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Evaluation of Millability and Recyclability of Asphalt with Paving Interlayers

Reference

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ABSTRACT

Reclaimed asphalt pavement (RAP) has been widely incorporated into roadway base and surface courses, as they provide economic and environmental benefits that lead to sustainable construction practices. However, because of the increasing use of paving interlayers (e.g., geotextiles, geogrids, and geocomposites) during roadway rehabilitation, the likelihood of milling projects involving asphalt layers with paving interlayers (referred to as GRAP) has significantly increased. Consequently, the assessment of potential GRAP reuse in geotechnical and pavement applications becomes essential. This research study aims at evaluating the millability and recyclability of asphalt layers with paving interlayers. Specifically, sections with and without paving interlayers were first milled to evaluate the millability of asphalt layers with paving interlayers. Subsequently, the recyclability of GRAP for the base and surface course of pavements was assessed by quantifying the geotechnical characteristics of millings collected from asphalt layers with paving interlayers, referred herein as geosynthetic RAP or GRAP, and those without paving interlayers (RAP). The evaluation of RAP and GRAP materials for road base suitability included blending them with virgin aggregates and investigating these blends via determination of particle size distribution, binder content, compaction characteristics, abrasion resistance, hydraulic conductivity, and resilient modulus. The evaluation of RAP and GRAP materials for surface course suitability involved preparing asphalt mixtures that incorporated RAP and GRAP and quantifying their particle size distribution, indirect tensile strength, and moisture susceptibility. Comparison of the results obtained from five different base course blends and five different asphalt mixtures demonstrated that the base course blends and asphalt mixtures with GRAP exhibited properties similar to those with RAP. Also, the results of this investigation indicate that asphalt mixtures (surface course) and granular base courses can incorporate up to 30 % and 50 % GRAP, respectively, thus leading to sustainable roadway construction practices.

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Keywords

geosynthetic, millability, recyclability, asphalt millings, unbound aggregate base, sustainability, asphalt course

Introduction and Background

A conventional flexible pavement rehabilitation program adopted to restore roadway serviceability includes milling the existing old and oxidized asphalt surface and replacing it with a structural asphalt overlay (Kumar, Saride, and Zornberg 2021). Such rehabilitation programs involve milling operations that result in the generation of large quantities of asphalt millings, also referred to as reclaimed asphalt pavement (RAP). Specifically, about 138 million tons of RAP were stockpiled in the US in 2019, which is about 20 % higher than that stockpiled in 2018 (NAPA 2019). The significant accumulation of RAP stockpiles necessitates developing sustainable construction techniques that can utilize RAP as a construction material in large quantities. Such sustainable construction techniques would ultimately reduce the burden on landfills and raw materials required for construction. Accordingly, use of RAP in the construction of roadway base, subbase, and surface layers has become an integral part of the pavement industry (Mousa, El-Badawy, and Azam 2021). The sustainable geotechnical use of RAP may also include their incorporation as backfill material in structures such as retaining walls and embankment fills. Soleimanbeigi et al. (2022) reported that the effective friction angle of compacted RAP was 39°, which is similar to that of a densely compacted sand, suggesting the possibility for use of RAP as an alternative to densely compacted sand. Additionally, Soleimanbeigi et al. (2022) reported that the hydraulic conductivity of RAP mixtures can be comparable to that of natural or other recycled aggregates, thus making it a good candidate for use in the embankment/fill applications. However, while RAP mixtures can potentially add the ability of the backfill to freely drain, minimizing the possibility of developing excess pore pressures, the thermal sensitivity due to the asphalt binder coatings on other geotechnical properties requires more attention.

In addition, the manufacture of new asphalt mixes incorporating RAP has been a major application in sustainable roadway construction practice. Several researchers (Daryaee, Ameri, and Mansourkhaki 2020; Guo et al. 2014; Huang et al. 2005; Marín-Uribe and Restrepo-Tamayo 2022; Singh, Chitragar, and Ashish 2017; Zhao et al. 2013) have evaluated the potential of incorporating RAP into hot mix asphalt (HMA) layers. Specific mix design concerns have been addressed by evaluating the cracking resistance potential, rutting resistance, and resistance to moisture damage of the asphalt mixtures containing RAP material. Moreover, RAP can also be used as granular base material in parking areas, shoulders, and residential driveways, as well as fill in trench drains. In addition, researchers (Guduru, Tavva, and Kuna 2022; Gupta, Kang, and Ranaivoson 2009; Kim, Labuz, and Dai 2007; Locander 2009; Mousa, El-Badawy, and Azam 2021; Plati and Cliatt 2018) have evaluated the possibility of adopting RAP in the construction of base and subbase layers, suggesting that a high-quality base can be produced by blending RAP with virgin aggregates or treating RAP with chemical additives such as lime or cement. Specifically, an evaluation of RAP blends should account for variations in the type of aggregate, particle size distribution, and binder content, as well as the resulting differences in mechanical and hydraulic properties.

The adoption of sustainable practices to extend pavement service life includes incorporating paving interlayers in the form of geotextiles, geogrids, and geocomposites within asphalt layers to minimize reflective cracks and enhance pavement structural capacity (Canestrari et al. 2022; Correia and Zornberg 2016; Kumar et al. 2022; Saride and Kumar 2019; Solatiyan, Bueche, and Carter 2020). The widespread adoption of paving interlayers as a sustainable technique has significantly increased the likelihood of milling asphalt layers having paving interlayers in-between them. Hence, experimental programs are needed to evaluate the characteristics and behavior of the RAP collected from such millings with paving interlayers. In addition, the current question within the asphalt pavement community on whether geosynthetics are indeed "millable" has remained largely unanswered because the existing literature on this topic is unfortunately very limited. The only available studies (Button and Lytton 2003; Marienfeld n.d.) have focused on evaluating the millability of geosynthetic-reinforced asphalt layers where large and strong pieces of fabrics obtained from milling operations have been observed to clog milling drums and make the RAP unfit for recycling back into asphalt concrete. On the other hand, Tran et al. (2012) investigated the problem of milling geosynthetic-reinforced asphalt layers and found that the asphalt layers reinforced with paving mat were millable without any issues. In addition, Tran et al. (2012) evaluated asphalt mixtures prepared with 30 % RAP (both with and without milled geosynthetic) and reported minor differences in terms of tensile strength properties, rutting performance, moisture susceptibility, and thermal cracking analyses of the evaluated asphalt mixtures. Recently, Gu, Andrews, and Marienfeld (2021) reported that use of RAP with up to 30 % geosynthetic fragments in the new asphalt mixtures showed excellent performance in terms of rutting resistance and moisture susceptibility.

In summary, only limited research has been carried out on the millability and recyclability of asphalt layers with interlayer fragments. As such, this requires a systematic evaluation that involves initially evaluating the millability of asphalt layers with paving interlayer, followed by evaluations for identification and characterization of asphalt millings containing geosynthetic fragments, or geosynthetic RAP (GRAP) in the preparation of new asphalt mixtures as well as in the construction of base and subbase materials. This study aims at determining whether the asphalt layers with paving interlayer is millable or not, followed by determining whether the presence of interlayer fragments in RAP blends has any impact on base course or asphalt surface course characteristics. An evaluation of base course blends incorporating GRAP and RAP materials included determination of particle size distribution, binder content, compaction characteristics, abrasion resistance, hydraulic conductivity, and resilient modulus. In addition, the actual asphalt mixtures comprising GRAP and RAP materials were evaluated via determination of particle size distribution, indirect tensile strength (IDT), and moisture susceptibility characteristics.

