Civil Engineering Infrastructures Journal 2023, 56(2): 381-392
DOI: 10.22059/CEIJ.2023.345511.1857

RESEARCH PAPER

Use of Reclaimed Asphalt Pavement (RAP) in Concrete in Perspective of Rigid Pavements

Jadoon, N.[1], Ullah, I.[2], Sarir, M.[3*], Noman, M.[4] and Shah, A.A.[5]

[1] M.Sc., Civil Engineering Department, University of Engineering and Technology, Peshawar, Pakistan.
[2] M.Sc., Department of Civil Engineering, Faculty of Engineering and Technology, International Islamic University Islamabad, Pakistan.
[3] Ph.D. Candidate, Department of Civil Engineering, Faculty of Engineering and Technology, International Islamic University Islamabad, Pakistan.
[4] Ph.D., Instructor, Department of Civil Engineering, Faculty of Engineering and Technology, International Islamic University Islamabad, Pakistan.
[5] Professor, Department of Civil Engineering, Faculty of Engineering and Technology, International Islamic University Islamabad, Pakistan.

Received: 06 Jul. 2022; Revised: 14 Nov. 2022; Accepted: 26 Nov. 2022

ABSTRACT: The demolishing of roads for repair and reconstruction produces an ample amount of Recycled Asphalt Pavement (RAP) which, if not utilized, may cause depletion of aggregate sources and pollution. The use of RAP in the plain cement concrete (PCC) is sustainable use of road waste material. However, the potential of incorporating RAP to replace natural aggregate needs to evaluate. This research targets the evaluation of mechanical properties of PCC made with extracted RAP materials through laboratory experiments and to achieve the optimized replacement of natural aggregate for rigid pavement composite design. The Virgin Coarse Aggregate (VCA) in PCC was replaced with RAP at 0:25:100 percent by weight. Results show that incorporating RAP in PCC causes a gradual decrease in mechanical properties. However, the decrease in compressive strength is more (57%) than the flexural and splitting tensile strength. RAP up to 25% was found as an optimum allowable replacement with VCA in the rigid pavement. From the Modulus Of Elasticity (MOE), it was detected that with the incorporation of RAP the ductility of PCC improved slightly.

Keywords: Concrete, Recycled Asphalt Pavement (RAP), Virgin Coarse Aggregate (VCA).

1. Introduction

Reclaimed Asphalt Pavement (RAP) is the waste material produced as a result of removal of asphalt concretes from the existing infrastructure and to a minor extent, of wasted or rejected mixes during the production process of asphalt concrete mixtures (Tarsi et al., 2020). In 2018, about 88% wt. and 72% wt. of RAP were utilized in USA and Europe, respectively as an aggregate for cold, warm and hot asphalt

