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Impact of Hard Reclaimed Asphalt Pavement on the Properties of Roller-Compacted Concrete

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Abstract. Reclaimed asphalt pavement (RAP) aggregates, which are typically deposited in surrounding areas either legally or illegally, accumulate in enormous quantities as a result of recycling flexible pavement. The selection of Roller-Compacted Concrete (RCC) for suitable applications yields a sustainable pavement that meets the economic, environmental, and social demands of contemporary infrastructure. The incorporation of RAP in RCC pavements offers several benefits and drawbacks. The notable advantages of employing RAP aggregates include reduced impact on RAP disposal issues, decreased greenhouse gas emissions, decreased dependence on natural aggregates, and lower transportation costs. Utilizing RAP as a substitute for aggregate in RCC may reduce the amount of natural aggregate used in RCC. This study examined the effects of substituting 25%, 50%, 75%, and 100% of the coarse aggregate weight in RCC with highly-aged reclaimed asphalt pavement (hard RAP) on compressive strength, splitting tensile strength, flexural strength, modulus of elasticity at 7, 28, and 91 days of curing, and drying shrinkage at 14, 21, 28, and 91 days of curing. The substitution of 100% hard RAP adversely affected the characteristics of RCC, resulting in lowered compressive, splitting tensile, and flexural strengths, as well as a reduction in the modulus of elasticity across all curing durations. After a curing time of 28 days, the M-50%H-RAP RCCP mixes exhibited a reduction in compressive, splitting tensile, and flexural strengths, along with the modulus of elasticity, of 26.5%, 30.6%, 20%, and 35.6%, respectively. The drying shrinkage significantly increases as coarse aggregate is substituted with hard RAP. After 28 days of curing, the drying shrinkage rate reaches 10% when 100% of the coarse aggregate is substituted with hard RAP.

Keywords: The modified proctor method, highly-aged RAP, hard RAP(H-RAP), optimum moisture content (OMC), and maximum dry density (MDD).

1. Introduction

Roller-compacted concrete (RCC) is utilized for the rapid construction of pavements, requiring fewer equipment and labor compared to traditional concrete pavements. It comprises water, cementitious substances, and aggregates. After being placed by pavers, it is compacted by vibratory rollers without the use of forms, polishing, or surface texture. RCC exhibits strengths higher than conventional concrete due to its low water-to-cement ratio and low water content. It does not necessitate formwork, reinforcing steel, dowels, or crossovers. In contrast to conventional flexible pavement, it produces pavement that is more durable and resilient. It will not slide during braking operations or turnings and will be able to withstand large axle loads. It will not become brittle or flexible even in high-temperature environments. It is not susceptible to degradation by substances such as diesel fuel (Harrington 2010). Designers are demonstrating a renewed interest in RCC pavements as a sustainable pavement option due to their potential to reduce total project costs, shorten the duration of road closures, incorporate recycled aggregates, and decrease the overall amount of cement used (Ferrebee, 2014). The methods of incorporating waste materials into road construction are the subject of extensive research by numerous engineers and researchers. Among all the waste, Reclaimed Asphalt Pavement (RAP) has been prioritized

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for use as an alternative in the production of concrete and asphalt mixtures (Fakhri & Amoosoltani, 2017b). Traditionally, RCC pavements have been constructed using virgin aggregates; however, researchers have conducted experiments with recycled aggregates in RCC. The concept of a sustainable-built road would be fulfilled by the use of RAP aggregates in low-cost surfacing technology such as RCCP (Debbarma, 2019a). After the removal or milling of bituminous pavement for maintenance or repair, RAP is frequently produced. Utilizing RAP as an alternative aggregate source could satisfy this requirement while also satisfying sustainability requirements. In new pavement applications, RAP aggregate utilization may benefit the environment and the economy by reducing aggregate costs and transportation costs due to on-site use (reduced carbon footprint) (Singh & Kumar, 2017; Shi & Zollinger, 2018).

Conversely, the principal challenge identified in various research regarding the incorporation of RAP into concrete pavements is the insufficient adhesion between the asphalt layer and the cementitious matrix (Huang, 2005; Huang, 2006; Brand & Roesler, 2015). The strength-related properties are reduced by approximately 50% due to the weak Interfacial Transition Zone (ITZ) (Brand and Roesler, 2017, Part I; Brand and Roesler, 2017, Part II; Settari, 2015; Brand and Roesler, 2012). Moreover, the agglomerated particles adhering to the surrounding area of the RAP aggregates may contribute to a further weakening of the tensile characteristics (Singh and Kumar, 2017; Huang, 2006; Shi, 2017). The amount of hard RAP particles added significantly impacts the compactness and density of RCCP mixtures containing hard RAP (Modarres and Hosseini, 2014; Settari, 2015). Moreover, some researchers have demonstrated that the integration of RAP may potentially increase the OMC value by up to 12% (Boussetta, 2020; Ferrebee, 2014; Settari, 2015). The adverse impact on the OMC is associated with the clustering of rigid RAP particles, which trap water within the spaces. Furthermore, the use of hard RAP aggregate, due to its lower specific gravity, may result in a reduction in maximum dry density (MDD). The incorporation of low-density RAP reduces the MDD of RCCP combinations by approximately 5% (Debbarma, 2019a, 2019b; Adamu, 2017). Consequently, the hardened properties of the hard RAP-RCCP mixtures, including compressive, flexural, and splitting tensile strengths, are reduced (Modarres & Hosseini, 2014). The weak adherence between the hard RAP and cement mortar may also be attributed to the lower specific gravity and density of RAP, which results in a reduction of the hardened properties of RAP-RCCP (Settari, 2015).