Field Millability Evaluation and Sample Collection

The limited field evidence on the millability of asphalt layers with paving interlayers has led to a concern within the transportation geotechnics sector that certain paving interlayers present between the asphalt layers may not be millable (Button and Lytton 2003; Marienfeld n.d.). Hence, it is essential to assess the millability of asphalt layers containing paving interlayers. Accordingly, the millability evaluation conducted in this study involved the milling of asphalt layers with and without paving interlayers separately using a cold milling machine. Specifically, asphalt layers with and without paving interlayers were milled as part of the rehabilitation program of an in-service highway (US 70/84) in Muleshoe, Texas. The rehabilitation program included milling the pre-existing asphalt layer partially or completely (i.e., a fraction or the entire depth of the asphalt layer), installing a level-up course, applying tack coat, installing the new paving interlayer, and finally placing and compacting a 50-mm-thick asphalt overlay. Among these multiple field construction stages, this study focuses only on a field evaluation of the milling operations conducted as part of the rehabilitation program, which is complemented with a subsequent experimental evaluation of the recyclability of the milled materials. **Figure 1*A*** shows the typical pre-existing roadway profile (cross-section) comprised of a sandy loam subgrade, 300-mm-thick granular base layer, and a 110-mm-thick dense-graded asphalt layer with a paving interlayer. The uppermost 110-mm-thick asphalt layer depicted in **figure 1*A*** consisted of a 50-mm-thick dense-graded asphalt layer, referred to as TY-C, overlain by a paving interlayer and a 60-mm-thick TY-C layer. The paving interlayer was a nonwoven geotextile manufactured using 60 to 80 % polypropylene and 20 to 40 % recycled polyester fibers with a mass per unit area of 139 g/m^2. This interlayer had been originally adopted to provide stress relief and moisture barrier functions and, therefore, had an ultimate grab tensile strength of only 0.45 kN at an elongation of about 50 %, and an asphalt retention capacity of 0.91 l/m^2.

As part of the rehabilitation of the pre-existing asphalt, the milling operation for the 110-mm-thick asphalt layer was conducted in two stages. The first stage involved milling the top 50 mm to evaluate the millability of the asphalt layer without a paving interlayer (see **fig. 1*B***). In the second stage, the rest of the asphalt layer, comprising a 50-mm-thick TY-C layer overlain by a paving interlayer and a remaining 10-mm-thick TY-C layer, was milled (see **fig. 1*C***) to carry out the millability evaluation of asphalt layers with a paving interlayer. **Figure 2*A*** shows different views of the asphalt millings from the first (RAP) and second (GRAP) stages of milling operations, which

FIG. 1 Cross-sections of typical roadway profiles: (*A*) pre-existing roadway, (*B*) after first stage of milling, and (*C*) after second stage of milling.

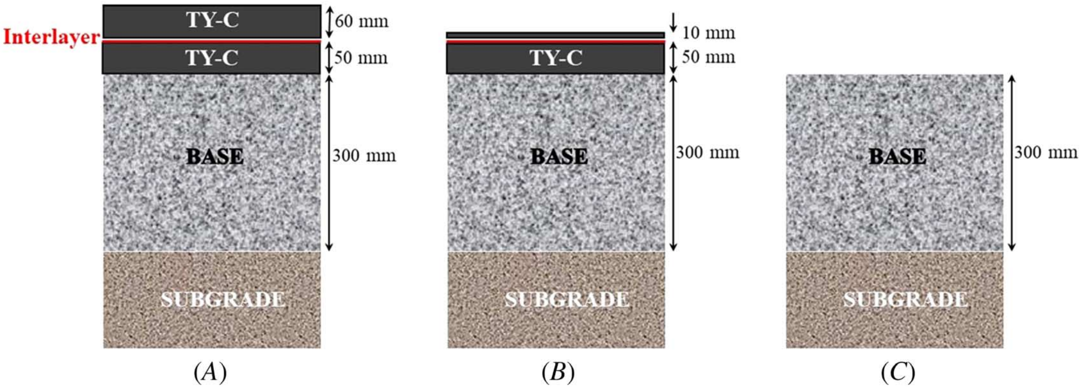
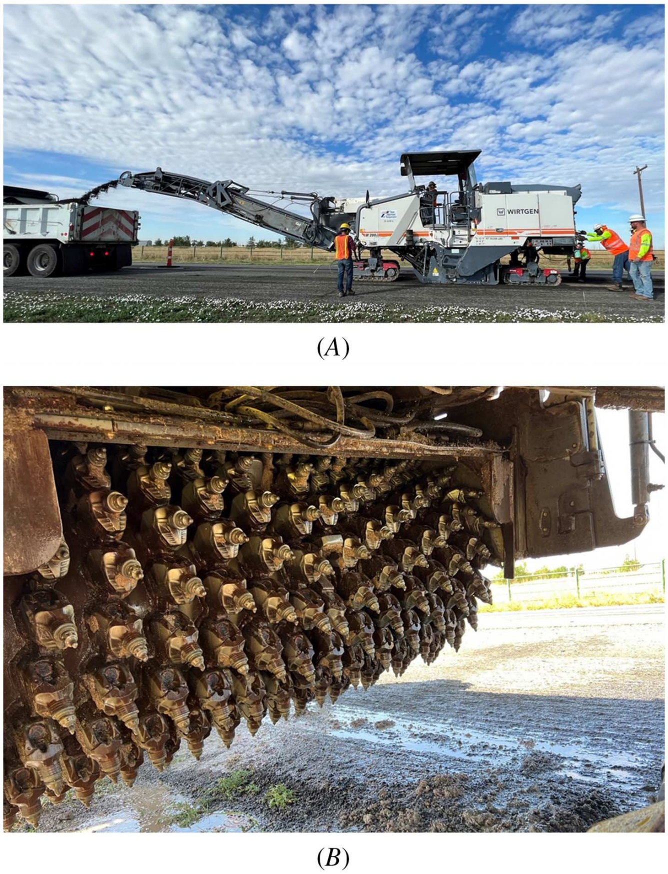


FIG. 2 Milling operation to collect RAP and GRAP samples: (*A*) view of equipment during operations and (*B*) detail of milling drum.



were collected separately by dump trucks and transported to the stockpile location. Notably, the presence of a paving interlayer between asphalt layers did not affect milling operations and no traces of interlayer fragments were detected on the milling drum (see fig. 2*B*) after conducting milling operations. In other words, no difference

FIG. 3

Representative samples of: (*A*) RAP and (*B*) GRAP.

(*A*) (*B*)

was found between the milling operations conducted on asphalt layers with and without paving interlayers. However, the RAP and GRAP materials visibly showed relevant differences in their particle sizes. The RAP and GRAP material obtained from their respective stockpiles in this study differ from each other in terms of their particle size. Specifically, the RAP particles are smaller in size compared to the GRAP particles. Additionally, GRAP material has fragments of the milled paving interlayer. **Figure 3** displays representative samples of the RAP and GRAP materials collected from their respective stockpiles. As shown in the figure, the GRAP sample had comparatively larger particles compared to those in the RAP sample because of the presence of interlayer fragments and asphalt coating on the aggregates. However, because of their larger particle sizes, neither the RAP nor the GRAP samples were directly reused in the project as base or surface course, requiring additional processing to achieve the required gradations.