* Corresponding author E-mail: muhammad.sarir@iiu.edu.pk

mixtures and for unbound layers (Tarsi et al., 2020). The asphalt concrete that has been removed as a waste material form an existing road pavement is a fully recyclable material for construction (EAPA, 2014; AAPA, 2018). The removed asphalt concrete consists of non-renewable resources such as approximately 95% wt. of aggregated and 5% wt. of bituminous binder. It has the ability to be re-used, reducing the demand for virgin aggregates or it can be re-used to produce unbound layers of pavements (SABITA, 2019). The mechanical properties such as stiffness modulus, indirect tensile strength, and cracking and fatigue characteristics were studied. The results showed that high amount of RAP up to 60% can be incorporated into bituminous mixtures to obtain satisfactory results (Valdés et al., 2011). The RAP content was used ranging from 0% to 40% in Warm-Mix Asphalt (WMA) and Hot-Mix Asphalt (HMA) and comparison were made by performing different tests such as rut resistance, fatigue resistance and moisture susceptibility. The results indicated that WMA with high RAP content exhibited less rutting and moisture resistance that HMA with high RAP content. Moreover, WMA-high RAP content mixes exhibit better fatigue resistance than HMA-high RAP content (Zhao et al., 2013). Laboratory investigations on asphalt mixes prepared with RAP and rejuvenating agent have been carried out and then compared with asphalt mixtures made with virgin aggregates. Different performance tests such as indirect tensile strength, retained stability, creep test, beam fatigue test, resilient modulus and wheel tracking test have been conducted and compared. The results showed that the asphalt mixtures with RAP and rejuvenating agent ended with better performance as compared to virgin asphalt mixtures (Pradyumna et al., 2013). The replacement of conventional stone dust with sugarcane bagasse ash has improved the performance characteristics of asphalt concrete mixtures (Sarir et al., 2022). The effect on the mechanical properties of hot mix asphalt mixtures partially and fully replaced with RAP were assessed. The results indicated that 100% replacement of granular material by RAP produced highest indirect tensile strength and resilient modulus in both dry and wet condition (Reyes-Ortiz et al., 2012). When the RAP, which was combination of two different sources in Latvia, was added at rates of 30% and 50% in local aggregates, the wheel tracking test results indicated that all the mixtures bear high rutting resistance and fatigue test results using four-point bending beam were similar to those of virgin asphalt mixtures (Izaks et al., 2015). The rheological and chemical analysis of the 100% RAP using rejuvenators was done by (Rathore et al., 2022) which concluded that the bitumen having rejuvenators possesses acceptable rutting performance. Laboratory performance tests such as asphalt pavement analyzer rutting test, wheel tracking test, tensile strength ratio test, indirect tension test and the beam fatigue test were carried out on asphalt mixtures having RAP ranging from 0% to 50%. The test results showed that mixtures with high percentages of RAP exhibit higher resistance to rutting, moisture damage and possessed better fatigue performance (Zhao et al., 2012). Moreover, the mechanical performance, environmental impacts and economic benefit criteria are assessed by (Jahanbakhsh et al., 2020) to introduce the use of RAP in asphalt concrete mixtures. The mechanical properties of asphalt concrete mixtures containing RAP in various percentages i.e. 30%, 60% and 100% along with other supplementary materials were better that or equal to that of the conventional asphalt mixtures. On the other hand, the blending process of RAP with virgin mixture was analyzed by (Huang et al., 2005) in which a blended mixture containing 20% of screened RAP was subjected to staged extraction and recovery. The result showed improved performance of the hot-mix asphalt mixture. The RAP was utilized in rubberized asphalt mixtures that contains crumb rubber. The results of experimental investigations indicated that the utilization of RAP and crumb rubber in the hot mix asphalt had the ability to effectively improve the rut resistance of the asphalt mixtures (Xiao et al., 2007). The laboratory investigation of high modulus asphalt concrete mixtures was done by (Izaks et al., 2022) having high content of RAP materials. Different tests such as wheel tracker test, water sensitivity test, four-point bending test etc. were performed. The tests performed indicated satisfactory results. The performance of high modulus asphalt mixtures containing RAP was examined. Different percentages of RAP was incorporated and was found that 40% RAP content resulted in optimal mixture in terms of dynamic modulus and moisture damage susceptibility (Zhu et al., 2020). The morphological study of RAP induced concrete was conducted by (Jindal and Ransinchung, 2022) apart from evaluation of mechanical properties which concluded that the addition of mineral admixtures at 15% amount refined the pore structure making the concrete less permeable. The RAP possesses particles of different sizes. Some of them are coarse particles while some are fine particles coated with asphalt binder around them. This phenomenon led to the agglomeration of RAP thus reducing the strength of the concrete modified with RAP (Zhu et al., 2020). However, with the ever-increasing concern about solid waste disposal and the sustainable use of natural resources, the incorporation of recycled materials in Portland Cement Concrete (PCC) has become increasingly popular in recent years. This research has aimed to make it possible the use of RAP as aggregate in rigid pavements.

Out of 276.4 million tons of black-top in Europe, available RAP was 49.6 million tons (17.94%). Similarly, Pakistan has an estimated 100,000 km of road network, mostly asphaltic roads; tonnes of RAP from it are being unearthed and dumping it elsewhere will pose serious environmental risks. The utilization of RAP in rigid (concrete) asphalts not just lessens the cost yet additionally builds strength. After the beginning of the Bus Rapid Transit (BRT) venture in Peshawar, Pakistan, huge amounts of black-top streets were peeled off for the laying of new tracks for the transports. The material is not being reused for any reason and goes to squander.

