 76% were re-used, 20% were recycled, and only 4% were used on unknown applications or put to landfill (EAPA 2023).

Pavement recycling practice involves the reuse of existing damaged pavements, including both asphalt and concrete, in new construction projects. This practice serves a three-fold purpose: preserving the natural environment, reducing waste and offering cost-effective construction material FHWA (Federal Highway Administration 2010).

The utilization of reclaimed asphalt pavement (RAP) as a recycled material has gained widespread acceptance in many countries globally due to its dual benefits of environmental sustainability and economic viability for construction endeavors (Selvam *et al*. 2022).

The RCC is typically composed of aggregate, cement, pozzolan, and water, with occasional inclusion of admixtures to modify specific properties Portland Cement Association PCA 2003, Debbarma *et al*. (2020), Bilodeau *et al*. (2011), and Neville and Brooks (2010). The dry concrete variant, featuring low cement content, is applied and compacted akin to soil, primarily for constructing massive structures like dams or large horizontal surfaces such as pavement foundations FHWA (Federal Highway Administration 2010).

The RCC constitutes a unique type of concrete mixture distinguished by dry consistency and absence of slump compared to conventional cement concretes, which finds widespread application in diverse construction contexts such as low-traffic pavements, remote area highways, dams, and large-scale structures. The compaction characteristics of extremely dry concrete are evaluated using a new method based on a variable vibration table, a fundamental relationship linking energy of compaction to ‘filled volume ratio’ is used to assess the efficiency of compaction and to evaluate the optimum mix composition as study by Kokubu *et al*. (1996). In road construction, RCC is applied using asphalt paving equipment, rendering its suitability for many construction projects World Highways (2013). Al-Abdul Wahhab and Asi (1994) pioneered the development of a mathematical model to predict the compressive strength of

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RCC mix designs in Saudi Arabia. Their research elucidated the optimal proportions of locally available materials by investigating the effects of varying water-to-cement ratios, coarse-to-fine aggregate ratios, and total aggregate-to-cement ratios on RCC's rollability, density, and strength characteristics. Various trials worldwide have investigated the use of RAP as a partial replacement in RCC mixes (Settari *et al*. 2010, Hassan *et al*. 2000, Mahdavi *et al*. 2021, Rezaei *et al*. 2022, and many others).

Rezaei *et al*. (2022) investigated the impact of replacing natural aggregates with RAP in Roller-RCC mixes, noting a decrease in mechanical strength of the mixture with RAP inclusion. They found optimal strength with 50% RAP replacement. To bolster strength in 50% RAP RCC, Micro Silica (MS) partially replaced cement at various levels, leading to improved strength in all mixes tested. Notably, 50% RAP and 9% MS RCC showed a 20% increase in compressive strength, with 6% and 2% gains in tensile splitting and flexural strength.

Hassan *et al*. (2000) observed that RAP reduced concrete strength proportionally to its use. Fly ash addition reduced porosity and permeability, enhancing performance. RAP concrete exhibited enhanced ductility and strain capacity, making it suitable for non-structural applications like road bases, sub-bases, and non-structural applications.

Bilodeau *et al*. (2011) assessed the impact of using RAP as aggregates on the mechanical properties of RCC mixtures, aiming to mitigate strength reduction by incorporating steel fibers. Coarse aggregates were replaced with RAP at rates of 40% and 80%, and tests were conducted to measure compressive strength, tensile strength, and compressive modulus of elasticity. The findings revealed significant decreases in mechanical properties with increased RAP content. Additionally, the complex modulus of elasticity showed heightened sensitivity to temperature and loading frequency with RAP inclusion, with decreases in temperature and increases in loading frequency resulting in higher complex modulus of elasticity in RCC mixtures containing RAP.

Nguyen *et al*. (2019) researched the use of RAP as aggregates in RCC for base layers in road pavement. They selected RAP from two different sources, incorporating it into RCC mix designs at three RAP contents (0%, 40%, and 80% by mass of aggregates) with two types of cement (PCB30 and PC40). Laboratory tests on the mixes assessed traditional mechanical properties over various curing periods, with results from one RAP source indicating promising performance for road pavement applications.

Ashteyat *et al*. (2024) conducted an assessment on the incorporation of recycled concrete aggregate (RCA), recycled asphalt pavement aggregate (RAPA), and silica fume (SF) in roller-compacted concrete (RCC). Mechanical properties examined included compressive strength, tensile splitting strength, modulus of elasticity, modulus of rupture, and density. Water absorption of the RCC was also measured as an indicator of durability. The study concluded that partial cement replacement with 2.5% and 5% SF enhanced the mechanical properties of conventional RCC mixes, along with other positive effects such as reducing dry density and water absorption. While replacing natural aggregates (NA) with RCA and RAPA slowed the improvement of mechanical properties, the RCC still achieved the required compressive stress.

Hosseinnezhad *et al*. (2021) investigated the mechanical properties of RCC mixtures incorporating recycled concrete aggregate (RCA). They focused on compressive strength, splitting tensile strength, pulse velocity, and drop weight impact resistance. The study replaced varying percentages of crushed limestone aggregate with RCA in RCC mixes with different cement contents. Results showed that increasing recycled aggregate reduced concrete's mechanical properties, with no significant impact up to a 25% replacement level, especially in mixes with higher cement content to offset the adverse effects.

Hajiebrahimi *et al*. (2024) investigated the use of waste rubber as a replacement of aggregates in roller compacted concrete (RCCP). The use of waste rubber reduced the compressive, flexural and splitting tensile strengths. RCC with a strength of 30 MPa could be produced at 10% waste rubber content and the RCCP concrete was more ductile than control sample.