The RAP samples are typically processed in the field by fractionating, which includes screening, crushing, and sorting the various size particles into different stockpiles that are consistent in size and composition. Specifically, a centrifuge that comprises a vertical spindle, rotator, and crushing chamber is typically used to fractionate the RAP samples through shearing, crushing, and abrasion processes. Accordingly, a laboratory procedure was developed to process the RAP and GRAP samples in this study by crushing, shearing, and wearing action. It is important to note that the field crushing process may be slightly different from the one adopted in this study. The RAP and GRAP sample processing procedure adopted in this study included crushing the samples in different batches using a modified Proctor compaction hammer. Specifically, GRAP samples weighing approximately 3 kg were placed in a modified Proctor mold and crushed by a 4.5 kg modified Proctor compaction hammer dropped about 100 times from a height of 450 mm. The RAP and GRAP samples are presented in **figures 4** and **5**, respectively, both before and after crushing. The crushing process reduced the particle sizes of both RAP and GRAP samples to less than 37.5 mm. The RAP and GRAP samples were determined to have a specific gravity of 2.38 and 2.22 and water absorption values of 1.71 % and 2.01 %, respectively. The asphalt content of the RAP and GRAP samples was established according to a binder extraction test defined in AASHTO T164-22, *Standard Method of Test Quantitative Extraction of Asphalt Binder from Asphalt Mixtures*, and determined to be 4.92 % and 5.87 %, respectively. The higher asphalt content in the GRAP sample is attributed to the application of tack coat that is conducted during installation of the paving interlayers.

Table 1 presents the particle size distribution of crushed GRAP and RAP samples. As indicated in the table, both samples had comparatively similar particle size distributions, although RAP samples showed slightly finer particle sizes. The particle size distribution of the crushed GRAP sample displayed the presence of paving interlayer fragments that were greater than 12.7 mm and of 0.02 % of particles that were finer than 0.075 mm. For the crushed RAP sample, the percentage of particles finer than 0.075 mm was determined to be 0.32 %, which is

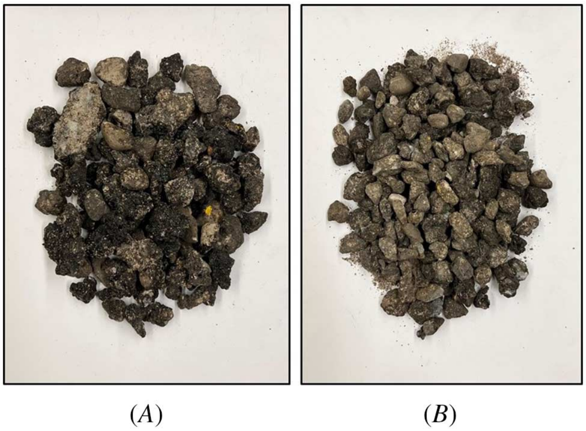


FIG. 4

RAP samples: (*A*) before processing and (*B*) after processing.

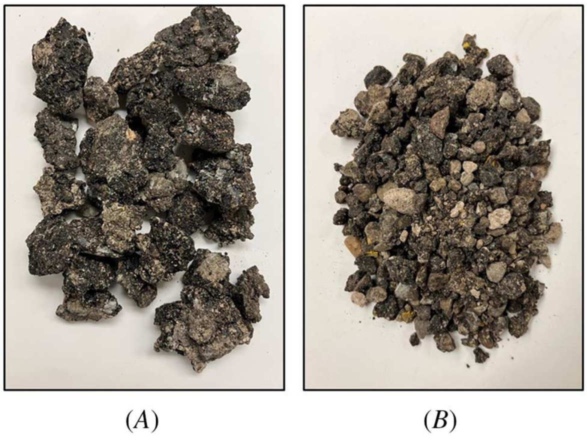


FIG. 5

GRAP samples: (*A*) before processing and (*B*) after processing.

TABLE 1

Particle size distribution of crushed GRAP and RAP samples

	Percentage Passing, %	
Sieve Size, mm	GRAP	RAP
37.50	100.00	100.00
25.00	90.49	99.16
19.00	73.31	90.32
12.70	53.25	66.58
9.50	28.34	42.11
4.75	8.31	15.17
2.38	3.93	7.60
0.60	1.19	3.60
0.30	0.43	1.72
0.075	0.02	0.32

also very low in relation to that conventionally required for base or surface courses. This condition necessitates blending the RAP and GRAP samples with virgin aggregate (VA) individually to achieve the gradation required for each blend (mixture) to be used as base and surface courses in roadway construction. The various RAP-VA and GRAP-VA blends prepared for this investigation as representative of those used in base and surface courses are detailed next.

Materials and Experimental Methods

BASE COURSE CHARACTERIZATION

Five different blends were prepared to evaluate the suitability and recyclability of GRAP material as a potential roadway base course. These blends consisted of 50 % GRAP:50 % VA (referred to as 50-50 GRAP), 50 % RAP:50 % VA (referred to as 50-50 RAP), 25 % GRAP:75 % VA (referred to as 25-75 GRAP), 25 % RAP:75 % VA (referred to as 25-75 RAP), and conventional base course (referred to as BC). The characteristics of the RAP and BC blends were evaluated and compared to those of the GRAP blends to assess the effects and suitability of incorporating GRAP as base course material. Specimens containing up to 50 % RAP/GRAP were prepared based on the mix proportions used in the previous studies (Cavalli, Partl, and Poulikakos 2017; MacGregor, Highter, and DeGroot 1999). Moreover, the existing literature indicates that 100 % RAP could not produce a high-quality base course because of its high deformation and creep (Dong and Huang 2014). Preparation of the GRAP and RAP blends entailed mixing the target proportions (by weight) of VA with crushed GRAP material and RAP material separately. **Table 2** shows the particle size distribution of the five base course blends, including the 50-50 GRAP, 50-50 RAP, 25-75 GRAP, 25-75 RAP, and conventional BC blends, evaluated herein, as well as Texas Department of Transportation (TxDOT) specifications (TxDOT 2014) aggregate size limits for base course. As shown in the table, the particle size distributions for the three blends (25-75 GRAP, 25-75 RAP, and BC) were well within the gradation requirements for granular base course per TxDOT specifications (TxDOT 2014). While a few particle sizes of 50-50 GRAP and 50-50 RAP were determined to be beyond the TxDOT specifications for base course. Such particle size gradations were obtained because of the presence of coarser particles of RAP and GRAP in a given blend, which now occupied 50 % weight of the total blend. The characterization of the base course blends to evaluate their suitability as base course material included compaction, water absorption, abrasion resistance, hydraulic conductivity, and resilient modulus tests, as detailed next. Please note that all the tests detailed next were repeated twice to confirm their repeatability and it was determined the tests were deemed repeatable, as the maximum variation in results was approximately 5 %.

