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Emulsion Mixtures of Fractionated Reclaimed Asphalt Pavement and Quarry By-Products: A Laboratory Evaluation

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Abstract: Emulsion aggregate mixtures (EAMs) are aggregate blends stabilized with an asphalt emulsion for pavement base layer applications. These are typically prepared using crushed aggregates and designed primarily using a tensile strength-based criteria. Advances in granular material testing technologies have led to the development of advanced resilient response characterization devices such as the University of Illinois FastCell (UI-FastCell). Simultaneously, fractionated reclaimed asphalt pavement (FRAP) and Quarry by-product (QB) materials are becoming increasingly common in pavement construction. This paper evaluates the inclusion of QB and FRAP in EAMs. First, the design of selected EAMs was performed using a combined Asphalt Academy TG2 and Anderson and Thompson mixture design approach. The selected mixtures were first assessed for Indirect Tensile Strength (ITS) and Tensile Strength Ratio (TSR) to track changes in both strength and moisture damage resistance with the inclusion of FRAP and QB. In addition, advanced anisotropic resilient characterization was performed using the UI-FastCell to assess the changes in resilient modulus and permanent deformation characteristics. Our results show significant enhancements in tensile strength, increased moisture damage resistance, and reduced permanent deformation with the inclusion of FRAP and QB materials in EAMs. The combined inclusion of 30% FRAP and 70% QB negatively affected the resilient response of the EAM; however, the inclusion of FRAP content to 50% with no QB materials improved its suitability for pavement base layer application.

Keywords: emulsion stabilization; resilient modulus; quarry by-products; fractionated reclaimed asphalt pavement

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1. Introduction

Emulsion aggregate mixtures (EAMs) or bituminous emulsion stabilized aggregate mixes are cold-mixed blends of emulsified asphalt binder, aggregate, and water, as shown in Figure 1. EAMs are generally suitable candidates for use as base or surface layers for low-volume rural roads due to their cost-effectiveness and reduced environmental footprint of asphalt emulsion compared to cutback asphalt [1,2]. Functionally, bituminous emulsion is used as a passive stabilizing agent along with small quantities of cement for unbound pavement material. Bituminous emulsions used for this purpose are typically ionically charged. The choice of an appropriate ionic charge depends largely on the surface charge of the aggregates. This is, in turn, governed by the aggregates' mineralogical composition. Opposing ionic charges help develop initial adhesive bonding and enhance adsorption between aggregate surface and asphalt emulsion [3]. Later, upon the breaking of the binder, the water in the emulsion dissipates, and the residual binder forms a continuous film over the aggregate surface [4]. While bituminous emulsion specifications can vary greatly based on the manufacturing process, emulsions used for base stabilization purposes are generally 'oil-in-water'-types with about 40–60% residual asphalt content [1]. As a result, a partially bound matrix of aggregates in the form of EAMs [5] is obtained and compacted to prepare the pavement's base layer.