Keles *et al*. (2024) studied the mechanical properties of RCC mixtures incorporating crumb rubber, RAP, and slag. The results indicated that increasing RAP percentages decreased indirect tensile strength but increased flexural strength. The optimum mix design included 70% RAP, 25% slag, and 10% crumb rubber.

Ahmadi *et al*. (2020) investigated the mechanical properties of RCC involving RAP with different percentages (10%, 20%, and 40%). The result revealed the incorporation of RAP decreases compressive strength, modulus of elasticity, and indirect tensile strength of RCC mixtures. In addition, the result showed increasing RAP percentages enhancing the toughness index of RCC.

Rahman and Khattak (2022) assessed the use of RAP and geopolymer cement binder (GPC) in RCC mixtures, showing that GPC-based RCC exhibited higher strength and flexibility than mixes with ordinary Portland cement (OPC). The study demonstrated comparable results between geopolymer-RAP mixtures and standard mixtures with 12% OPC.

Tavakoli *et al*. (2022) used waste clay bricks (ranging from 0% to 100%) as a substitute for sand in RCC mixtures. They also incorporated silica fume (SF) to enhance the mechanical properties of the developed RCC mixtures, with SF percentages ranging from 5% to 15%. The optimal percentage of SF was found in RCCP mixtures, and this optimal percentage was used in the brick combination. The results showed that up to 25% of brick substitution did not have any detrimental effect on the properties of the concrete. However, if the clay brick percentage increased to more than 50%, the concrete properties were adversely affected. The SF did not consistently enhance the concrete properties due to the negative effect of the high clay brick content.

Abut and Yildirim (2022) focused on the durability properties of RAP-containing RCC pavement. They found that incorporating up to 20% RAP in RCC had no significant impact on freeze-thaw resistance but led to a decrease in flexural strength during freeze-thaw cycles.

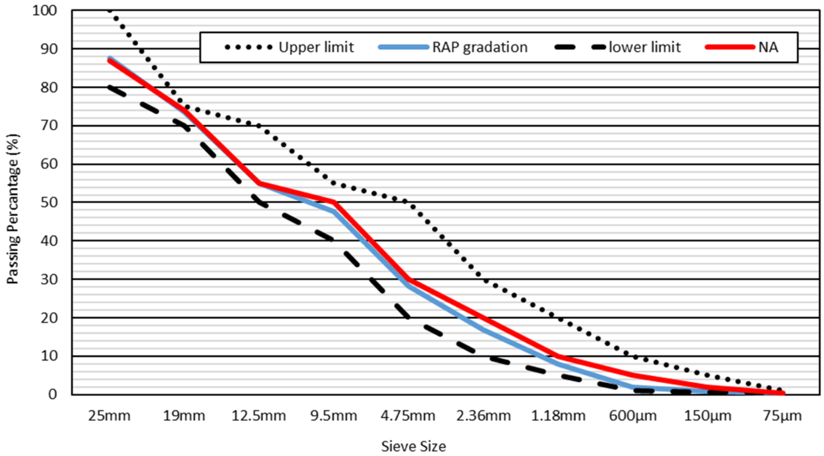

Fig. 1 RAP and NA gradations with specification limits

Chaikaew *et al*. (2024) explored using RAP as a substitute for natural coarse aggregate in RCC and determined optimal ratios of cement to RAP for maximum dry density and compressive strength. The study concluded that a 1:6 ratio was ideal for achieving these properties while minimizing environmental impact.

Ramkumar and Ramakrishna (2024) investigated the sustainable use of red mud and RAP in RCC mixtures, finding that a 50% replacement of natural aggregates with RAP led to decreased mechanical properties and increased moisture content. They identified an optimal 15% red mud by cement weight for maintaining mechanical properties

This study explores the utilization of RAP as a partial replacement NAs in RCC, aiming to assess its mechanical and durability behavior in laboratory testing. The research evaluates the efficacy of incorporating RAP, a waste material, in concrete construction applications.

2. Experimental work

2.1 Materials

The RCC mixes were prepared using standard Portland pozzolanic cement type (CEM II/B-P 42.5N) in compliance with the European standard specification (BS EN197-1 2011) and Jordanian standard specification (JS 2238-4 2019). In every mix, two components of course and fine aggregate were utilized. The RAP was collected from a demolished road pavement disposed in Greater Amman Municipality. The RAP aggregates were obtained by breaking the junk using mechanical crusher.

The NA was collected from a nearby crusher. For all aggregate types (NA, RAP), crushed coarse aggregates with a maximum size of 19 mm were utilized, and fine aggregates (mixture of crushed aggregate and sand) were used as the fine aggregate. All types of concrete underwent sieve analysis to get well-graded mixed aggregate in compliance with the ACI211.3R-02 requirements (ACI 2002). The aggregate gradation and suggested gradation used for RCC are shown in Fig. 1. The aggregate's characteristics, like specific gravity and the absorption were calculated using the coarse and fine aggregate specifications. Table 1 lists the physical characteristics of the NA and RAP aggregates. The SF produced from burning elemental silicon or silicon-containing alloys in electric arc furnaces was used as a partial replacement of cement in all mixes. SF has a bulk density of 250 kg/m³, specific gravity of 2.2, and particle size from 0.1-0.2 µm as specified by ASTM C1240. Portland cement has a higher specific gravity than silica fume (3.15 compared to 2.22). Additionally, Type 4 steel fiber (St.F) was used as concrete reinforcement for all mixes. This material has dimensions of 60 mm in length and 0.75 mm in diameter as specified by ASTM A820 M04 with anchorage (hooked end) at both ends and aspect ratio (L/D) equal 80.