3. Methodology

Materials and Tests

Fine Aggregate

This study utilized fine aggregate, namely normal-weight natural sand sourced from the Al-Najaf quarry. The sand was sieved through a 4.75 mm sieve before being added to the concrete mixture. Figure 1 presents the grading of sand. The results of the physical and chemical analysis performed on the sand utilized in this investigation are displayed in Table 1.

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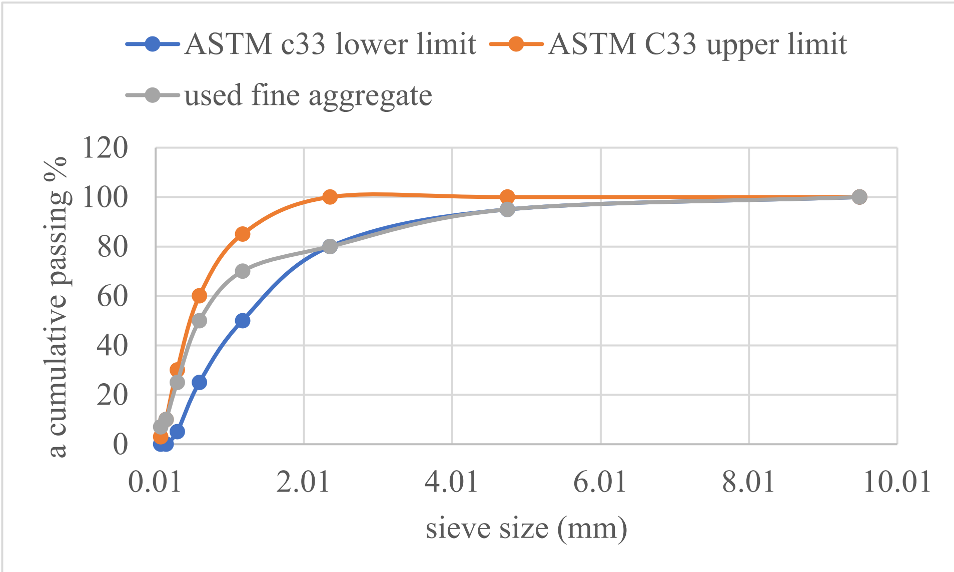

Fig.1 Grading of fine aggregate

Table 1. The physical and chemical properties of sand*

Property	Specification	Result	Limit of I.O.S NO. 45/1984
Bulk Specific gravity	ASTM C128-2003	2.6	
Absorption,%	ASTM C128-2003	1.1	
Dry loose unit weight, kg/m^3	ASTM C29-2003	1580	
Sulfate content (as SO_3),%	I.O.S No.45-84	0.36	0.5 (Max.)
Materials finer than 0.075 mm sieve,%	ASTM C117-17	4.1	5.0 (Max.)

* The test was carried out by Al-Mawal company for soil investigations. Babylon, Iraq.

Coarse Aggregate: Natural Coarse Aggregate

Natural crushed gravel with a maximum size of 19.5 mm from the Al–Nibaey region was used in this work. The absorption, specific gravity, and sulfate content (as SO3) of the used gravel are (0.5%), (2.63), and (0.058%) respectively. Fig. 2 shows the grading of this aggregate and the limits specified by ASTM C33-18.