This research investigated the feasibility of using Reclaimed Asphalt Pavement (RAP) to replace virgin aggregates in concrete pavements. Specifically, this research considered using minimally processed RAP (i.e., simply fractionating into fine and coarse components) in this capacity for roadways in Pakistan.

2. Material and Methods

2.1. Cement

Ordinary Portland Cement (OPC), locally available with the brand name of Kohat cement complying with ASTM C 150 and having a specific gravity of 3.15, was used. The consistency, initial setting time, final setting time, and fineness of cement were found to be 30%, 45 min, 120 min, and 6.9%, respectively.

2.2. Fine Aggregate

The fine aggregate (sand) used in this research was Galbai river sand having Fineness Modulus (FM), specific gravity (by water pycnometer) of 2.76 and 2.78 respectively, while the water absorption was found 1.27 percent according to ASTM C128.

2.3. Coarse Aggregates

The VCA used in this research was acquired from a local quarry site had a size range of 4.75- 25.4 mm. The bulk density as per ASTM C39 (ASTM C39/C39M, 2003) was found to be 1550.1 kg/m^3 (96.77 lb/ft^3). The saturated surface dry (SSD) specific gravity, absorption, and abrasion loss (class B) were 2.70 and 0.60% and 23.72%, respectively.

2.4. Reclaimed Asphalt Pavement (RAP)

RAP aggregates were obtained by breaking the junk from the demolished pavement disposed near M-1 motorway (Peshawar-Islamabad Motorway) into pieces, shown in Figures 1a and 1b, which reportedly was lying in the dumb site for almost 2 years; hence it was exposed to the external weathering conditions. The specific gravity of RAP was 2.9 and determined 4.40% of bitumen content by centrifugal extractor as shown in Figure 1c. The result of VCA and RAP sieve analysis according to ASTM C136 is shown in Table 1. Figure 2 shows the gradation of VCA and RAP aggregate.

Table 1. Sieve analysis

Sieve sizes (inches)	Weight retained on each sieve (g)		Individual percent retained on each sieve		Cumulative weight retained		Percent passing	
	VCA	RAP	VCA	RAP	VCA	RAP	VCA	RAP
1	0	121	0	6.12	0	6.12	100	93.88
¾	628	786	28.88	39.78	31.4	45.9	68.60	54.1
½	768	1039	45.76	52.58	69.80	98.48	30.20	1.52
3/8	280	16	14.56	0.81	83.80	99.29	16.20	0.71
No.4	324	10	10.48	0.51	100	99.8	0	0.2

(a) (b) (c)