Table 1 Characteristics of RAP and NA aggregates used in the study

Aggregate type	Specific gravity		Absorption		Abrasion	
	Fine	Coarse	Fine	Coarse	Fine	Coarse
NA*	2.363	2.63	7.75	2.85	-	60
RAP**	2.157	2.30	1.55	2.00	-	50

*NA: Crushed natural aggregate
**RAP: Reclaimed asphalt pavement

2.2 Methodology

The research encompasses the following key elements:

- Establishing the optimum water content for the mixtures through the soil compaction technique to observe the correlation between various water content levels and dry density (kg/m³). During this phase of testing, seventy-five unique combinations were created and compacted.
- Incorporating a consistent percentage of 10% by weight of Silica Fume (SF) to replace cement, along with 2% by weight of Steel Fiber (St.F). These additives aim to improve the physical characteristics of the final mixtures. These proportions remain constant across all combinations of RAP and NA in the RCC mixes.

Table 2 Experimental design of the study

Test name	Mix*	No. of samples
Optimum water content	NA	12
	NA+10%SF + 2% St.F	12
	0%NA + 100%RAP + 10%SF +2% St.F	9
	30%NA + 70%RAP + 10%SF +2% St.F	15
	50%NA + 50%%RAP + 10%SF +2% St.F	15
	70%NA + 30%RAP + 10%SF +2% St.F	12
Compressive strength	NA	3
	NA+10%SF + 2% St.F	3
	0%NA + 100%RAP + 10%SF +2% St.F	3
	30%NA + 70%RAP + 10%SF +2% St.F	3
	50%NA + 50%%RAP + 10%SF +2% St.F	3
	70%NA + 30%RAP + 10%SF +2% St.F	3
Tensile splitting strength	NA	3
	NA+10%SF + 2% St.F	3
	0%NA + 100%RAP + 10%SF +2% St.F	3
	30%NA + 70%RAP + 10%SF +2% St.F	3
	50%NA + 50%%RAP + 10%SF +2% St.F	3
	70%NA + 30%RAP + 10%SF +2% St.F	3
Absorption and density	NA	3
	NA+10%SF + 2% St.F	3
	0%NA + 100%RAP + 10%SF +2% St.F	3
	30%NA + 70%RAP + 10%SF +2% St.F	3
	50%NA + 50%%RAP + 10%SF +2% St.F	3
	70%NA + 30%RAP + 10%SF +2% St.F	3

(*) NA: Crushed Natural Aggregate; RAP: Reclaimed Asphalt Aggregate;
SF: Silica Fume; St.F: Steel Fiber

- Developing six diverse RCC mixes. The initial mix was composed solely of NA without any SF or St.F modifications. The second mix served as the control, using pure NA aggregates, 10% silica fume, and 2% steel fiber . The remaining four mixes involved substituting NA with RAP at varying percentages of 30%, 50%, 70%, and 100%. The experimental design detailing these combinations is presented in Table 2.
- The specified cement content of 300 kg/m³ was maintained consistently for all testing combinations.
- Assessing the mechanical properties of the final mixtures, which include water absorption, density, toughness, modulus of elasticity, tensile splitting strength, and compressive strength. The molded samples were covered with a wet burlap for an entire day. Following this, the samples were extracted from the molds and submerged in a water bath maintained at a temperature of 22 to 25 °C. The evaluations of the RCC mixes were conducted after a curing period of 28 days.

3. Testing procedures

3.1 Optimum water content

As per ACI 325.10R-95, the vibrating tables historically employed include the Vebe table, those compliant with the relative density test for cohesionless soils (ASTM D4253 2019 and ASTM D4254 2016), and those meeting ASTM C192 (2015) standards. When considering mix proportions and vibrating table options, it may prove advantageous to conduct trial batches at slightly elevated moisture levels than optimal for concrete compaction facilitation. Based on ASTM C192/192M (2015) guidelines, all mix samples underwent compaction via vibrating table procedures. A total of 75 samples across the four mentioned combinations were tested, with three replicates at water contents ranging from 4.5% to 7.5% utilized in casting these mixes.

The relationship between the dry density and water content for each RCC mixture is shown in Fig. 2 and summarized in Table 3.

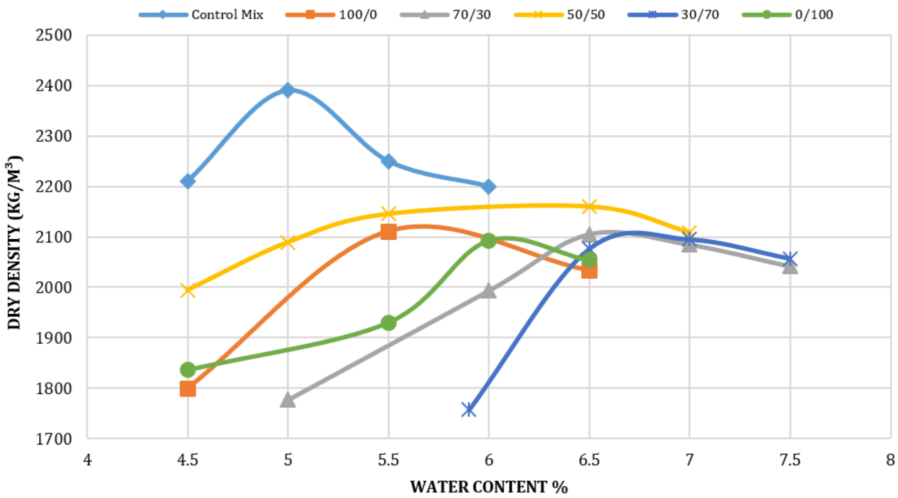

Fig. 2 Determining the optimum water content for all mixes

Table 3 Summary of the optimum water content for all mixes

RCC mixes (NA/RAP Ratio)	Optimum water content %	Maximum dry density weight (Kg/m³)	(W/C) ratio	Water content for 1 m³ RCC (Kg)
Control Mix	5.0	2368	0.34	102.7
100/0	6.1	2100	0.42	125.4
0/100	5.7	2120	0.39	117.1
30/70	6.8	2100	0.44	131.5
50/50	6.5	2170	0.46	133.6
70/30	6.5	2102	0.47	139.7