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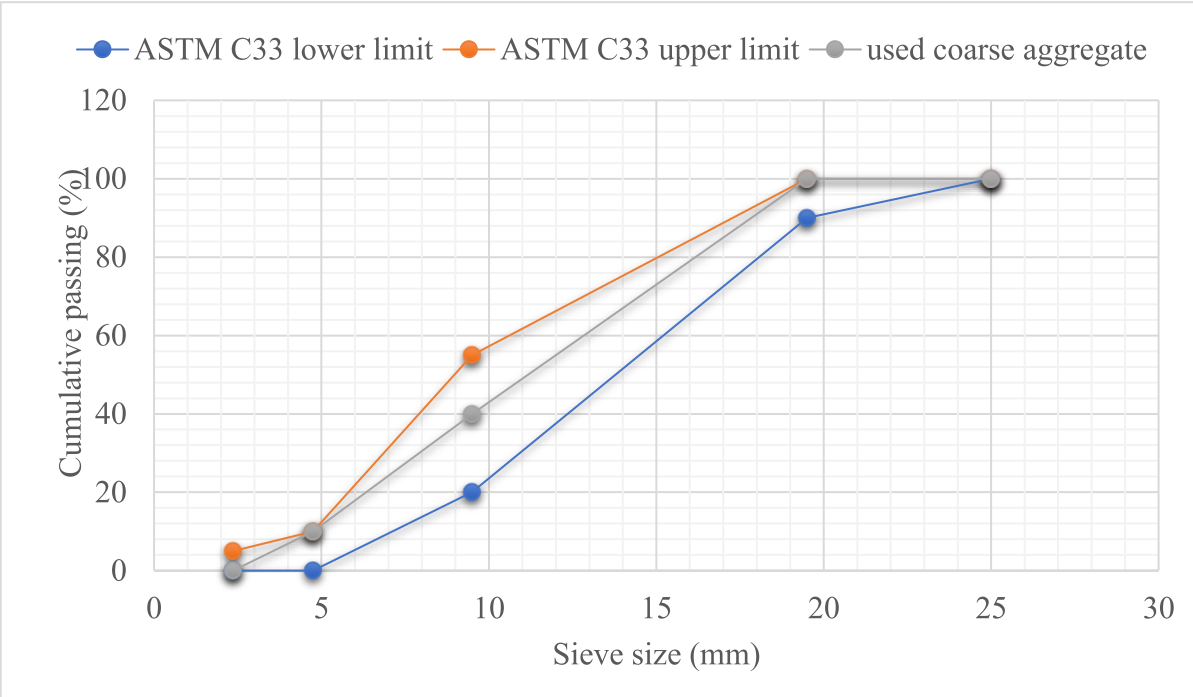

Figure 2. Grading of Coarse aggregate

Coarse Aggregate: hard Reclaimed Asphalt Pavement (H-RAP)

The hard RAP utilized in the current research was obtained from a highly distressed asphalt pavement located near Ya Hussain Road in Al Najaf. The hard RAP was obtained through the demolition of full-depth pavement and was stored in a loose condition in an open environment for almost 10 years. The properties of H-RAP, along with their respective precise specifications, are detailed in Table 2.

Table 2. Properties of hard RAP aggregate

Property	Specification	H-RAP
Specific gravity	ASTM C127-2003	2.34
Absorption, %	ASTM C127-2003	0.86
Asphalt content, %	ASTM D2172-2003	4.5

Cement

Sulfate Resisting Cement (Type V) produced by Karbala Cement Factory (Lafarge Al Jiser) was used in every mixture throughout this study.

Mix Design

Five different RCC mixes were used in this study, identified as:

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•M-0%hard RAP: 0%hard RAP, 100% natural coarse aggregate (control mix).
•M-25%hard RAP: 25%hard RAP, 75% natural coarse aggregate.
•M-50%hard RAP: 50%hard RAP, 50% natural coarse aggregate.
•M-75%hard RAP: 75%hard RAP, 25% natural coarse aggregate.

Due to the rigid character of Roller-Compact Concrete, the modified Proctor method (see Fig. 3) is the most commonly used soil compaction method for designing RCCP mixes. This approach is based on ASTM D1557-12. The results of the modified Proctor method are represented by a curve showing a definite γ dry density (g/cm³) and MC (moisture content) (%), See Fig.4. It can be observed that the maximum dry density (MDD) decreased as the hard RAP replacement increased for the mixes (M-25%hard RAP, M-50%hard RAP, M-75%hard RAP, and M-100%hard RAP), and the optimum moisture content (OMC) increased.