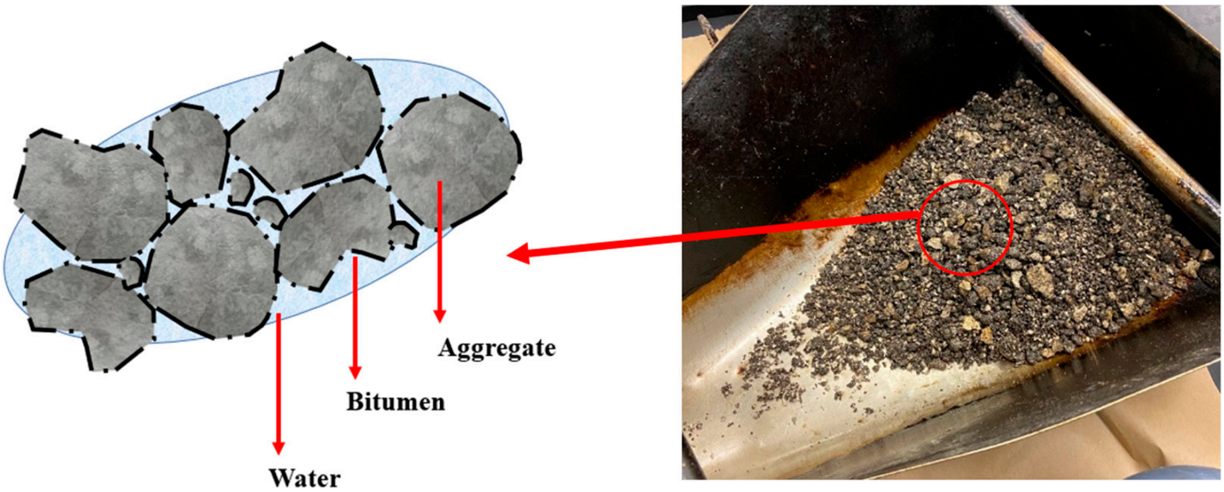

Figure 1. Composition of a typical EAM.

The curing of bituminous emulsions refers to the breaking process wherein moisture content reduces, and the precipitation of more stable bituminous residue occurs. The time sink needed to achieve fully cured EAMs can impede the construction process and delay opening to traffic. As a result, medium-to-rapid-setting bituminous emulsions are generally preferred. A paper by George published in 1987 highlighted that while cationic emulsions are suitable for sands, anionic emulsions offer the best mixing stability prospects. The study also recommended a 2 to 3% additional moisture content to achieve uniform mixing and improve the stability of EAMs [3].

A substantial part of the literature focuses on the mechanical testing of EAMs to understand their potential for use and the factors that affect their properties. The following paragraphs describe these studies in chronological order. In the 1960s, Finn et al. evaluated the field performance of various EAMs and concluded that EAMs provide sufficient resistance to environmental agents. They established an empirical relationship between the resilient modulus (M_R) and the gradation characteristics of the mix. This study also proposed one of the early thickness design methodologies for EAMs [6]. In the early 1970s, Darter et al. and Schmidt et al. determined the factors influencing the mechanical behavior of EAMs by evaluating the Marshall stability, tensile strength, and diametric resilient modulus $\left(M_R^D\right)$ of various laboratory-compacted specimens [7,8]. According to Darter et al., the Marshall stability ranges between 2 and 13 kN depending on the emulsion type and dosage. The authors also developed a standardized design procedure for optimizing field performance based on laboratory testing [7]. Schmidt et al. reported an increase in the diametral resilient modulus $\left(M_R^D\right)$ of EAMs with increasing curing duration [8].

In 1995, Anderson and Thompson reported on various properties of EAMs in relation to their laboratory performance. They conducted rapid shear tests, repeated loading triaxial tests (RLTT), and dynamic cone penetrometer (DCP) tests to evaluate shear strength and permanent deformation, M_R, and predicted in situ strength. Their results indicated a direct relationship between moisture loss and enhancements in mechanical response behavior [1]. Further, the modulus of EAMs was found to be higher than that of the untreated aggregates, and the stress hardening behavior of EAMs indicated an enhanced response at high stress states [1]. Also, in the early 1990s, Horak and Rust reported on the enhancement of moisture resistance in EAMs, along with better cracking resistance compared to cement-treated bases (CTB). The shear strength parameters (cohesion and internal friction angle) decreased in response to the lubricating effects of the emulsion, but the effective elastic modulus of EAMs steadily increased with the number of passes of a heavy vehicle simulator (HVS), alluding to the self-healing abilities due to the presence of the emulsion. CTB, on the other hand, experienced a reduction in elastic modulus with an increasing number of passes due to the development of cracking [9].

Later, in 2008, Wilde proposed a methodology to determine EAM thickness specifically for surfacing applications in low-volume roads. The methodology is largely based on inputs from DCP and M_R correlations with the back-calculated layer moduli from Falling Weight Deflectometer (FWD). The author suggested that EAM surfacing may lead to safety issues at high speeds due to a higher rutting potential and raveling potential due to snow-shoveling activities [10]. One limitation of unified design methods, such as the one proposed by Wilde, is that they necessitate a project-specific design approach. In addition, the use of empirical correlations between layer response parameters should be carefully adopted as they may be specific to certain materials and conditions [10].