NA: Crushed natural aggregate; RAP: Reclaimed asphalt aggregate; W/C: Water to Cement Ratio

3.2 Compressive strength

A concrete cylindrical mold, 150 mm diameter and 300 mm height, was used to prepare the RCC samples according to ASTM C39 (2017). Eighteen samples, three for each RCC combination, were mixed and molded for the test. MFLPruf-systeme Universal Testing Machine was used for measuring the applied load and the corresponding deformation for all samples after 28 days of water curing. The compressive strength of modified RCC mixes was calculated. A total of 18 samples were cast and tested. Fig. 3 shows the test setup.

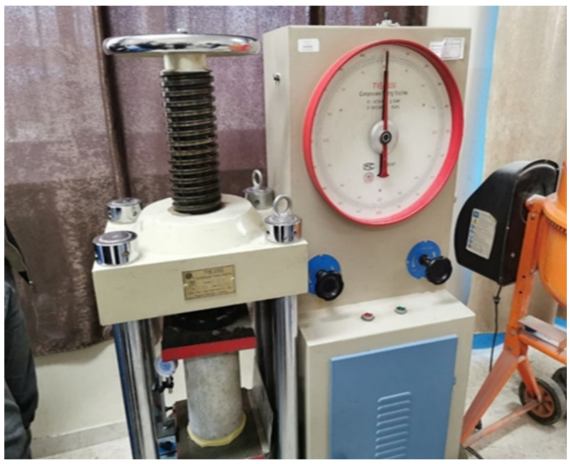

Fig. 3 Compressive strength set-up

3.3 Tensile splitting strength

MFLPruf-systeme Universal Testing Machine in accordance with ASTM C496 (2017) was used to perform this test for all mix combinations after 28 days of curing. A total of 18 cylindrical samples were cast and tested. Fig. 4 shows the test setup.

3.4 Modulus of elasticity

When a uniaxial compressive force is applied as explained before, the applied load and the corresponding deformation were used to calculate the static modulus of elasticity for concrete samples from the stress-strain relationship. The static modulus of elasticity is calculated as the slope of the elastic range in the stress-strain curve according to ASTM C469 (2014). This region can be specified using a simple relation, as the linear or elastic region is extended from zero to 0.45 f'c (stress corresponding 45% from maximum load), especially for brittle materials like concrete. Typical stress-strain curve for modulus of elasticity calculation is shown in Fig. 5.

Fig. 4 Tensile splitting strength set-up

3.5 Density

Wet or dry density has an impact on RCC mixtures for obtaining the highest compressive strength with the least amount of water and cement content. The ideal water content for each mixture depends on the maximum density and soil compacting technique. The density calculation for all samples was done in accordance with ASTM C138 standard. The obtained value is the wet density, whereas the dry density is obtained as discussed in section 3.1 above.

3.6 Water absorption

Absorption test shows the concrete ability to absorb water, indicating how durable the material would be over its complete service life. ASTM C642-13 standard was used for the determination of the percentage of water absorption in all RCC samples.

3.7 Concrete modulus toughness

Modulus of toughness is the ability of a material to absorb energy in plastic deformation before breaking which is the total strain energy per unit volume which can be stored in the material without fracture (Gopalaratnam *et al*. 1991). It is calculated, in accordance with ASTM C39 (2017), as the total area under the stress-strain curve up to fracture point. Since the modulus of toughness is less for brittle materials, such as concrete, than it is for other ductile materials. Modulus of toughness is calculated from the compressive strength test results and measured in stress units (Pascal). Typical calculation of modulus of toughness is shown in Fig. 6.

4. Analysis of test results

The experimental test results are explained in detail in this section for each modified RCC mix combination. Three replicates of each combination were evaluated for