Fig. 3 The modified Proctor

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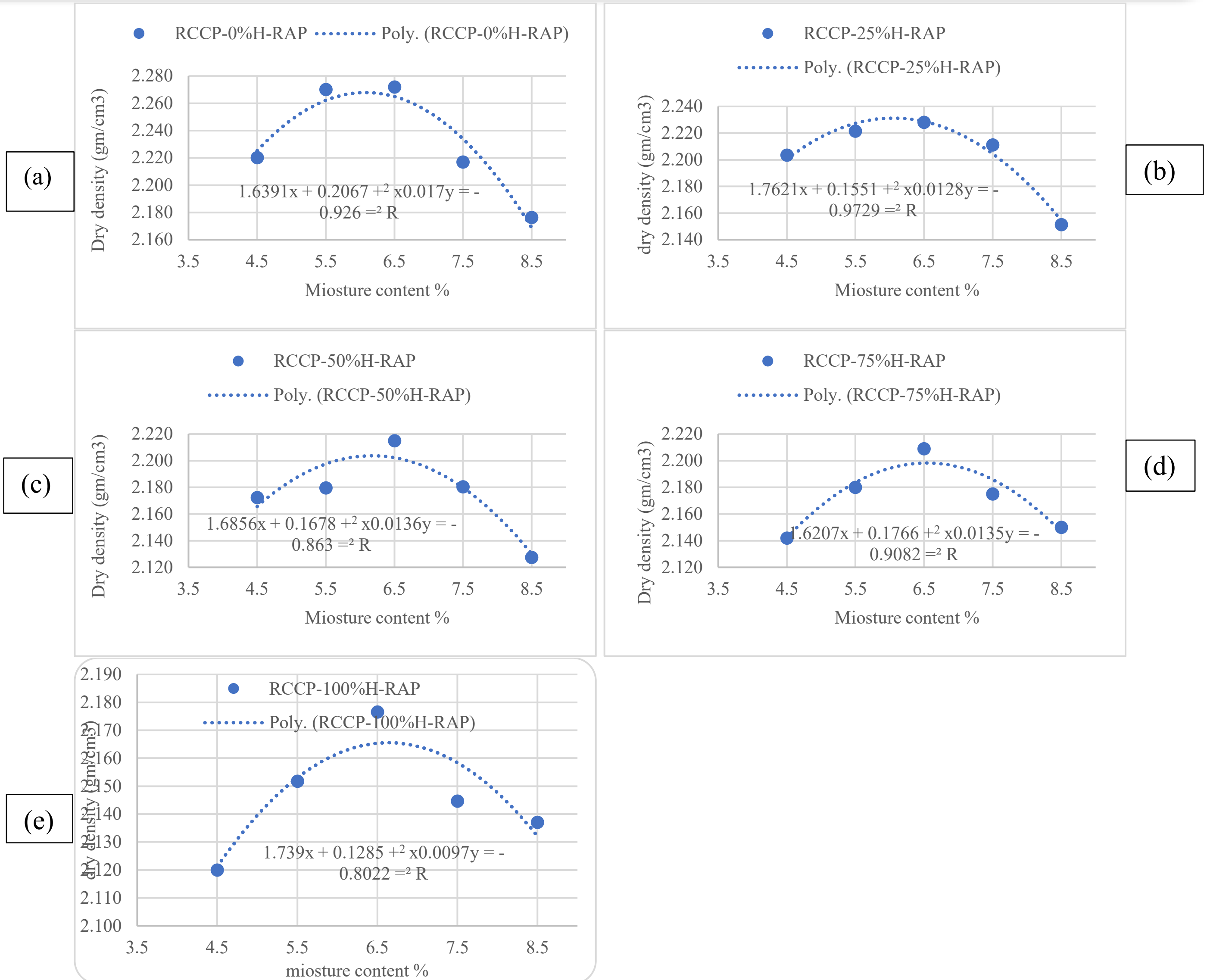

Fig.4 Proctor test results for the samples (a) (M-0%H-RAP), (b) (M-25%H-RAP), (c) (M-50%H-RAP), (d) (M-75%H-RAP), and (e) (M-100%H-RAP)

Preparation, Casting, Compaction, and Curing of RCC samples

For all the tests carried out during this study, cylindrical steel mold size (150 x 300) mm and prism size (100 x 100 x 400) mm are used for preparing the RCC specimens. The molds are cleaned, rigidly tightened, and lightly oiled before casting to keep concrete from sticking to them. The materials are placed on the molds by filling the prisms into two layers and the cylinders into three layers, then compacting the mixture with a hammer and tamping plate. After that, compaction of the concrete under the tamping plate begins when the hammer vibrates. The concrete in the annular space, the area between the tamping plate edge and the mold’s inside wall, should be observed. When the concrete consolidates, the annular gap that exists between the interior mold wall and the outer surround of the tamping plate

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should be filled with mortar. This mortar must be watched until it creates a ring around the entire tamping plate. The vibrating hammer must be stopped upon the completion of the mortar ring on the tamping plate. The vibrating hammer must be stopped after 20 seconds if a significant amount of the mortar ring has not formed; the next layer of concrete must then be applied (ASTM C1435–99). Fig.5 shows the vibrating compaction hammer with a minimum mass of 10 ± 0.2 kg (without a tamping plate). It can also produce at least 2000 impacts per minute and requires a minimum power input of 900 watts.
Tamping plate: For prism and cylindrical molds, a (390 ×90) mm rectangle steel plate and a (140) mm circular steel plate, respectively. A metal shaft with a steel plate attached is placed into the vibrating hammer chuck (ASTM C 1435–99). After that, all concrete test specimens were demolded after 24 hours and stored in a water tank for 7, 28, and 91 days, except for those related to drying shrinkage, which were cured according to ASTM C157 (2005). Table 3 shows a summary of the various tests conducted on concrete.