Compaction Testing Program

Modified Proctor compaction tests were conducted per ASTM D1557-12(2021), *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft^3 (2,700 kN-m/m^3))*, on

TABLE 2
Particle size distribution of base course blends

Sieve Size, mm	Percentage Passing, %					
	50-50 GRAP	50-50 RAP	25-75 GRAP	25-75 RAP	VA	TxDOT Specification
37.50	100.0	100.0	100.0	100.0	100.0	100-98
25.00	89.2	95.0	90.3	92.1	90.0	94-78
19.00	74.1	88.5	79.7	83.2	82.0	85-64
12.70	52.3	67.3	61.8	64.3	65.0	70-50
4.75	27.1	32.4	37.7	38.8	48.0	50-30
2.36	20.3	23.4	26.1	26.5	34.0	36-22
0.60	18.1	18.3	15.6	16.0	21.0	23-8
0.30	9.6	10.2	12.6	12.6	17.0	19-3
0.075	1.3	1.8	4.6	4.2	6.0	7-2

the five base course blends to determine their moisture-unit weight characteristics. The test procedure involved adding a molding water content to the blends and mixing before placing them in a compaction mold in five equal layers. Each layer was compacted by dropping a 0.04 kN rammer from a height of 457 mm about 56 times, which applied a total compactive effort of 2,700 kN-m/m^3 for all five layers. The total weight of the compacted sample and volume of the compaction mold were measured to calculate the corresponding bulk unit weight of the compacted sample. Additionally, a portion of the compacted sample was collected, weighed, and placed in a hot air oven to obtain the sample's moisture content as well as its bulk unit weight to determine the sample's dry unit weight. The test was repeated for different molding moisture content values, and the dry unit weight and moisture content corresponding to each was obtained for the compacted sample. The variations in dry unit weight with molding moisture content were then plotted to determine the maximum dry unit weight and optimum moisture content of the base course blends evaluated in this study.

Water Absorption Testing Program

Water absorption tests were conducted per AASHTO T85, *Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate*, on all five base course blends to determine their ability to absorb moisture under specific conditions, which in turn showed the material's internal structure (e.g., if the material is porous or comparatively impervious). The test procedure involved oven-drying a sample of about 3 kg in a hot air oven, and then cooling it at room temperature for one to three hours and recording the sample weight. The samples were subsequently immersed in room temperature water for about 24 hours. The samples were then removed from the water bath and weighed after surface drying by rolling the samples on an absorbent cloth until no visible traces of water remained. The water absorption value was ultimately determined using the relationship between the oven-dried mass and saturated surface dry mass of the samples.

Abrasion Resistance Testing Program

The Los Angeles (LA) abrasion test was conducted per ASTM C131/C131M-20, *Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*, to determine the toughness of the base course material evaluated herein, which in turn establishes the material's resistance to mechanical degradation. The test procedure involved oven-drying a sample of about 10 kg, and then cooling it at room temperature for one to three hours and recording the sample weight. The sample was then placed together with 12 steel spherical balls in the drum of an LA abrasion machine rotating at a speed of 30 to 33 revolutions/minute for about 500 revolutions. The samples were then removed from the rotating drum, sieved through a 1.6 mm sieve and the retained sample weighed. The abrasion resistance value was ultimately determined using the relationship between the oven-dried and retained mass of the samples.

Hydraulic Conductivity Testing Program

The drainage characteristics of a base course material play a crucial role in pavement performance. Specifically, moisture entrapped in the base layer can lead to severe deterioration of the base and subgrade layers, thereby compromising pavement performance. Constant head hydraulic conductivity tests were conducted according to ASTM D2434, *Standard Test Methods for Measurement of Hydraulic Conductivity of Coarse-Grained Soils*, on the five base course blends to determine their hydraulic characteristics. The test procedure involved compacting samples of each blend at its maximum dry unit weight and optimum moisture content in five equal layers in a mold measuring 152 mm in diameter and 254 mm in height. The compacted samples were fully saturated via a constant pressure head and the hydraulic conductivity was thereby obtained for the different blends evaluated in this study.

Resilient Modulus Testing Program

The stiffness of the three different base course blends evaluated herein were determined by conducting resilient modulus tests per AASHTO T307, *Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials*. Specifically, a triaxial cell was used to maintain a constant confining pressure while simultaneously applying cyclic axial loading. Specimens for the resilient modulus tests were prepared at their respective maximum dry densities and optimum moisture contents in a cylindrical mold that had a diameter and height of 100 mm and 200 mm, respectively. For a typical Type 1, or compacted specimens of Type 2 base course materials, the diameter of molded specimens should be equal to five times the size of the maximum particle, per AASHTO T307 recommendations. In this study, because cylindrical specimens of 100 mm diameter and 200 mm height were used, the particles greater than 19 mm were replaced with an equivalent weight of particles having size less than 19 mm. Similar specimen preparation procedures have been previously adopted by Dong and Huang (2014) and Wu et al. (2012). The test procedure adopted in this study involved placing the specimen assembly that required use of porous stones, specimen caps, membrane, and O-rings inside the triaxial cell. The axial loading piston and triaxial cell were positioned so that the loading piston came into contact with the specimen. The confining pressure applied to the specimen was controlled via cell pressure and back pressure valves before the axial load was applied. The testing program involved pre-conditioning the specimen by applying haversine load pulses for about 500 cycles at a frequency of 1 Hz, with each load cycle consisting of 0.1 seconds of loading followed by a rest period of 0.9 seconds. Following the specimen pre-conditioning, about 15 sequences of 100 load cycles each were applied with increasing confining pressure and axial loads. The resilient modulus was calculated as the average value obtained from the last five cycles of each sequence.

SURFACE COURSE CHARACTERIZATION

To evaluate the suitability and recyclability of GRAP material as a potential dense-graded asphalt surface course, five different asphalt mixtures were prepared. These mixtures included 30 % GRAP:70 % VA (referred to as 30-70 GRAP), 30 % RAP:70 % VA (referred to as 30-70 RAP), 15 % GRAP:85 % VA (referred to as 15-85 GRAP), 15 % RAP:85 % VA (referred to as 15-85 RAP), and a conventional dense-graded asphalt course mix (referred to as AC). Item 340 of TxDOT specifications (TxDOT 2014) suggests that no more than 30 % of RAP should be used in the surface course. Moreover, Singh, Chitragar, and Ashish (2017) reported that moisture damage of asphalt mixtures containing RAP improved until 30 % RAP content, and a further increase in RAP content made the asphalt mixture vulnerable to moisture damage. In this study, the characteristics of the RAP and AC mixtures were evaluated and compared to those of the GRAP mixtures to assess the effects and suitability of incorporating GRAP into dense-graded HMA. Preparation of the GRAP and RAP mixtures consisted of separately blending about 30 % and 15 % crushed GRAP material (by weight) respectively with 70 % and 85 % VA, and 30 % and 15 % crushed RAP material (by weight) respectively with 70 % and 85 % VA. **Table 3** shows the particle size distribution of the aggregates in the five dense-graded surface course mixtures, including the 30-70 GRAP, 30-70 RAP, 15-85 GRAP, 15-85 RAP, and AC mixtures evaluated in this study. As shown in the table, the particle sizes for all the five mixtures were well within the dense-graded asphalt surface course requirements per TxDOT specifications. A performance grade (PG) 64-22 binder was used in the preparation of all five asphalt mixtures.