Fig. 1. a) RAP chunks; b) RAP aggregate; and c) Centrifugal extractor

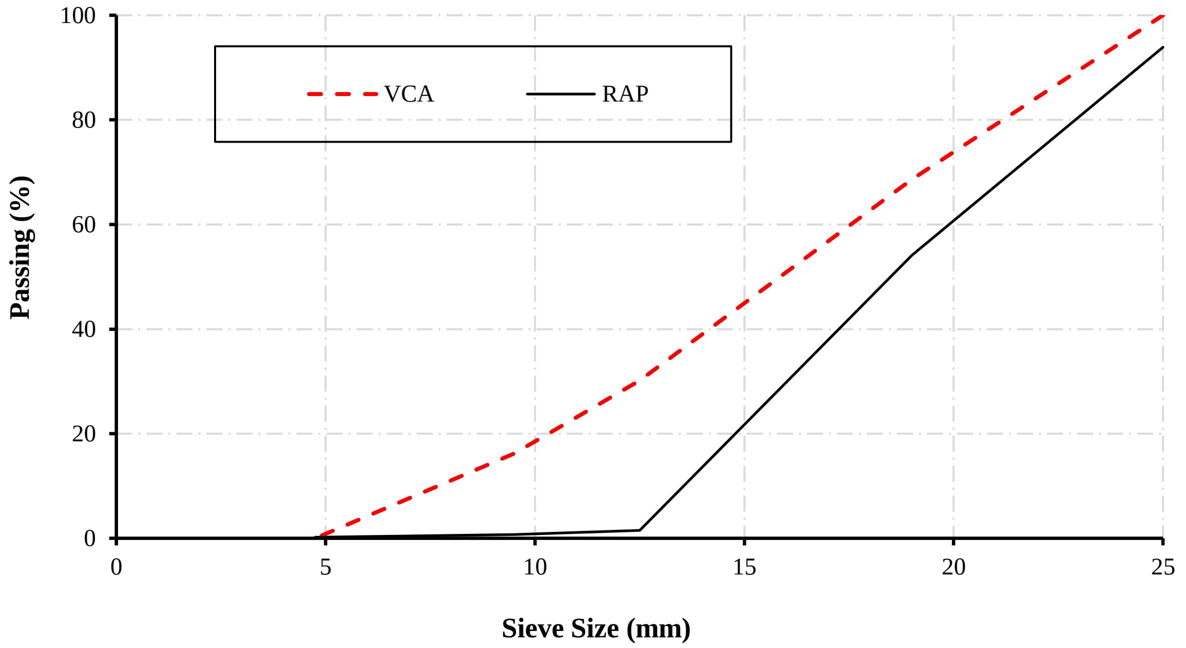

Fig. 2. RAP and VCA gradation

2.5. Mix Design

The controlled mix was designed to achieve class A3 concrete for design strength of 4000 psi compressive strength with water-cement ratio of 0.57 as per National Highway Authority of Pakistan Standards (NHA, 1998). A total of 30 test specimens were prepared in the lab at an average temperature of 26.4 °C, with VCA being replaced by RAP at 0, 25, 50, 75, and 100 % by weight of VCA, with an average slump of 3.5 inches (90 mm). The nomenclatures of an alphabet preceding by a digit, whereas the alphabet represents the type of test and the digit represents the percent replacement of VCA, and proportions of mixes are provided in Table 2. The mix design ratio for 75% and 100% RAP replacement was different from others to avoid honeycombing in concrete specimens. The specimens were cured in a chamber containing fresh drinking water for 28 days.

3. Experimental Investigation

The VCA was replaced with RAP at an increment of 0, 25, 50, 75, and 100 percent by weight. Tests were performed to investigate the concrete specimens' compression strength, splitting tensile strength, flexural strength, and modulus of elasticity. The average value of three specimens was taken to avoid human or machine error. For the investigation of compression and splitting tensile strength, cylindrical specimens with dimensions of 12 × 6 inches (300 × 150 mm) were cast and tested according to ASTM C39 (ASTM C39/C39M, 2003) and ASTM C496 (ASTM C496/C496M-17, 2011), respectively, as shown in Figures 3 and 4. Flexural tests were performed on beams of length 12 inches and 4 × 4 inches cross-sections. The beams were tested using the 3-point loading method (Figure 5) according to ASTM C78 (ASTM C78/C78M-22, 2010).

Two cylinders were tested for MOE under UTM connected to the data logger and strain gauges (Figure 6). UCAM software was used to find the modulus of elasticity. Used sidekick guides to choose the compressive quality according to test method ASTM C39 preceding the test for modulus of elasticity.

Table 2. Mix design detail

Sr. No.	Mix design name	VCA (kg/m^3)	RAP (kg/m^3)	Materials Fine Aggregate (kg/m^3)	Cement (kg/m^3)	Water (kg/m^3)	Ratio
1	CR0	981.9	0.0	811.9	353.9	201.7	1:2.29:2.77
2	CR25	736.4	245.5	810.4	353.9	201.7	
3	CR50	491.0	491.0	810.4	353.9	201.7	
4	CR75	230.9	692.7	870.5	353.9	201.7	1:2.46:2.61
5	CR100	0.0	923.6	870.5	353.9	201.7	
6	TR0	981.9	0.0	811.9	353.9	201.7	1:2.29:2.77
7	TR25	736.4	245.5	810.4	353.9	201.7	
8	TR50	491.0	491.0	810.4	353.9	201.7	
9	TR75	230.9	692.7	870.5	353.9	201.7	1:2.46:2.61
10	TR100	0.0	923.6	870.5	353.9	201.7	
11	FR0	981.9	0.0	811.9	353.9	201.7	1:2.29:2.77
12	FR25	736.4	245.5	810.4	353.9	201.7	
13	FR50	491.0	491.0	810.4	353.9	201.7	
14	FR75	230.9	692.7	870.5	353.9	201.7	1:2.46:2.61
15	FR100	0.0	923.6	870.5	353.9	201.7	