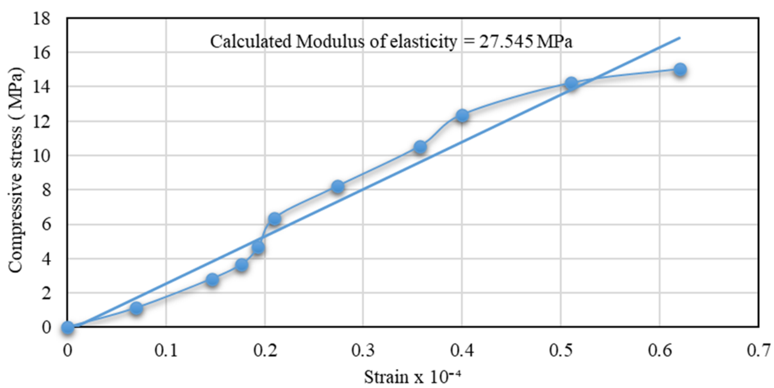

Fig. 5 Typical stress-strain curve for modulus of elasticity calculation

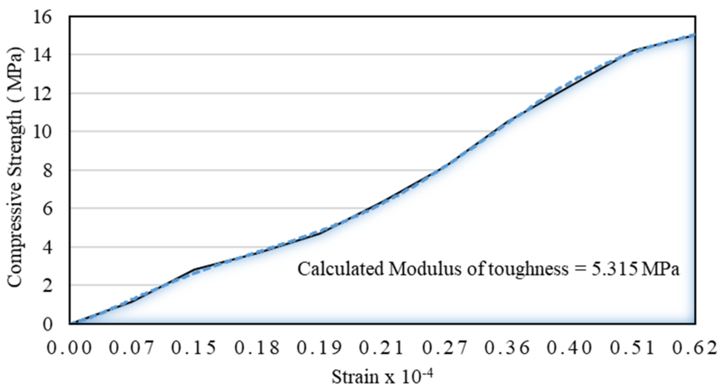

Fig. 6 Typical calculation of RCC modulus of toughness

Table 4 Summary test results of RCC mixes

Type of samples (NA/RAP Ratio) (*)	Compressive strength (MPa)	Tensile splitting strength (MPa)	Modulus of elasticity (MPa)	Modulus of toughness (MPa)	Absorption (%)	Wet density (Kg/m^3)
Control Mix (No SF/St.F)	25.0	2.00	43640	12.8	4.40	2486
100/0	30.0	2.20	55916	16.3	3.84	2200
0/100	20.5	1.19	35907	6.3	1.57	2322
30/70	18.7	2.35	33699	5.2	1.94	2228
50/50	13.0	1.40	31200	4.5	2.57	2207
70/30	12.9	1.18	27994	4.0	4.28	2269

(*) 10% SF and 2% Steel Fiber (St.F) were added for all samples other than control mix

compressive strength and tensile splitting strength. Some selected samples were selected to calculate the modulus of elasticity, modulus of toughness, density, and absorption tests. Table 4 summarizes all test results. Figs. 7 and 8 show typical tested samples for compressive and splitting tensile test, respectively. These results are discussed as follows:

Fig. 7 Compressive stress tested sample

Fig. 8 Tensile splitting strength tested sample

4.1 Compressive strength

The use of 10%SF in this research was essential to enhance the mechanical properties of RCC. It was reported by Tak *et al*. (2023) that SF has immense potential for replacing cement in concrete. As SF% increased, workability decreased. The compressive strength of the tested sample first increases to its maximum at 11% SF replacement and then decreases. At 11% SF substitution, the maximum tensile splitting strength was obtained. The replacement of cement with SF decreases the compressive strength and splitting strength. Therefore, the use of 10%SF in this study is reasonable. Fig. 9 shows the test results for all mixes. Addition of 10% SF to the RCC mixture with natural aggregate increased the compressive strength 20% (25 to 30 MPa), which can be attributed to cementation properties of SF. The partial replacement of NA with RAP reduced the compressive in all combinations compared to NA mixes (with and without SF).

The use of 100% RAP integration in RCC reduced compressive strength by 70% or to 5 MPa, whereas 50% RAP replacement resulted in a 50% drop or to 8 MPa Settari *et al*. (2015). The same result was concluded by Modarres and Hosseini (2014) that a 100% RAP in RCC reduced compressive strength by 65% with 14% cement content, or a value of 14 MPa. However, the use of 70% Rap with 30% RCA was found to reduce the by 41% or 16.44 MPa (Ashteyat *et al*. 2024). Furthermore, it was found that combinations with a high percentage of RAP perform significantly better than those with a high percentage of RCA, the drop 31.5% by using 100%RAP.

According to Australian standards (2002), the minimum compressive strength for concrete sub-base layer for road pavements is 5 MPa, and the maximum compressive strength is 15 MPa at 28 days. As indicated in Table 4, the compressive strength of 100%, 70% RAP at 28 days was higher than the maximum value (about 20 MPa for both), and 50%, 30%RAP had just met the criteria at 28 days.

As the percentage of RAP increases, the compressive strength increases. This implies that as more RAP replacement is used, better results, in terms of compressive strength of RCC mixes, will be obtained. In this regard, the value of about 20 MPa compressive strength (for 100% RAP) provides adequate strength and durability, it can easily withstand the weight of regular foot and vehicular traffic. Hence, it is used for constructing pavements,