TABLE 3
Particle size distribution of asphalt mixtures

	Percentage Passing, %					
Sieve Size, mm	30-70 GRAP	30-70 RAP	15-85 GRAP	15-85 RAP	AC	TxDOT Specification
19.00	100.0	100.0	100.0	100.0	100.0	100
12.70	98.4	98.6	98.5	98.4	98.0	100-98
9.50	94.7	92.6	94.8	94.0	94.3	100-85
4.75	69.2	66.6	69.1	68.6	67.0	70-50
2.36	40.2	39.9	40.2	40.1	38.0	46-35
0.60	27.5	25.2	27.5	27.1	20.0	29-15
0.30	13.3	14.2	14.1	14.6	11.0	20-7
0.075	4.7	3.7	4.8	6.0	5.3	7-2

An optimum binder content corresponding to a target air void content of 7 % was determined to be 3.55 % (30-70 GRAP), 3.7 % (30-70 RAP), 4 % (15-85 GRAP), 4.10 % (15-85 RAP), and 4.45 % (AC) per ASTM D6925-15, *Standard Test Method for Preparation and Determination of the Relative Density of Asphalt Mix Specimens by Means of the Superpave Gyratory Compactor*. As expected, the binder content of the AC mixture was higher than that of the RAP and GRAP mixtures because of the presence of binder in the RAP and GRAP materials. A Superpave gyratory compactor was used to compact all specimens prepared for the evaluation of asphalt mixtures containing GRAP and RAP materials. Specimen preparation involved heating the aggregates and binder to temperatures of 110°C and 150°C, respectively, after which the aggregates and binder were mixed at a temperature of 160°C and then compacted at a temperature of about 145°C. Multiple specimens of the five different asphalt mixtures were prepared to determine the optimum binder content. In addition to the tests described to characterize the base course materials, characterization of the dense-graded asphalt mixtures, including IDT and moisture susceptibility tests, are detailed next. Please note that all the tests detailed next were repeated at least twice to confirm their repeatability and it was determined the tests were repeatable with variations of less than 5 % between them.

IDT Testing Program

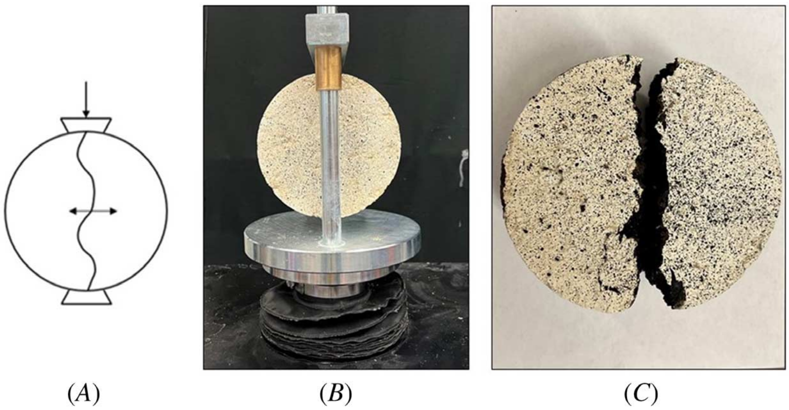
The IDT test was used to characterize the tensile strength and viscoelastic properties of the asphalt mixtures and evaluate their rutting and cracking potential. The IDT was conducted per ASTM D6931-17, *Standard Test Method for Indirect Tensile (IDT) Strength of Asphalt Mixtures*, to obtain the indirect tensile strength of the five different asphalt mixtures evaluated herein. Specifically, a cylindrical specimen was loaded vertically in its diametrical position so that uniform tensile stresses were generated perpendicular to the load along the diameter of the specimen (see fig. 6*A*). The cylindrical specimens were prepared to a target air void content of 7 % using the Superpave gyratory compactor, resulting in dimensions of 150 mm in diameter and 95 mm in thickness. Three specimens were prepared and tested from each of the five different asphalt mixtures. The IDT test procedure involved conditioning the specimens at a constant temperature (25°C) for about 2 hours, followed by placement in the loading frame (see fig. 6*B*) after which the load was applied at a displacement rate of 50 mm/min until failure (see fig. 6*C*). The load and displacements are recorded so that the maximum load and corresponding displacement are determined for each test to calculate the indirect tensile strength, as follows:

$$\sigma_{IDT} = \frac{2000 P_{max}}{\pi t d} \quad (1)$$

where σ_{IDT} is the indirect tensile strength, in kPa; P_{max} is the ultimate load applied, in N; and t and d are the thickness and diameter of the specimen, respectively, in mm.

FIG. 6

Indirect tensile strength test (IDT): (*A*) schematic view, (*B*) IDT specimen before testing, and (*C*) IDT specimen after testing.



Moisture Susceptibility Testing Program

Moisture susceptibility tests are performed to determine the potential for moisture damage to the asphalt mixtures subjected to the presence of moisture over prolonged periods of time. The test procedure per ASTM D4867/D4867M-22, *Standard Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures*, involves conducting IDT to determine the moisture susceptibility in terms of tensile strength ratio. Six specimens were prepared for each of the five different asphalt mixtures to a target air void content of 7 % using the Superpave gyratory compactor. The specimens were then tested under both dry and wet conditions. The dry condition test series involved conditioning the specimens at 25°C for about 2 hours, while the wet condition test series involved partially saturating the specimens (to a degree of saturation of 70–80 %) and then immersing them in a 60°C water bath for about 24 hours. IDT tests were conducted using the dry and wet specimens by loading them at a displacement rate of 50 mm/minute under a temperature of about 25°C, ultimately resulting in the dry and wet indirect tensile strengths of the asphalt mixtures. The ratio of the wet and dry indirect tensile strengths is referred to as the tensile strength ratio (TSR), which is determined as follows:

$$TSR = \frac{\sigma_{IDT,wet}}{\sigma_{IDT,dry}} \tag{2}$$

where $\sigma_{IDT,wet}$ and $\sigma_{IDT,dry}$ are the indirect tensile strengths at wet and dry conditions, respectively, in kPa. The TSR is a measure of the asphalt mixtures' potential for moisture damage, i.e., a greater TSR value results in the least moisture damage and vice versa.

Discussion of the Experimental Results

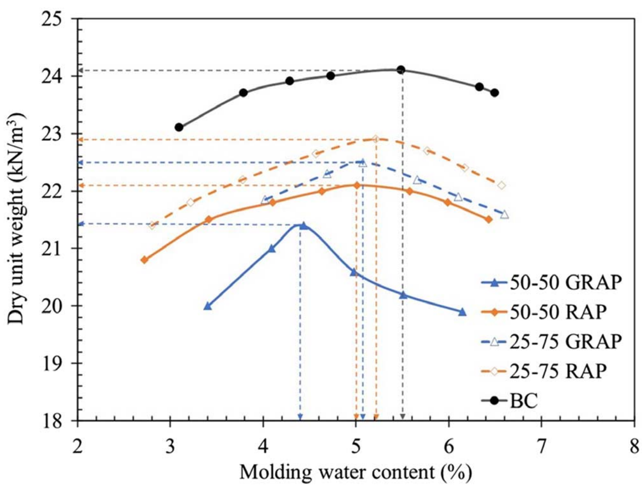
RECYCLABILITY EVALUATION OF THE BASE COURSE

Compaction Characteristics

The moisture-unit weight characteristics of the five base course blends evaluated herein were determined following the procedures described previously. Specifically, the relationships between dry unit weights and molding moisture contents were determined, with the results presented in figure 7. As the results in this figure indicate, the trends that are typical of soils were also observed in the GRAP and RAP blends. That is, the compaction curves for all base course blends show an initially increasing dry unit weight with increasing molding moisture content up to a peak value, subsequently showing a decreasing unit weight with further increase in moisture content.

FIG. 7

Compaction curves of the different base course blends.