Moaveni et al. reported the use of a combined approach consisting of Anderson and Thompson's Illinois EAM design approach and Asphalt Academy design methodology. The researchers performed California Bearing Ratio (CBR), indirect tensile strength (ITS), and advanced anisotropic triaxial testing on cationic emulsion-stabilized crushed limestone aggregates [11]. The results suggested that emulsion stabilization led to an appreciable increase in tensile strength and rutting resistance. In addition, the researchers reported an increased horizontal-to-vertical resilient moduli ratio for the emulsion-stabilized mixtures, which is an indirect parameter that indicates the material quality and shear strength properties [11]. A similar study by Sangiorgi et al. in 2017 assessed the use of emulsion-stabilized mixtures containing 100% reclaimed asphalt pavement (RAP) material [12]. The researchers highlighted the importance of the mixture design procedure and RAP quality towards ensuring a durable pavement base layer. The ITS and indirect tensile stiffness modulus (ITSM) of the mixture containing 100% RAP were found to be comparable to the control mixture and consistent over a period of one year [12].

More recently, Ullah and Tanyu proposed a methodology to develop guidelines for the design of pavement base layers containing RAP materials [13]. The authors recommended weight-based blend proportioning for laboratory performance evaluation. This results in a gradation that better represents the in-situ grain size distribution. The authors argued that while permanent deformation testing produced the most reliable design guidelines, any performance-based mix design should be based on site-specific conditions [13]. Also, recently, researchers at the University of Illinois have reported the performance, durability, and sustainable properties of quarry by-products (QB), which are excessive fines (mostly sand-sized) that accumulate from aggregate production processes [14,15].

QB fines have found numerous applications in pavements as an aggregate subgrade, subbase, and base material [14,15]. Efforts are being made to determine and evaluate innovative applications of QB with large-scale utilization potential. One such study led to the development of a geotextile and QB (GT-QB) geocomposite system (GCS). Laboratory and bench-scale testing of the proposed GCS revealed that the interlayer QB can be compacted to outperform dense-graded crushed limestone material in terms of penetration resistance and hydraulic permittivity [16]. Another potential large-scale utilization of QB in pavement applications is in EAMs, which have not been widely studied in prior research.

Researchers [14,17] have evaluated the environmental benefits of using FRAP and QB in pavement base layers. Plati and Cliatt [17] performed repeated load triaxial testing (RLTT) to evaluate the rutting performance of base materials containing 100% and 50% RAP. The researchers reported an increased stress-independent behavior with the inclusion of higher quantities of RAP. This improved the resilient response behavior of aggregates containing RAP to sustain a larger number of wheel load repetitions. However, it should be noted that the study highlighted the need for a permanent deformation model for such materials. This becomes especially important as other studies have reported the higher rutting potentials of base layer materials containing RAP [18].

Recent research projects at the University of Illinois Urbana-Champaign [14] demonstrated the reduced environmental impact of QB materials used in pavement base layer applications. The researchers analyzed the global warming potential of QB and a standard dense-graded base layer material from the sourcing stage to the manufacturing stage and up to the construction phase. The result was then normalized to a standard equivalent single-axle load (ESAL). The normalized global warming potential of aggregate base layers constructed with cement-stabilized QB and FRAP was found to be significantly smaller than a dense-graded granular material [14].

While many studies have described the use of fractionated reclaimed asphalt pavement (FRAP) in base layer applications and the associated design methodology concerning EAMs, others have focused on the effects of including FRAP on hot mix asphalt (HMA) performance [19–21]. There is still a knowledge gap in the literature regarding the strength, durability, and resilient characteristics of EAMs that use FRAP and/or QB in combination. This study attempts to fill this gap by demonstrating the viability of using recycled aggregates and waste aggregates as emulsion-stabilized base layer materials through the extensive testing matrix described herein.

2. Objective and Scope

The primary objective of this paper was to evaluate EAMs containing FRAP and QB. EAM blends with varying compositions were prepared using a combined mixture design approach (Anderson and Thompson's Illinois EAM design method and Asphalt Academy's Level 2 mix design). The EAMs were then evaluated for Indirect Tensile Strength (ITS), anisotropic resilient moduli (M_R^V, and M_R^H) [22], and permanent deformation characteristics. For this, first, a blend of emulsion-stabilized aggregates was prepared using a virgin coarse aggregate material to serve as a control. Then, two blends were prepared by mixing the control aggregate with 25% and 50% FRAP. Finally, a third mixture was prepared by blending FRAP and QB in a 30–70 weight ratio.