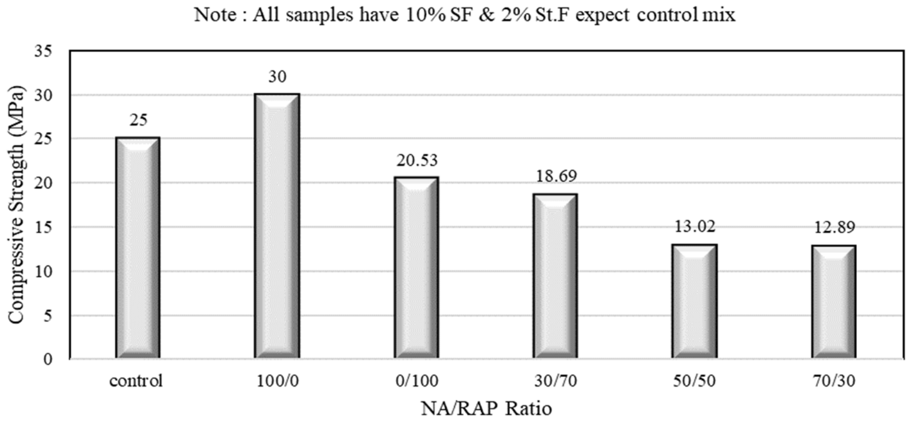

Fig. 9 Summary of the compressive strength results

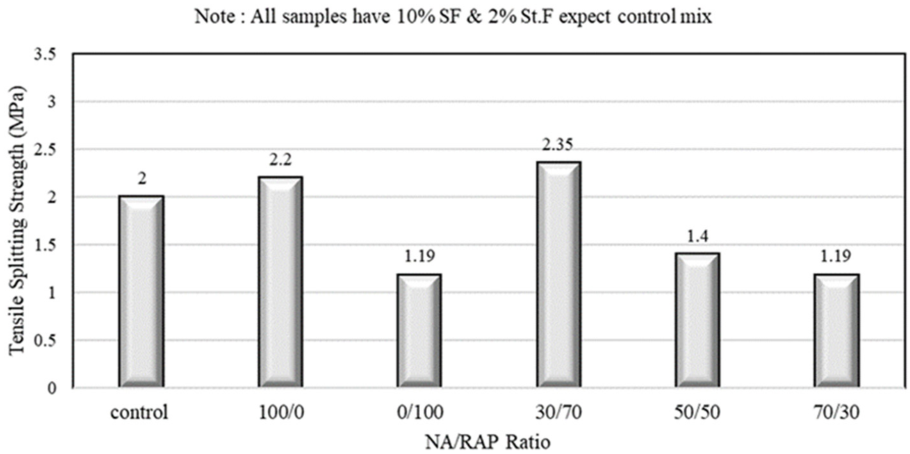

Fig. 10 Summary of the tensile splitting strength results

driveways, and other similar structures JK Cement (2023). However, looking at the complete picture, Other RCC mechanical properties should be considered for real life construction projects.

4.2 Tensile splitting strength

Table 4 and Fig. 10 show the results of tensile splitting strength for all mixes. It is observed that there is a marginal increase of about 10% to the samples with SF replacement and St.F addition compared to the control mix. However, as shown in Fig. 10, there is a substantial decrease in the tensile splitting strength RAP replacement of 100%, 50%, and 30%. The absolute values of tensile splitting strength were 1.19, 1.4, and 1.19 MPa for the mentioned RAP percentages above, respectively. However, for 70% RAP replacement, the tensile splitting strength has higher value than all other mix combinations including the control mix with a value of 2.35 MPa.

The research studies covered in this study showed that the tensile splitting strength did not exceed 2.5 MPa when employing RAP or RCA. For example, the results reported by Ashteyat *et al*. (2024) indicated that 2.05 MPa was the maximum splitting tensile strength with 70% RAP + 30% RCA and 5% SF. As Settari *et al*. (2015) reported that by applying 50% RAP, the maximum tensile splitting strength of 2.5 MPa was obtained. The findings of Shafigh *et al*. (2012) showed that, for regular concrete, the ratio of tensile splitting strength to compressive strength ranged from 8 to 14%. All mixed combinations have met the requirements, except for 100% RAP.

Fig. 10 also shows that there is no clear trend behavior in tensile splitting strength with the change of NA/RAP ratio.

4.3 Statics modulus of elasticity

The modulus of elasticity and the compressive strength of RCC exhibit similar variations. Additionally, the elastic modulus results in Fig. 11 and Table 4. The addition of St.F and SF to the control mixes improves the modulus of elasticity by 28%. However, the replacement of RAP steadily decreases the modulus values with percentage range (36-50%) compared with the control mix enhanced by addition of St.F and SF. The modulus of value of 35907 MPa for the RCC with 100% RAP, was the maximum obtained value in this study. This obtained result is higher than other results reached by different previous studies. For example, the study conducted by Settari *et al*. (2015) revealed that the decrease in modulus elasticity increased to 53% with the use of RAP aggregates, while the maximum value of 20, 15 GPa for RCC was achieved using 50%RAP and 100%RAP, respectively. Ashteyat *et al*. (2024) indicated that the maximum modulus of elasticity for RCC with 70% RAP+30% RCA and 5% SF was 24260 MPa.

4.4 Modulus of toughness

Addition of SF and St.F gives higher compression strength and modulus of elasticity which implies that the mix can absorb higher energy. Thus, the toughness is increased as measured by the area under (stress-strain) curve. However replacing the NA by RAP, the compression strength and elasticity decrease due to the asphalt components coating the aggregate particles in the RAP; so, the energy absorption will decrease as measured by the area under (stress-strain) curve. Fig. 12 shows the results of modulus of toughness. The St.F and SF enhanced the modulus of toughness of RCC by about 27% (16.3 compared with 12.8 MPa). The results showed that a (61%-75%) decrease in the modulus of toughness value by decreasing RAP replacement occurred. Fakhri and Amoosoltani (2017) found in their study that the maximum reduction of modulus of toughness was at 50%RAP + 50%NA ratio. On the other hand, the use of steel and SF do not have any effect on using the RAP in RCC. These results match and confirm the result shown in Fig. 12.

4.5 Water absorption

Table 4 and Fig. 13 show the percentage of water absorbed by all RCC mix combinations. The fineness of the SF particles (higher than cement) added to the control mix (and other mixes), reduce the water absorption of these mixes. Fig. 13 shows that the amount of reduction for modified control mix is 12.7%, which is considered as a benefit to the mix in the field. There is a general increasing water absorption values as the ratio of NA/RAP increases. The highest percentage for 70/30 NA/RAP ratio 4.28%. The asphalt coating of the aggregate reduces the ability of aggregate to absorb water and hence causes the decrease in the water absorption with the addition of RAP. This implies that the partial replacement of NA with RAP improved the durability of the RCC mixes. Based on the findings reported by Ashteyat *et al*. (2024), the maximum water absorption was 7.2 % for 60% RCA + 40% RAP and 5% SF.