Fig. 3. Compression test

Fig. 4. Splitting tensile test

Fig. 5. Flexural test

Fig. 6. Compression test in UTM

4. Results and Discussion

4.1. Damage Pattern

The damage pattern of specimens under loading was diverse. The cylinders CR0 and CR25 showed cracks under the compression strength test from top to bottom. It showed that there might be a continuous bond between the aggregates. The spalling of concrete in CR25 at the mid-span as shown in Figure 7a, is possibly due to the presence of RAP because these cracking and spalling were noted in all specimens containing RAP. The CR50 specimen had a wider crack opening on its top side shown in Figure 7b. The cracks in CR75 and CR100 were much wider compared to other specimens due to the presence of more RAP aggregates depicted in Figure 8.

(a) Damage/Crack pattern in CR25 **(b)** Damage/Crack pattern in CR50

Fig. 7. Damage/Crack pattern during the compression tests

(a) Damage/Crack pattern in CR75 **(b)** Damage/Crack pattern in CR100

Fig. 8. Damage/Crack pattern during the compression tests

Upon applying loads for the flexural test, the rupture in FR0, FR25, and FR50 was sudden, and the failure was brittle represented in Figure 9. On the other hand, FR75 and FR100 showed ductile failure due to the presence of more RAP shown in Figure 10. Likewise, the greater RAP percentage in the beams contributed to reducing brittleness. The failure was at the middle third of the beam in this case.

During the splitting tensile test, the cracks in the specimen were quite visible. In the case of TR0, there was only a single crack initiated from the top of the cylinder's circular cross-section. The crack initiated in TR25 was similar but was a bit wider revealed in Figure 11. Wide and multiple crack failure was observed in the case of TR50, TR75 and TR100 as shown in Figure 12. These cracks show that aggregates' binding ability was reduced with an increase in RAP contents. During the MOE test, the cracks in R0, R25, and R50 were wider and saturated at the upper loading portion, while R75 and R100 revealed significant cracks from top to bottom and multiple cracks in every direction throughout the circumference as shown in Figure 13.

(a) Damage/Crack pattern in FR25 **(b)** Damage/Crack pattern in FR50

Fig. 9. Damage/Crack pattern during flexural tests

(a) Damage/Crack pattern in FR75 **(b)** Damage/Crack pattern in FR100

Fig. 10. Damage/Crack pattern during flexural tests

(a) Damage/Crack pattern in TR0 **(b)** Damage/Crack pattern in TR25

Fig. 11. Damage/Crack pattern during splitting tensile tests

(a) Damage/Crack pattern in TR50 **(b)** Damage/Crack pattern in TR100

Fig. 12. Damage/Crack pattern during splitting tensile tests

(a) Damage/Crack pattern in R25 **(b)** Damage/Crack pattern in R75 **(c)** Damage/Crack pattern in R100

Fig. 13. Damage/Crack pattern during MOE tests

4.2. Test Results of Hardened Concrete Upholding RAP

4.2.1. Compressive Test

The compressive strength of the conventional concrete i.e., CR0 was more than 4000 psi, and the compressive strength of concrete made after certain replacement of VCA with RAP decreased. The results show a decrease in compressive strength of the modified concrete. The percent reduction in compressive strength of RAP-modified concrete varies from 28% for 25% replacement to a maximum of 57% for 100% replacement. This reduction in compressive strength is mainly attributed to the presence of agglomerated particles containing lumps of different sizes of particles. Moreover, the RAP contains aged asphalt which makes the asphalt film harder and stiffer. This may also be the possible reason for the reduction of compressive strength of the RAP induced concrete.