Table 3. Different tests realized on concrete

Tests	Specimen (mm)	standard
Compressive Strength	Cylinder (150 * 300) mm	ASTM C39 (2003)
Flexural Strength	Prisms (100*100*400) mm	ASTM C78 (2005)
Tensile Strength	Cylinder (150 * 300) mm	ASTM C496 (2003)
Elastic Modulus	Cylinder (150 * 300) mm	ASTM C469 (2003)
Drying Shrinkage	Prisms (100*100*400) mm	ASTM C157 (2005)

Fig. 5 hammer, rectangular head, and circular head are used for compacting RCC samples

4. Results and Discussion

Compressive Strength

Figure 6 summarizes the compressive strength results of the hardened RCCP mixes containing H-RAP at 7, 28, and 91 days of curing. The comparison with the reference mix (M-0%H-RAP) shows that an increase in H-RAP content results in a decrease in compressive strength on all curing days. For instance, the percentage decrease in compressive strength relative to the control mixture (M-0%RAP) for the mixtures (M-25%H-RAP, M-50%H-RAP, M-75%H-RAP, and M-100%H-RAP) at 28 days of curing was 14%, 26%, 36%, and 44%, respectively. Also, at 91 days of curing, the reduction was about 17%, 30%, 38%, 46% for mixes (M-25%H-RAP, M-50%H-RAP, M-75%H-RAP, and M-100%H-RAP), respectively. The observed reduction in strength may be attributed to the asphalt film coating on hard RAP aggregates, which results in a weak aggregate-cement bond. The minimum recommended compressive strength of 27.6 MPa at 28 days of curing for the construction of RCC pavements, as outlined by ACI 327 (2014), was attained solely by M-25%H-RAP and M-50%H-RAP.
(Huang et al. 2006; Settari 2015; Debbarma, 2020b; Debbarma, 2019a; Fakhri & Amoosoltani, 2017b), Also, a reduction in compressive strength was found. Debbarma (2019a) indicates that the use of hard RAP leads to a decrease of approximately 9–37%.

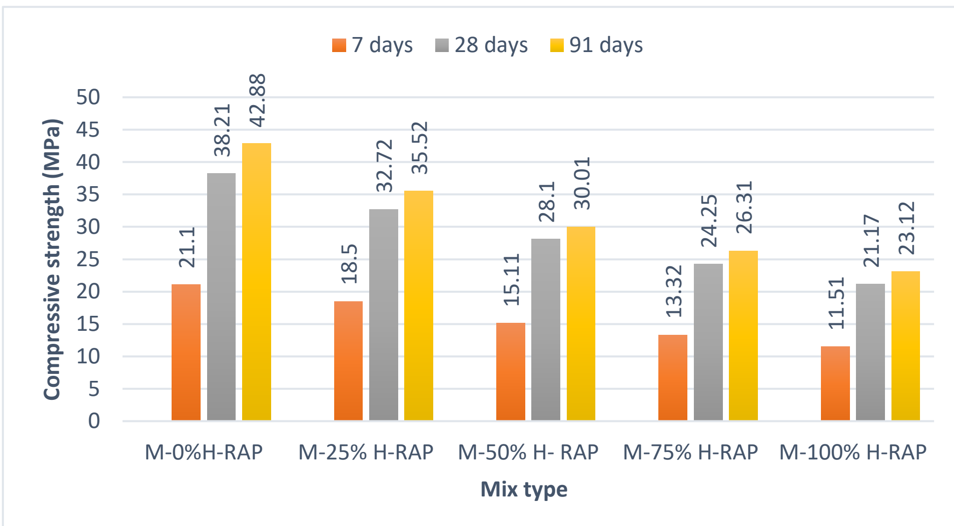


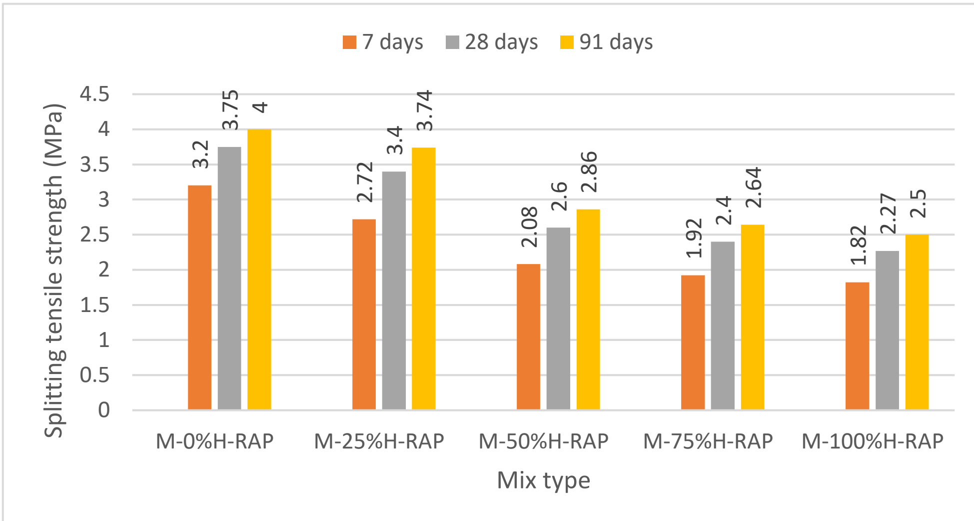
Fig. 6. Effect of hard RAP on compressive strength of RCCP