3. Materials

EAMs largely consist of aggregates and emulsions. In the past, researchers have used both RAP and QB in these mixtures instead of virgin aggregates [12,23]. Typically, RAP refers to an aggregate partially covered with asphalt binder and produced as a result of recycling hot mix asphalt (HMA) layers [19]. The coverage of the asphalt binder is higher in finer aggregate fractions (passing 4.75 mm sieve size); therefore, quarries generate coarse-sized waste known as Fractionated RAP (FRAP). On the other hand, QB collectively refers to screenings (passing 6 mm sieve size) generated during aggregate production to meet grading requirements [15]. In this study, the effects of QB and FRAP on the strength and performance characteristics of EAMs are evaluated. Furthermore, emulsion selection is not very well-defined for EAMs, with many studies using different types of emulsions with various charges depending on aggregate source and typically classifying them based on penetration grade [24–26]. The rheological characterization of emulsion binders was performed, and the procedure for this is reported in Section 3.2.

3.1. Aggregate Composition

Four mix blends with varying constituent compositions were selected and prepared. The selected blends are described in Table 1. The control mixture (0R-0QB) was prepared using crushed aggregates graded to type CA 6 in accordance with The Illinois Department of Transportation (IDOT) classification of dense-graded aggregate base materials [27]. Crushed limestone, FRAP, and QB materials were sourced from local quarries and asphalt plants in Illinois. Mixtures 25R-0QB and 50R-0QB were selected to evaluate the effects of replacing crushed limestone with 25% and 50% FRAP, respectively, on the strength and performance characteristics of the EAMs. A fourth mixture was prepared using FRAP and QB to assess the viability of completely replacing crushed limestone with recycled and by-product aggregates, both of which are sustainable.

Table 1. Composition of EAM blends studied.

Mixture ID	Constituents		
	Crushed Limestone (%)	FRAP (%)	QB (%)
0R-0QB	100	0	0
25R-0QB	75	25	0
50R-0QB	50	50	0
30R-70QB	0	30	70

The ratio of constituents in the 30R-70QB mixture was based on a previous study by LaHucik et al. [28]. The researchers recommended a 30% FRAP and 70% QB blend based on minimum void content or maximum packing density as per ASTM C29. The study also reported the optimal performance of cement-stabilized FRAP-QB material for base layer applications. In the present study, a sieve analysis was performed on all selected mixture types as per ASTM C136, and the results are shown in Figure 2. It should be noted that 0R-0QB and 30R-70QB contain 8% fines passing the No. 200 sieve. On the other hand, both 25R-0QB and 50R-0QB contained 5.1% and 3.1% fines passing the No. 200 sieve. 0R-0QB and 30R-70QB blend gradations were within the ideal gradation limits specified by Asphalt Academy Technical Guideline 2 [5]. However, the 25R-0QB and 50R-0QB gradations were slightly less coarse but within the less suitable gradation band [5].