4.2.2. Flexural Test

The results obtained from flexural test also showed a decrease in flexural strength of concrete with the increase in replacement of VCA with RAP. The results showed a maximum decrease of approximately 40% in flexural strength for 100% RAP replacement and a minimum decrease of approximately 10% for 25% replacement. The incorporation of RAP in concrete has also reduced the flexural strength however the reduction is comparatively lower than the compressive strength. This reduction might also be the reason of the presence of agglomerated particles. Moreover, the presence of particles coated with bitumen might have reduced the bond between the RAP and VCA due to which the flexural strength has reduced.

4.2.3. Split Tensile Test

The trend of strength loss in split tensile strength was somehow identical to that of compressive strength. The decrease was minimum at 25% RAP replacement showing 21% decrease while for 100% replacement, it showed a decrease of 51%. The strength reduction pattern was somehow similar to that of compressive strength. However, the percentage reduction in split tensile strength is lower than that of compressive strength. This might be due to the fact that the RAP is obtained from flexible pavement which possesses flexibility thus inhibiting tensile strength.

4.2.4. Modulus of Elasticity (MOE)

The Modulus Of Elasticity (MOE) is a very important property considered for concrete samples. Minimum decrease of 25% had been observed for RAP replacement of 25% while a maximum decrease of 84% had been observed for RAP replacement of 100%. Moreover, the ductility being more makes R75 less brittle. The ductility path followed by the graph came out to be the highest for R100 sample. It shows that the ductility increases with an increase in RAP content and vice versa. The increase in elasticity is due to the presence of RAP which is obtained from flexible pavement. The RAP possesses elasticity thus making the RAP induced concrete more ductile as the RAP content is increased.

Table 3. Mechanical properties of RAP modified concrete samples

RAP (%)	Compression average (psi)	Flexure average (psi)	Splitting tensile average (psi)	Modulus of elasticity average (psi)
0	4023	630	347	175440
25	2905	566	274	131069
50	2401	508	267	125390
75	1965	467	190	33150
100	1715	376	168	28500