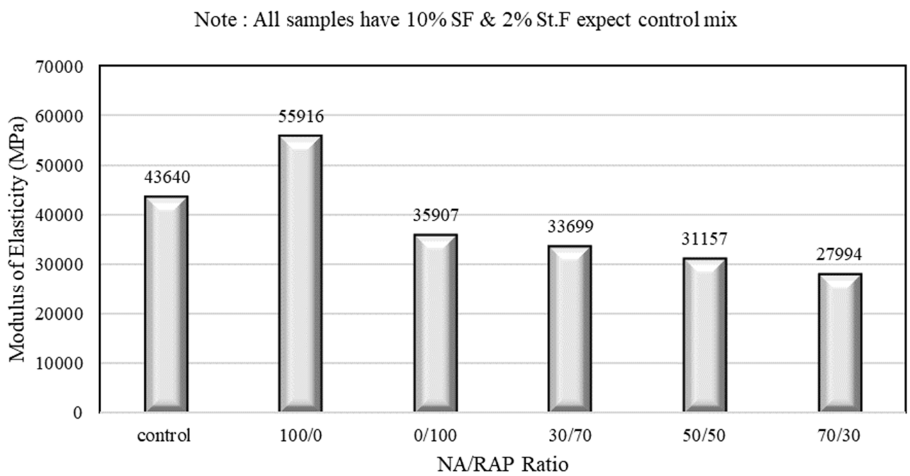

Fig. 11 Summary of the modulus of elasticity results

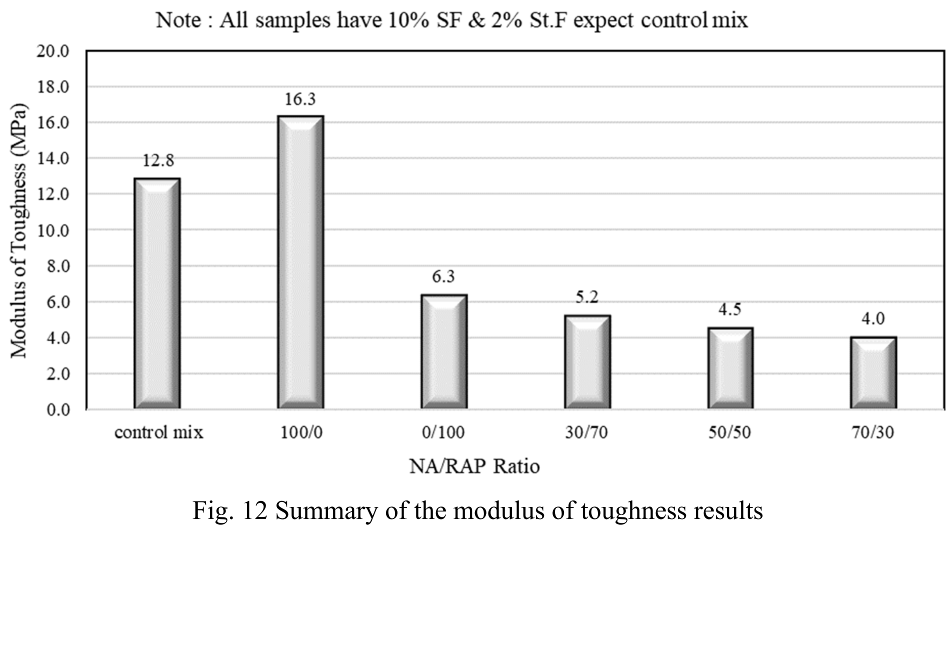

Fig. 12 Summary of the modulus of toughness results

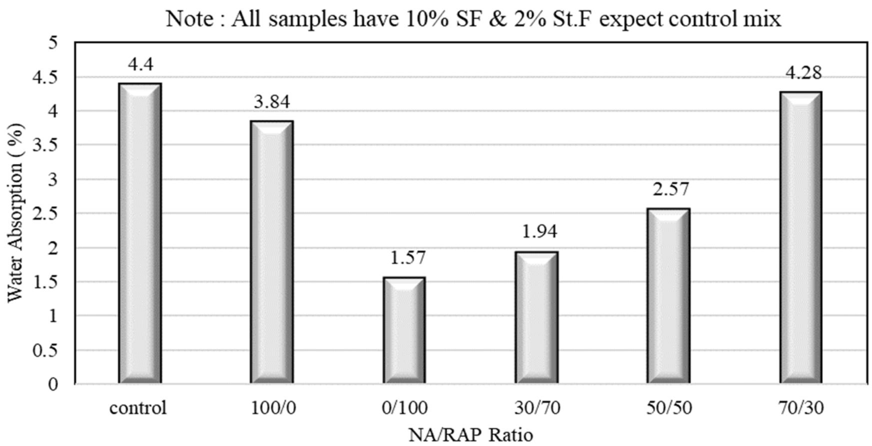

Fig. 13 Summary of the water absorption results

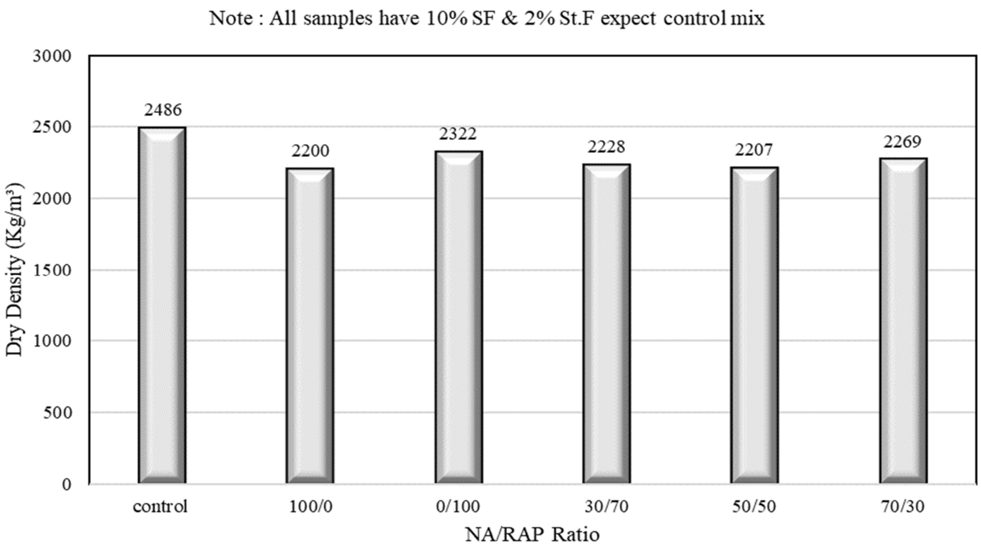

Fig. 14 Summary of the dry density results

4.6 Density

The maximum dry density of RCC with optimum water content based on soil compaction method is a vital factor to obtaining maximum concrete strength. The dry density of RCC presented in Fig. 14 shows that adding SF decreases the maximum dry density of the control mix. This is due to the lower specific gravity of SF compared to the cement one. Another observation is that replacement of RAP in the RCC mixes increases the dry density values when compared to the enhanced control mix with the other mixes. The range of increase is (0.3-6%) which is considered a marginal value in the total weight of the RCC mixes that will not affect the overall structural behavior of the construction.

4.7 Observed failure patterns

The use of SF and St.F in RCC concrete in this study has a remarkable observation. Fig. 15(a) shows the failure pattern of compressive strength, in control mix samples. It is clearly a shear angled failure. Modification of the mix by St.F and SF changes the failure pattern to shattering the sample from its surface not with a shear angles failure line as in control mix as shown in Fig. 15(b).

For the tensile splitting strength shown, Fig. 16 shows the effect of the addition of St.F in the mix which keeps the sample intact without splitting when compared to the control sample (without St.F and SF modification). This pattern may be important in the pavement structure, which is highly prone to tensile failure compared to compression failure.

5. Findings and discussion

This experimental study has been conducted on RCC by varying the percentage of RAP as 0%, 30%, 50%, 70%, and 100% as partial replacement of NA. Addition of 10%SF and 2% SF was used for all mix combinations. Mechanical RCC properties (compressive strength, modulus of elasticity, tensile splitting strength, modulus of toughness, density, failure pattern and water absorption) were determined for all mixes. The test results were compared to a control mix which is purely an RCC mix with only NAs. Based on this

Fig. 15 Compressive failure patterns for control and modified mix

Fig. 16 Tensile splitting failure patterns for control and modified mix

study, and within its experimental design shown in Table 2, the findings are discussed as follows:

- There was a 33% reduction in the compressive strength when the mix had 100% RAP compared to mixes with 100% NA. The obtained compressive strength (20.53 MPa) for 100% RAP is still a reasonable value for pavement with light traffic, sidewalks, or similar constructions using RCC mixes.