Splitting Tensile Strength

Similar to compressive strength, the incorporation of hard RAP reduces the splitting tensile strength of RCC pavement mixtures at all curing ages. Fig. 7 illustrates the impact of varying proportions of hard RAP aggregates on the splitting tensile strength of the investigated RCCP mixtures after 7, 28, and 91 days of typical curing. It can be observed that the percentage reduction in the splitting tensile strength of the mixes (M-25%H-RAP, 50%H-RAP, 75%H-RAP, and 100%H-RAP) at 7 days of curing is 15%, 35%, 40%, 43%, respectively. At 28 days of curing, the mixtures (M-25%H-RAP, 50%H-RAP, 75%H-RAP, and 100%H-RAP) exhibit reductions of approximately 9%, 31%, 36%, and 39%, respectively. Additionally, the reductions are 6%, 29%, 34%, and 38% at 91 days of curing for mixes (M-25%H-RAP, 50%H-RAP, 75%H-RAP, and 100%H-RAP), respectively. This reduction may be due to the asphalt layer on the hard RAP, which inhibits the formation of a robust interfacial bond between the cement mortar and hard RAP aggregates. (Debbarma, 2019a; Ferrebee, 2014; Settari, 2015), Also noted this decrease.

In addition, Mohammed Ali (2024) found that the inclusion of 45%H-RAP at 28 days of curing resulted in a 32% reduction in splitting tensile strength.

Fig.7 Effect of hard RAP on the splitting tensile strength of RCCP



Flexural Strength

The replacement of natural coarse aggregates with hard reclaimed asphalt pavement (RAP), regardless of the percentage or replacement ratio, may result in a decrease in the flexural strength of roller-compacted concrete (RCC) pavement mixtures. Unlike the compressive strength results, the reduction in flexural strength is slightly better than the reduction in compressive strength. For instance, the flexural strength of (M-25%H-RAP, M-50%H-RAP, M-75%H-RAP, and M-100%H-RAP) at 7 days of curing was 7%, 15%, 18%, and 22%, respectively. And also, the reduction in the flexural strength at 28 days of curing is 12%, 20%, 23%, and 27% for mixes (M-25%H-RAP, M-50%H-RAP, M-75%H-RAP, and M-100%H-RAP), respectively. Whereas there is a reduction of about 11%, 18%, 22%, and 28% at 91 days of curing of mixtures (M-25%H-RAP, M-50%H-RAP, M-75%H-RAP, and M-100%H-RAP), respectively, as shown in Fig. 8.

The reduction in the flexural strength of RCC pavement mixtures, ranging from approximately 5% to 31%, has been found by Debbarma et al. (2019a), Fakhri & Amoosoltani (2017), and Modarres & Hosseini (2014). In addition, Mohammed Ali 2024) states that a decrease of 18.5% in the flexural strength of M-45%H-RAP.

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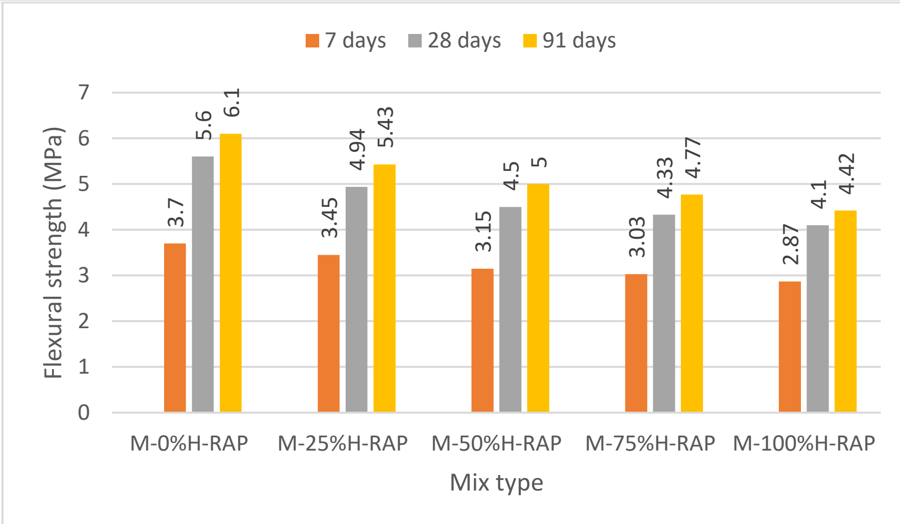