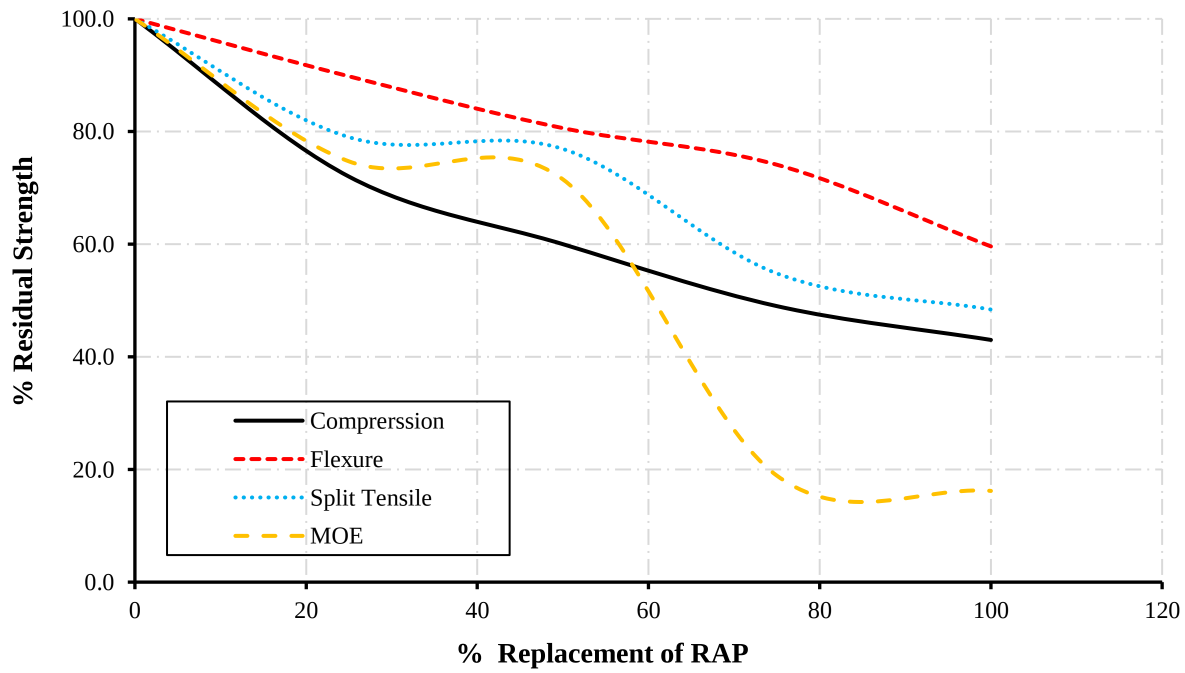

Fig. 14. Percentage residual strength vs percent RAP replacement

5. Conclusions

RAP material is a waste product produced after the demolishing of old pavements. The utilization of RAP in concrete is an innovative technique. This paper addresses the use of RAP in concrete as an alternative way of disposal of waste. The mechanical properties such as compressive strength, flexural strength, split tensile strength and modulus of elasticity decrease with the increase in the percent replacement of RAP in virgin concrete aggregates. The decrease was maximum at replacement of 100% of VCA with RAP. Minimum percent decrease was observed at 25% replacement. At all replacements, RAP concrete mixes had lower strength parameters such as compressive strength, flexural strength, and splitting tensile strength as compared to control concrete mixes. However, mixes with 25% replacement achieved characteristic compressive strength of 2900 psi. Concerning the percentages of RAP content, the extent of the reduction in strengths was investigated. The maximum reduction in compressive, flexural, and splitting tensile strengths at 100% replacement of RAP was 57 %, 40.4%, and 51.6%, respectively. However, the optimum replacement of RAP aggregate is found to be 25% replacement.

6. References

ASTM C39/C39M. (2003). *Standard test method for compressive strength of cylindrical concrete specimens*, ASTM Standard Book, (pp. 1-5), ASTM International, West Conshohocken, PA, United States.

ASTM C78/C78M-22. (2010). *Standard test method for flexural strength of concrete (using simple beam with third-point loading) 1*, ASTM Standard Book, (pp. 1-4), ASTM International, West Conshohocken, PA, United States, https://doi.org/10.1520/C0078_C0078M-22.

ASTM C496/C496M-17. (2011). *Standard test method for splitting tensile strength of cylindrical concrete specimens ASTM C-496*, ASTM International, (pp. 1-5), ASTM Standard Book, (pp. 1-5), ASTM International, West Conshohocken, PA, United States.

Australian Asphalt Pavement Association (AAPA). (2018). *Reclaimed Asphalt Pavement (RAP) management plan*, National Technology and Leadership Committee, Port Melbourne, Australia.

European Asphalt Pavement Association (EAPA). (2014). *Asphalt the 100% recyclable construction product*, EAPA, Brussels, Belgume.

Huang, B., Li, G., Vukosavljevic, D., Shu, X. and Egan, B.K. (2005) “Laboratory investigation of mixing hot-mix asphalt with reclaimed asphalt pavement”, *Journal of Transportation Research Board*, 1929(1), 37-45, https://doi.org/10.3141/1929-05.

Izaks, R., Rathore, M., Haritonovs, V. and Zaumanis, M. (2022). “Performance properties of high modulus asphalt concrete containing high reclaimed asphalt content and polymer modified binder”, *International Journal of Pavement Engineering*, 23(7), 2255-2264, https://doi.org/10.1080/10298436.2020.1850721.

Izaks, R., Haritonovs, V., Klasa, I. and Zaumanis, M.J.P.E. (2015). “Hot mix Aasphalt with high RAP content”, *Procedia Engineering*, 114, 676-684, https://doi.org/10.1016/j.proeng.2015.08.009.

Jahanbakhsh, H., Karimi, M.M., Naseri, H. and Nejad, F.M. (2020). ‘Sustainable asphalt concrete containing high reclaimed asphalt pavements and recycling agents: Performance assessment, cost analysis, and environmental impact”, *Journal of Cleaner Production*, 244, 118837, https://doi.org/10.1016/j.jclepro.2019.118837.