The maximum dry unit weight (MDU) and optimum moisture content (OMC) values obtained for the five blends evaluated in this study were 21.4 kN/m^3 and 4.43 % (50-50 GRAP), 22.1 kN/m^3 and 5 % (50-50 RAP), 22.5 kN/m^3 and 5.07 % (25-75 GRAP), 22.9 kN/m^3 and 5.21 % (25-75 RAP), and 24.1 kN/m^3 and 5.5 % (VA), respectively. The MDU inclines decrease with an increase in RAP/GRAP content in the blends. Moreover, OMC also decreases with an increase in RAP/GRAP content in the blends. From figure 7, it can be observed that the MDU of 50-50 GRAP, 50-50 RAP, 25-75 GRAP, and 25-75 RAP is about 11.2 %, 8.3 %, 6.6 %, and 5 % respectively, lower than that of the BC blend. Additionally, the OMC of 50-50 GRAP, 50-50 RAP, 25-75 GRAP, and 25-75 RAP is about 19.45 %, 9.09 %, 7.81 %, and 5.27 % respectively, lower than that of the BC blend. Such a condition may be because the moisture holding capacity of RAP is lower than that of BC, because RAP material has fewer fines (passing 0.075 mm sieve) than BC, and most of the RAP/GRAP particles are coated with asphalt, which reduces the moisture absorption capacity of the blends (Mousa et al. 2021). Among the GRAP and RAP blends, the MDU and OMC of the 50-50 GRAP blend were lower than those for the 50-50 RAP blend, which were in turn lower than those for the 25-75 GRAP blend, followed by the 25-75 RAP blend. These reductions in MDU and OMC may be attributable to the presence of asphalt in the GRAP and RAP material, while the presence of interlayer fragments may account for the additional reductions in the 50-50 GRAP and 25-75 GRAP blends in comparison with 50-50 RAP and 25-75 RAP blends, respectively. Similar trends showing a reduction of about 11 % in the MDU of RAP as compared to that for conventional base were reported by Mousa, El-Badawy, and Azam (2021). Additionally, Saride, Avirneni, and Javvadi (2016) reported that the OMC of RAP bases were lower than those for conventional bases.

Water Absorption Capacity

The water absorption capacity of the five base course blends evaluated herein were determined to be 2.51 % (50-50 GRAP), 2.06 % (50-50 RAP), 2.64 % (25-75 GRAP), 2.53 % (25-75 RAP), and 2.82 % (VA). The lower water absorption capacity values of the GRAP and RAP blends in relation to that of the BC blend can be attributed to the presence of asphalt in the RAP and GRAP blends. Specifically, the asphalt in the RAP and GRAP blends would fill the pores of aggregates and thereby reduce their ability to absorb moisture, while the pores of the VA are comparatively less impeded to absorb moisture. However, of the GRAP and RAP blends evaluated herein, both the 50-50 and 25-75 GRAP blends showed higher water absorption capacity compared respectively to 50-50 RAP and 25-75 RAP blends, possibly because of the presence of interlayer fragments that may absorb additional moisture. Saride, Avirneni, and Javvadi (2016) also reported lower water absorption capacities for RAP blends compared with those for conventional base, suggesting the hydrophobic nature of the asphalt coating is responsible for the lower water absorption capacities of RAP material in comparison with conventional road base. It is also important to note that lower water absorption capacity can result in a comparatively better resistance against moisture degradation of the roadway base.

Abrasion Resistance Characteristics

The abrasion resistance characteristics of the five base course blends tested in this study were evaluated using the LA abrasion test. Abrasion values were determined to be 9.5 %, 17.2 %, 17.66 %, 21.12 % and 25.4 % for the 50-50 GRAP, 50-50 RAP, 25-75 GRAP, 25-75 RAP, and VA blends, respectively. It should be noted that the limiting value of abrasion obtained via the LA abrasion test for coarse aggregate particles to be used as road base is 50 % per AASHTO M147, *Standard Specification for Materials for Aggregate and Soil-Aggregate Subbase, Base, and Surface Courses*. The abrasion values for the GRAP and RAP blends were determined to be lower than that for the BC blend, which suggests that the RAP and GRAP material exhibits greater resistance to abrasion and impact loading. Specifically, the impact energy is expected to be more efficiently absorbed by the asphalt and interlayer fragments in the GRAP blends, resulting in reduced particle breakage as compared to that for the RAP blends. Among the GRAP and RAP blends evaluated herein, the 50-50 GRAP blend had the lowest abrasion value, followed by 50-50 RAP, 25-75 GRAP, and finally 25-75 RAP blends. Such resistance against abrasion may be due to the presence of interlayer fragments that allow additional capacity to absorb the impact energy and reduce damage to aggregate particles in GRAP mixtures. Additionally, the asphalt on RAP surface absorbs the impact energy and dissipates, which results in lesser separation of the agglomerated fine aggregate, thus leading to a reduction in fragmentation value (particle breakage value) (Guduru, Tavva, and Kuna 2022).

Hydraulic Characteristics

The saturated hydraulic conductivity values were determined for all five blends investigated in this study via the constant head permeability test. The results, plotted in figure 8, show that the hydraulic conductivity was lowest in the BC blend, followed by the 25-75 RAP and 50-50 RAP blend, and finally the 25-75 GRAP and 50-50 GRAP blend, which had the highest hydraulic conductivity. The higher hydraulic conductivity values in the GRAP and RAP blends compared to BC blends can be attributed to the lower unit weight (i.e., higher void) achieved during preparation of the specimens, compacted to the same compaction energy. Additionally, the higher permeability determined for the GRAPs blend as compared to that for the corresponding RAPs blend can be attributed to the presence of interlayer fragments that absorb moisture. Similar hydraulic conductivity values for the RAP and BC blends were reported by Gupta, Kang, and Ranaivoson (2009). In contrast, Locander (2009) and Mousa, El-Badawy, and Azam (2021) reported comparatively lower permeability values for RAP blends in comparison with conventional road base material, suggesting that the presence of RAP reduced the porosity of the blends. Additionally, they reported that the interlocking between the RAP and VA particles resulted in reduced permeability because of the aggregation of RAP particles during compaction of the blends. However, it should be noted that the percentage of particles finer than 0.075 mm was lower in the GRAP and RAP blends than that in the BC blend (see Table 2). This is consistent with the comparatively higher permeability values that were determined for the GRAP and RAP blends tested herein. The differences in permeability values reported in the aforementioned studies could be because of variability in the properties of the VA and RAP materials used.

Resilient Modulus Characteristics

Figure 9 shows the resilient modulus test results obtained for the five base course blends evaluated herein, presented as a function of the bulk stress. The cyclic testing program involved application of three different amplitude loadings for each confining pressure. That is, three different deviatoric stresses were applied for each of the five

FIG. 8

Saturated hydraulic conductivity of base course blends.

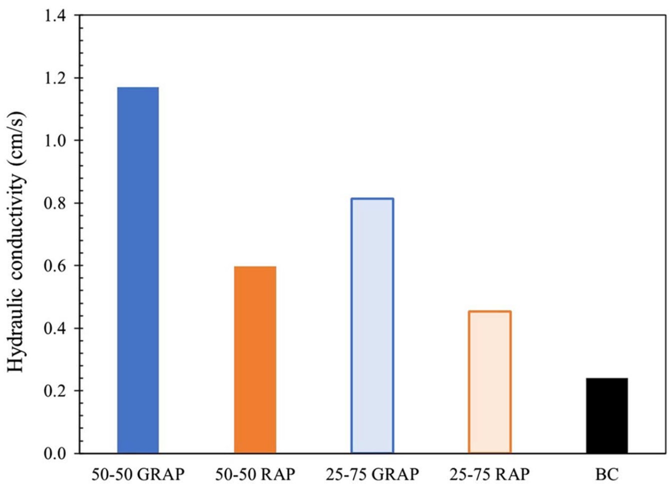
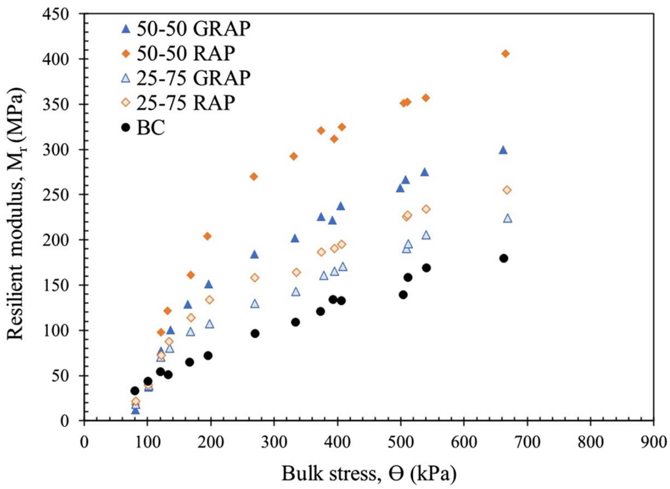