Fig.8 Impact of hard RAP on the flexural strength of RCCP

Modulus of Elasticity

Incorporation of hard RAP aggregates has been found to reduce the modulus of elasticity (Ec) of Roller Compacted Concrete (RCC). Fig.9 illustrates how the modulus of elasticity decreases with the addition of hard RAP. It can be observed that, when the replacement ratio of H-RAP was 25%, 50%, 75%, and 100% by weight of natural aggregate, the modulus of elasticity at 7 days was 17 GPa, 15 GPa, 13.8 GPa, and 10.5 GPa, respectively. And also, the modulus of elasticity was 27.6 GPa, 22.4 GPa, 20 GPa, and 15.52 GPa at 28 days of curing for mixes (M-25%H-RAP, M-50%H-RAP, M-75%H-RAP, and M-100%H-RAP), respectively. In addition, the mixtures (M-25%H-RAP, M-50%H-RAP, M-75%H-RAP, and M-100%H-RAP) have modulus of elasticity at 91 days of curing about 29.7 GPa, 24.2 GPa, 22.1 GPa, and 16.6 GPa, respectively. Since hard RAP aggregates differ from conventional aggregates in terms of material properties, it is evident that using them can have a significant effect on the modulus of elasticity of RCC Pavement mixes (Debbarma, 2020b). The relative softness of asphalt compared to cement paste at ambient temperature results in a notable adverse impact of hard RAP on the modulus of elasticity of RCC. Furthermore, it has been observed that the incorporation of hard RAP can decrease the modulus of elasticity of RCC pavement mixtures by approximately 80% (Boussetta et al., 2020; Fakhri & Amoosoltani, 2017b). Also, according to Mohammed Ali (2024, the incorporation of 45%H-RAP results in a reduction in the modulus of elasticity of RCC of approximately 31.5%.

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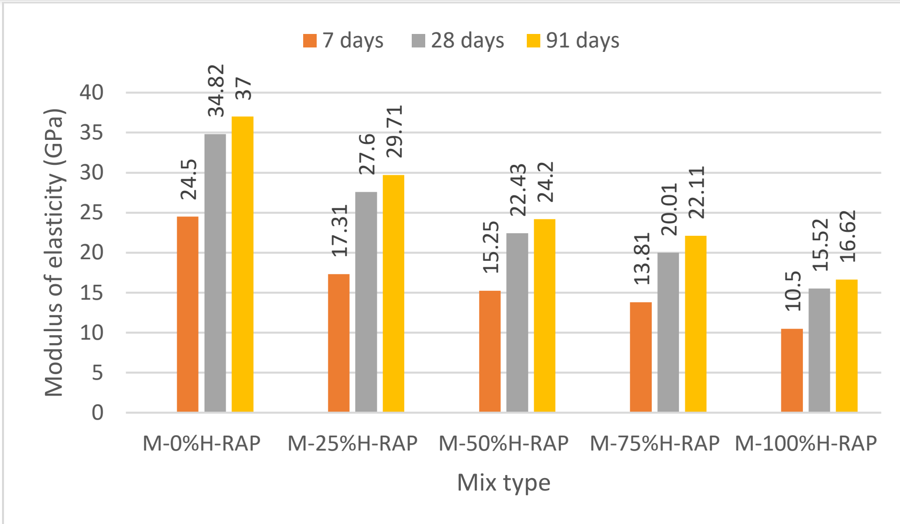

Fig.9 Effect of hard RAP on Modulus of elasticity strength of RCCP

Drying shrinkage

As seen in Fig. 10, the drying shrinkage increases significantly with the H-RAP replacement of coarse aggregate. The increase rate is about 42%, 66% 80%, and 85% when replacing (25%, 50%, 75%, and 100%) coarse H-RAP aggregate at 14 days of curing. Whereas, at 28 days of curing, the drying shrinkage of mixtures (M-25%H-RAP, M-50%H-RAP, M-75%H-RAP, and M-100%H-RAP) is 1%, 3%, 6%, and 9%, respectively. Additionally, the increase rate reached 2%, 4%, 6%, and 8% at 91 days of curing for the mixes (M-25%H-RAP, M-50%H-RAP, M-75%H-RAP, and M-100%H-RAP).