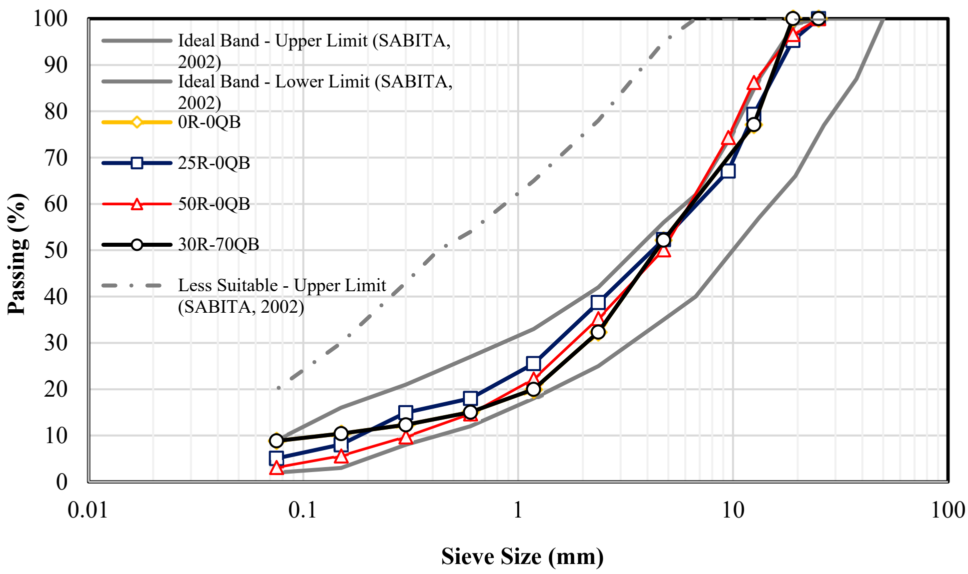

Figure 2. Gradation curves for selected EAM blends [5].

3.2. Anionic Emulsion

The emulsion used in this study was procured from a local source in Illinois and is a high-float anionic (HFE-90) type, containing demulsified binder with a penetration grade of 90. Further laboratory tests were performed on the residual binder recovered from the emulsion as per ASTM D7497. The asphalt emulsion was poured onto a silicon mat and then placed into a forced-draft oven at 25 °C for 24 h. After this, the mat was transferred to a forced-draft oven at 60 °C for an additional period of 24 h. A rheology test revealed that the true performance grade of the emulsion binder to be 58 °C (Figure 3). According to the specifications provided by the manufacturer, the water content of the emulsion is 30% by weight of the emulsion. Therefore, the residual binder content was assumed to be 70%. The choice of anionic emulsion was based on its compatibility with crushed limestone and dolomitic aggregates commonly encountered in the Illinois region, which carry a positive surface charge.

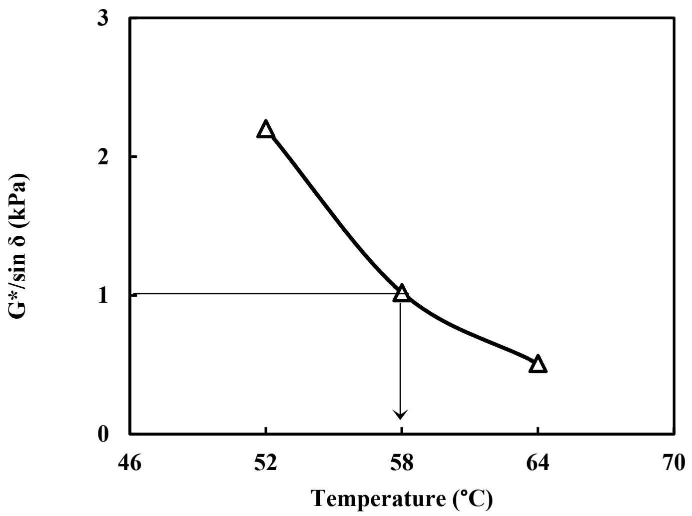

Figure 3. Performance grade of asphalt binder extracted from HFE-300 anionic emulsion.

3.3. Residual Asphalt Content

The optimum emulsion content for each mixture type was calculated using the IDOT EAM mix design procedure specified by Anderson and Thompson [1]. As shown in Table 2, the mixture residual asphalt content was calculated by using the gradation-based criterion given by Equation (1). Additionally, 2% water was added while preparing the EAM blends, in accordance with recommendations found in the existing literature [1,3,11] to enhance the workability and uniformity of constituent blending.

$$\mathrm{Res_{AC}}\ (\%) = 0.00138\ (\mathrm{P_{+4}})\ (\mathrm{P_{-4}}) + 6.358 \log\ (\mathrm{P_{200}}) - 4.655 \quad (1)$$

where Res_{AC} is the residual asphalt content of the mix (measured as a percent weight of the dry aggregate), P_{+4} is the percentage of aggregates retained on No.4 sieve (larger than 4.76 mm), P_{-4} is the percentage of aggregate passing No.4 sieve but retained on No.200 sieve (0.075 mm), and P_{200} is the percentage of aggregate passing the No.200 sieve.

Table 2. Computed emulsion content.