- The tensile splitting test results did not show a clear trend by altering the RAP percentages. The 70% RAP replacement showed the maximum tensile value of 2.35 MPa. This value represents 12.6% of the compressive strength value (18.69 MPa) for the same mix.
- Modulus of elasticity exhibited similar behavior of compressive strength. The addition of St.F and SF to the control mixes improves the modulus of elasticity by 28%. However, the replacement of RAP steadily decreases the modulus values with percentage range (36-50%) compared with the control mix enhanced by addition of St.F and SF.
- As the RAP percentage is increased, the modulus of toughness increases. This implies the reduction in the absorbed energy in the mix in its plastic phase. However, the use of SF and St.F increase the toughness value by about 27% for non-RAP mix when compared with the control mix. Moreover, the toughness values increase by increasing the RAP percentage in the modified mixes.
- The use of RAP and SF in the modified mixes showed lower values for the maximum dry density compared to the control mix. However, the reduction in the dry density for the modified mixes were marginal that will not affect the overall structural performance of the construction.
- The use of SF and St.F reduced the water absorption of the modified mixes compared to the control mix. However, the higher NA percentage in the mix (lower RAP percentage), the water absorption increased. This is due to the asphalt coating to the aggregate particles which hinders the water from being absorbed. Hence, the mix durability is better especially when the RCC mixes are used in moist areas or near water sources such as pavement subbase courses.
- The modified mixes have different failure patterns or shapes than the control mixes. The tested samples, at

failure, have shown patterns that keep the sample intact without shear-angled faces for the modified mixes compared to the control mix samples. This is due to the use of steel fiber (St.F) and stronger aggregate bonding due to the use RAP materials in the modified mixes

6. Conclusions

Looking to the above findings, the following can be concluded:

- The use of SF and St.F modification of the RCC mixes enhanced the performance of the mix. Moreover, the NA partial replacement with RAP is a potential utilization of a known waste material in the RCC construction. The preparation of RAP materials for the utilization in RCC including transportation, breaking, sieving, and mixing is not a costly process. Thus, this utilization compared to the saving of the NAs used in the RCC mix is a cost-effective option.
- RAP is a waste material that is considered and has a bad environmental impact which needs to be disposed safely. The reuse of this waste material is a good option for this disposal.

The results showed that the RAP utilization can adequately and reasonably be used in low-traffic pavements, or as road base or subbase layers. Other massive constructions can be used by these modified cost-effective mixes.

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