Jindal, A. and Ransinchung, G.D. (2022). “Behavioural study of incorporation of recycled concrete aggregates and mineral admixtures in pavement quality concrete”, *Civil Engineering Infrastructures Journal*, 55(2), 351-372, https://doi.org/10.22059/CEIJ.2022.326564.1766.

National Highway Authority (NHA). (1998). *General specifications*, Islamabad, Pakistan.

Pradyumna, T.A., Mittal, A. and Jain, P.K. (2013). "Characterization of Reclaimed Asphalt Pavement (RAP) for use in bituminous road construction”, *Procedia, Social and Behavioral Sciences*, 104, 1149-1157, https://doi.org/10.1016/j.sbspro.2013.11.211.

Rathore, M., Haritonovs, V., Meri, R.M. and Zaumanis, M. (2022). “Rheological and chemical evaluation of aging in 100% reclaimed asphalt mixtures containing rejuvenators”, *Construction and Building Materials*, 318, 126026, https://doi.org/10.1016/j.conbuildmat.2021.126026.

Reyes-Ortiz, O., Berardinelli, E., Alvarez, A.E., Carvajal-Muñoz, J. and Fuentes, L.G. (2012). “Evaluation of hot mix asphalt mixtures with replacement of aggregates by Reclaimed Asphalt Pavement (RAP) material", *Procedia, Social and Behavioral Sciences*, 53, 379-388, https://doi.org/10.1016/j.sbspro.2012.09.889.

Sarir, M., Khan, R., Alam, M., Khan, M.T. and Imran, W. (2022). 'Performance evaluation of asphalt concrete mixtures using bagasse ash as filler", *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, 46(2), 1553-1570, https://doi.org/10.1007/s40996-021-00641-8.

Southern African Bitumen Association (SABITA). (2019). *Use of reclaimed asphalt in the production of asphalt MANUAL 36/TRH 21*, SABITA: Western Cape, South Africa.

Tarsi, G., Tataranni, P. and Sangiorgi, C. (2020). "The challenges of using reclaimed asphalt pavement for new asphalt mixtures: A review", *Materials*, MDPI AG., 13(18), 4052, https://doi.org/10.3390/ma13184052.

Valdés, G., Pérez-Jiménez, F., Miró, R., Martínez, A. and Botella, R. (2011). "Experimental study of recycled asphalt mixtures with high percentages of Reclaimed Asphalt Pavement (RAP)", *Construction and Building Materials*, 25(3), 1289-1297, https://doi.org/10.1016/j.conbuildmat.2010.09.016.

Xiao, F., Amirkhanian, S. and Juang, C.H. (2007). "Rutting resistance of rubberized asphalt concrete pavements containing reclaimed asphalt pavement mixtures", *Journal of Materials in Civil Engineering*, 19(6), 475-483, https://doi.org/10.1061/(ASCE)0899-1561(2007)19:6(475).

Zhao, S. Huang, B., Shu, X. and Woods, M. (2013). "Comparative evaluation of warm mix asphalt containing high percentages of reclaimed asphalt pavement", *Construction and Building Materials*, 44, 92-100, https://doi.org/10.1016/j.conbuildmat.2013.03.010.

Zhao, S., Huang, B., Shu, X., Jia, X. and Woods, M. (2012). "Laboratory performance evaluation of warm mix asphalt containing high percentages of RAP", *Journal of the Transportation Research Board*, 2294(1), 98-105, https://doi.org/10.3141/2294-11.

Zhu, J., Ma, T., Fan, J., Fang, Z., Chen, T. and Zhou, Y. (2020). 'Experimental study of high modulus asphalt mixture containing reclaimed asphalt pavement", *Journal of Cleaner Production*, 263, 121447, https://doi.org/10.1016/j.jclepro.2020.121447.

Zhu, J., Ma, T. and Fang, Z. (2020). "Characterization of agglomeration of reclaimed asphalt pavement for cold recycling", *Construction and Building Materials*, 240, 117912, https://doi.org/10.1016/j.conbuildmat.2019.117912.