FIG. 9

Relationship between resilient modulus and bulk stress.



confining pressures considered in the testing program, which resulted in three resilient moduli at a given confining pressure for each one of the five blends investigated in this study. Subsequently, the bulk stress (Θ), which is the summation of confining stresses acting in three different directions on the specimens and deviatoric stress acting in vertical direction on the specimen, was determined. As expected, the resilient modulus increased with increasing bulk stress for all the blends evaluated herein. In addition, resilient modulus values increased with the increase in the percentage of RAP/GRAP in the blends. It can be observed from figure 9 that the 50-50 RAP blend has higher resilient modulus followed by 50-50 GRAP, 25-75 RAP, 25-75 GRAP, and finally the BC blend. This is because blending of RAP/GRAP with the VA to constitute RAP/GRAP blends enhance the cohesion between particles because of the existing asphalt that coats the VA in RAP/GRAP blends that leads to a stiffer blend. The resilient modulus values obtained in this study for 50-50 RAP and 25-75 RAP complies with the findings from studies conducted by Kim et al. (2007), MacGregor et al. (1999), and Mousa et al. (2021). However, it should also be noted that different studies have reported different amplitudes of resilient modulus, which may be due to the variation in the RAP source, aged binder on RAP, RAP gradation. Moreover, the results also indicate that the resilient moduli of the BC blend are the highest at low bulk stress but increases gradually as bulk stress increases. In contrast, the resilient moduli of the 50-50 GRAP, 50-50 RAP, 25-75 GRAP, and 25-75 RAP blends were comparatively lower than that of the BC at low bulk stress, but they increased significantly with increasing bulk stress. For instance, at a bulk stress of 81 kPa, the resilient moduli of 50-50 GRAP, 50-50 RAP, 25-75 GRAP, 25-75 RAP, and BC blends were on the order of 12.22 MPa, 18.23 MPa, 18.56 MPa, 21.34 MPa, and 32.43 MPa, respectively. While at bulk stress of around 665 kPa, these values increased to 299.63 MPa, 405.85 MPa, 224.04 MPa, 255.40 MPa, and 179.18 MPa, respectively, for 50-50 GRAP, 50-50 RAP, 25-75 GRAP, 25-75 RAP, and BC blends. These trends suggest that the particles in the GRAP and RAP blends may have been rearranged with increasing bulk stress, resulting in stiffer configurations. On the other hand, the BC blend had a well-graded particle size distribution that resulted in comparatively higher moduli at low confining pressures and increased comparatively more gradually with increasing confining pressures. Kim, Labuz, and Dai (2007) reported similar trends, which highlighted that 50-50 RAP blends develop stiffness equivalent to that of conventional base blends at lower confining pressures, which increases with increasing confining pressures. Among the RAP/GRAP blends, the 50-50 RAP blend shows the highest resilient modulus followed by 50-50 GRAP, 25-75 RAP, and finally 25-75 GRAP blends. Such a performance in GRAP blends may be attributed to the presence of interlayer fragments that may have resulted in higher expansion and contraction when subjected to cyclic loading.

RECYCLABILITY EVALUATION OF THE SURFACE COURSE

IDT Characteristics

The IDT results for all specimens tested in this study are presented in the form of load-displacement trends, as shown in figure 10. As the figure shows, for all the specimens the applied load increased with increasing displacements until a peak value was reached and decreased thereafter as displacements increased further. The peak load and corresponding displacement along with the specimen dimensions were noted for all specimens tested. As can be seen in figure 10, incorporation of RAP and GRAP increased the strength of HMA mixtures. However, because of the increase in the brittleness (decreased failure displacement), the fatigue life of HMA mixtures may be compromised. This increase in load carrying capacity and decrease in failure displacement can be attributed to the stiffening effect of the aged asphalt in RAP and GRAP blends. Although the specimens were observed to fail at lower strain value for the asphalt mixtures with GRAP/RAP material, a higher load was required to initiate the crack in the specimen. Finally, the average indirect tensile strengths for all specimens were determined and plotted in figure 11. The average indirect tensile strength value was observed to be highest for the 30-70 RAP specimen, followed by the 30-70 GRAP, 15-85 RAP, 15-85 GRAP, and finally AC specimens. The higher indirect tensile strength and lower displacement values for the 30-70 RAP and 30-70 GRAP specimens compared respectively to those for the 15-85 RAP, 15-85 GRAP, and AC specimens can be attributed to the comparatively stiffer and more brittle behavior of the aged asphalt and the amount of GRAP/RAP present in the 30-70 GRAP and 30-70 RAP mixtures. Notably, the indirect tensile strength of the AC specimen was 38 %, 31 %, 20 %, and 18 % lower than that of the 30-70 RAP, 30-70 GRAP, 15-85 RAP, and 15-85 GRAP specimens, respectively. However, there was no significant difference between the indirect tensile strength and corresponding displacement values observed for the 30-70 GRAP and 30-70 RAP specimens, or the 15-85 GRAP and 15-85 RAP specimens. Similar observations between RAP and GRAP specimens were reported by Tran et al. (2012), which indicated that no appreciable differences in tensile strength were recorded between specimens with only 30 % RAP and those with 30 % RAP with geosynthetic fragments. On the other hand, 15-85 GRAP had lower indirect tensile strength values at higher strains at failure compared to those for 15-85 RAP specimens, followed by the 30-70 GRAP specimens, and finally, 30-70 RAP specimens with the highest indirect tensile strength at lower strains at failure. Such responses may be because of the amount of GRAP/RAP and the presence of interlayer fragments that reduce the stiffness of the specimen.

Moisture Susceptibility

The moisture susceptibility of the five asphalt mixtures tested herein was evaluated by determining the TSR of the specimens. The TSR values were calculated using the indirect tensile strength values obtained for the specimens

FIG. 10

IDT load-displacement curves of different asphalt mixtures.