Multiple studies on RCC mixes indicate that the 28-day drying deformation occurs within the range of 25–300 micro strain (Pittman and Ragan, 1998; Khayat and Libre, 2014). Whereas, Mohammed Ali 2024 noted that the drying shrinkage significantly increased with the replacement of coarse aggregate by H-RAP, with a rate of increase reaching 30% when 45% of the coarse aggregate was replaced with hard RAP.

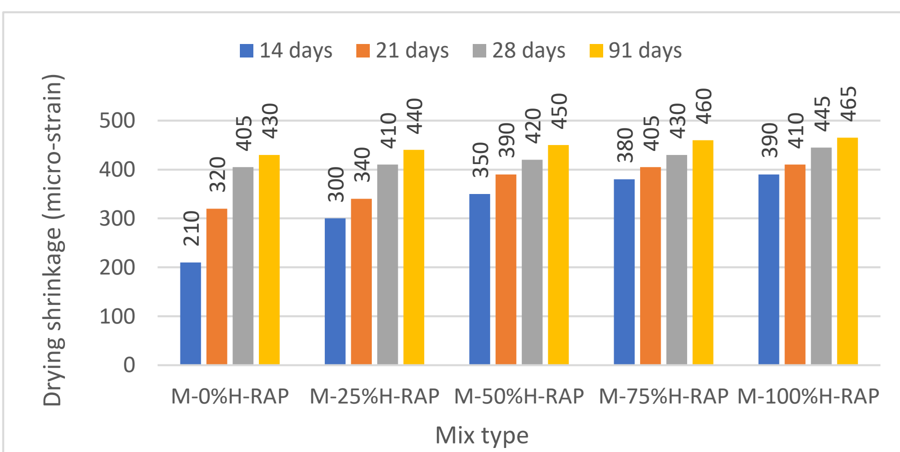

Fig.10 Drying Shrinkage Strains of RCCP Mixes after 14, 21, 28, and 91 days

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5. Future works

Extensive experimental studies are necessary to determine the optimal type and percentage of pozzolanic materials that enhance the mechanical properties of Roller Compacted Concrete Pavement (RCCP) containing hard Reclaimed Asphalt Pavement (H-RAP).

6. Conclusion

The characteristics of RCC were examined in this study through laboratory tests to investigate the impact of highly aged RAP (hard RAP) materials. The test results indicate that the particles of hard Reclaimed Asphalt Pavement have a lower density and a greater capacity for water absorption due to the association of some bitumen with them. Hard RAP materials are different than natural aggregate. Additionally, the quantity of H-RAP materials significantly affects the density and compactness of RCC. Furthermore, the optimal moisture content (OMC) values increased when coarse H-RAP partially replaced natural aggregates in the RCCP mixes under investigation. Additionally, it was found that the maximum dry density (MDD) of RCCP mixtures decreased as the proportion of hard RAP aggregates increased. Lastly, the addition of coarse hard RAP led to a significant decrease in the compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity of the RCCP mixtures at all curing ages, as well as an increase in drying shrinkage.

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Impact of Hard Reclaimed Asphalt Pavement on the Properties of Roller-Compacted Concrete.

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Keywords: The modified proctor method, highly-aged RAP, hard RAP(H-RAP), Optimum moisture content (OMC), and maximum dry density (MDD).

Abstract. Reclaimed asphalt pavement (RAP) aggregates, which are typically deposited in surrounding areas either legally or illegally, accumulate in enormous quantities as a result of recycling flexible pavement. The selection of Roller-Compacted Concrete (RCC) for suitable applications yields a sustainable pavement that meets the economic, environmental, and social demands of contemporary infrastructure. The incorporation of RAP in RCC pavements offers several benefits and drawbacks. The notable advantages of employing RAP aggregates include reduced impact on RAP disposal issues, decreased greenhouse gas emissions, decreased dependence on natural aggregates, and lower transportation costs. Utilizing RAP as a substitute for aggregate in RCC may reduce the amount of natural aggregate used in RCC. This study examined the effects of substituting 25%, 50%, 75%, and 100% of

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the coarse aggregate weight in RCC with highly-aged reclaimed asphalt pavement (hard RAP) on compressive strength, splitting tensile strength, flexural strength, modulus of elasticity at 7, 28, and 91 days of curing, and drying shrinkage at 14, 21, 28, and 91 days of curing. The substitution of 100% hard RAP adversely affected the characteristics of RCC, resulting in lowered compressive, splitting tensile, and flexural strengths, as well as a reduction in the modulus of elasticity across all curing durations. After a curing time of 28 days, the M-50%H-RAP RCCP mixes exhibited a reduction in compressive, splitting tensile, and flexural strengths, along with the modulus of elasticity, of 26.5%, 30.6%, 20%, and 35.6%, respectively. The drying shrinkage significantly increases as coarse aggregate is substituted with hard RAP. After 28 days of curing, the drying shrinkage rate reaches 10% when 100% of the coarse aggregate is substituted with hard RAP.