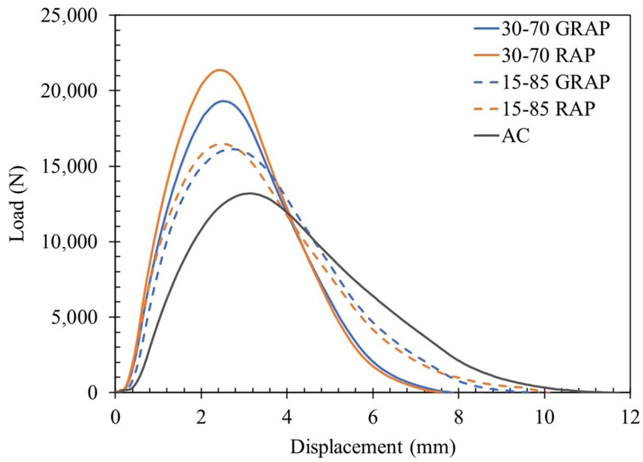
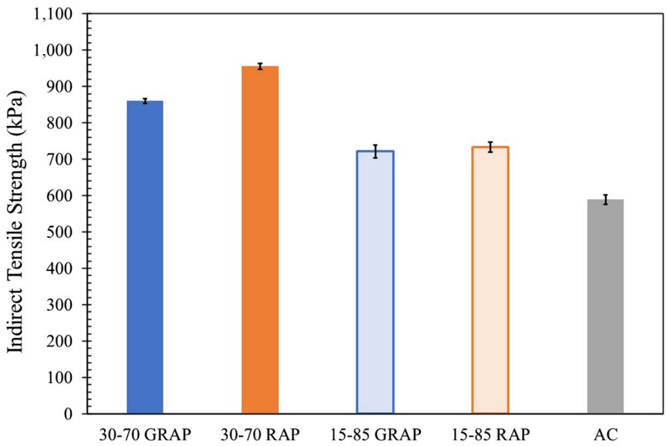


FIG. 11

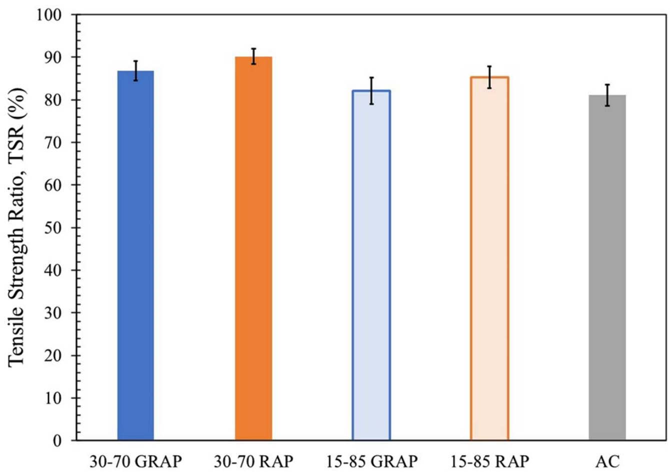
IDT characteristics of asphalt mixtures.



tested under both dry and wet conditions (see equation (2)). **Figure 12** shows the TSR values obtained for the 30-70 GRAP, 30-70 RAP, 15-85 GRAP, 15-85 RAP, and AC specimens. As shown in the figure, the 30-70 RAP specimens had the highest TSR value of 0.90 followed by the 30-70 GRAP specimens with a TSR of 0.87, 15-85 RAP specimens with a TSR of 0.85, 15-85 GRAP specimens with a TSR of 0.82, and finally, the AC specimens with the lowest TSR value of 0.81. However, it is important to note that the minimum required TSR value for an asphalt mixture is about 0.80, per India's Ministry of Road Transport and Highways (MoRTH) specifications (MoRTH 2013). Accordingly, all the asphalt mixtures evaluated in this study including those with GRAP/RAP are acceptable. In addition, the TSR values indicate that the RAP or GRAP present in the asphalt mixture effectively resists moisture damage as compared to conventional asphalt mixtures. Specifically, the aged asphalt may have resulted in mechanisms of interlocking and bonding with the aggregates that may not be present for specimens with VA mixtures (Shu et al. 2012). Additionally, Huang et al. (2005) reported that the aged asphalt in the RAP mixture increases the stiffness of the mixture that improves the performance of asphalt mixtures against moisture damage. The TSR for the 15-85 GRAP specimen was found to be slightly lower than that for the 15-85 RAP specimen, followed by the 30-70 GRAP specimen, and finally the 30-70 RAP specimen.

FIG. 12

Moisture susceptibility characteristics of asphalt mixtures.



Such a response may be because of the amount of RAP/GRAP and the presence of interlayer fragments in GRAP specimens that may absorb moisture. However, all the GRAP and RAP mixtures exhibited better resistance to moisture damage compared to that of the conventional asphalt mixture evaluated in this study. Similar observations were reported by Tran et al. (2012) and Gu, Andrews, and Marienfeld (2021).

Conclusions

In this study, the millability and recyclability of asphalt layers with paving interlayers were evaluated by milling asphalt layers with and without paving interlayers. Asphalt millings with and without interlayer fragments, known as GRAP and RAP, respectively, were collected and used together with VA to constitute five different blends for base course (50-50 GRAP, 50-50 RAP, 25-75 GRAP, 25-75 RAP, and BC) and five different asphalt mixtures (30-70 GRAP, 30-70 RAP, 15-85 GRAP, 15-85 RAP, and AC). Their suitability and performance as potential base and surface course materials were evaluated and the following conclusions were drawn from this study:

- Millability of asphalt layer was found not to be affected by the presence of a paving interlayer, at least for the materials evaluated in this study.
- The MDU and OMC of the 50-50 GRAP blend were found to be lower than those for the 50-50 RAP blend, which were in turn lower than those for the 25-75 GRAP, 25-75 RAP, and BC blend. The decreased MDU and OMC values for the RAP and GRAP blends could be attributed respectively to the lower unit weight and hydrophobic nature of asphalt available on the surface of RAP and GRAP materials.
- The asphalt coated on the RAP particles were found to reduce the water absorption capacity in the RAP and GRAP blends, while interlayer fragments may have absorbed moisture, thus increasing the water absorption capacity of the 50-50 GRAP and 25-75 GRAP blends compared to that of 50-50 RAP and 25-75 RAP blends, respectively.
- The presence of asphalt was found to increase the abrasion resistance of the RAP and GRAP blends, while further increased abrasion resistance was observed for the GRAP blend, possibly because of the presence of interlayer fragments, which might have resulted in dissipation of the impact energy.
- The saturated hydraulic conductivity of the specimens containing GRAP/RAP materials is found to be higher than BC blends. Among the GRAP and RAP materials, specimens prepared with GRAP material have resulted in higher hydraulic conductivity. The higher permeability determined for the GRAP blends as compared to that for the RAP blends can be attributed to the presence of interlayer fragments that absorb moisture.
- The resilient moduli of the BC blend were higher than those in the GRAP and RAP blends at low bulk stress, which gradually increased with increasing bulk stress. In contrast, the resilient moduli of the GRAP and RAP blends were lower at low bulk stress and increased significantly with increasing bulk stress.
- The incorporation of RAP and GRAP materials into the asphalt mixture was found to improve the indirect tensile strength and resistance against moisture damage compared to the conventional asphalt mixture tested in this study. The improved performance observed for asphalt mixtures with RAP and GRAP material could be attributed to the presence of aged asphalt that increases the stiffness of the mix.

Overall, it may be concluded that the millability and recyclability of asphalt layers with and without a paving interlayer is similar. Additionally, the results of this investigation suggest that up to 30 % GRAP and 50 % GRAP can be incorporated into asphalt mixtures (surface course) and granular base courses, respectively, thus leading to sustainable roadway construction practices. The future scope of this research study may be focused on the evaluation of the millability of asphalt layers with different paving interlayers to confirm that the asphalt layers with paving interlayers are indeed millable with the existing milling equipment and techniques. An additional scope includes working toward the development of an ASTM specification to evaluate the suitability of GRAP material in transportation geotechnical applications, including backfill material in retaining walls and embankment fills, roadway base and surface courses, slope protection, and landfill capping systems.

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