Mixture ID	Emulsion Content (%)
0R-0QB (Control)	5.5
25R-0QB	4.5
50R-0QB	3.0
30R-70QB	5.5

4. Methods

4.1. Indirect Tensile Strength and Tensile Strength Ratio

A combined approach consisting of TG2 and AASHTO T 283 was undertaken to determine if the materials could be subjected to stripping and to measure the effectiveness of the additives. The test was performed on duplicate specimens for each blend composition. The samples were mixed using a drum mixer and, as shown in Figure 4a–c, compacted using the Superpave gyratory compactor (SGC) by applying 75 gyrations. The mixture weight was calibrated via the trial-and-error compaction of specimens to achieve a specimen height of 95 mm with the target compaction effort of 75 gyrations in SGC. Two curing protocols were adopted as per the Asphalt Academy's TG 2. Initially, the specimens were left to air-dry for 24 h, after which they underwent forced oven draft curing at 40 °C in sealed bags for 48 h, as illustrated in Figure 4d–f. These specimens were selected as a baseline, i.e., tested without moisture conditioning at 25 °C, and the corresponding tensile strength was denoted as ITS_{Dry}. An equal number of duplicate specimens were conditioned by saturating them in a water bath maintained at 25 °C for 24 h prior to testing, as shown in Figure 4d–g. The specimens were placed in the testing rig (Figure 4h) within 10 min of removal from the water bath to ensure minimal moisture loss and tested at 25 °C. The corresponding tensile strength of the latter specimens was recorded as ITS_{wet}. The ratio of ITS_{wet} to ITS_{Dry} is referred to as the tensile strength ratio (TSR).

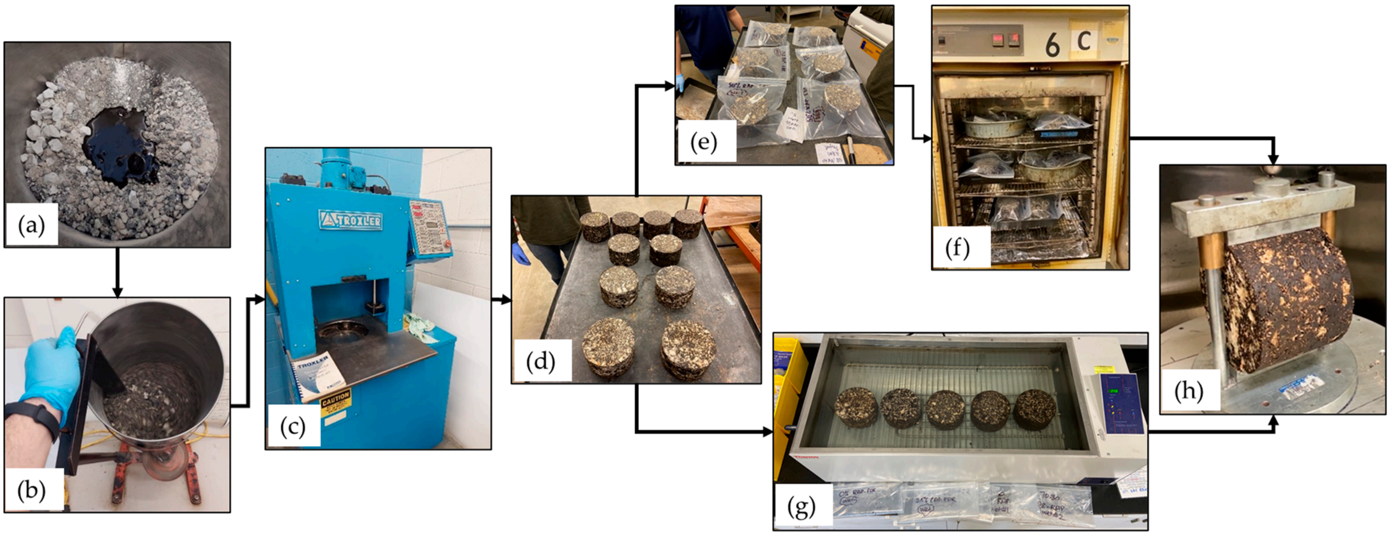

Figure 4. ITS specimen preparation and testing: (**a**) emulsion in aggregate blend, (**b**) drum mixing, (**c**) SGC, (**d**) air drying for 24 h, (**e**) sealed specimens, (**f**) oven draft curing at 40 °C for 48 h, (**g**) wet curing in water bath at 25 ° C for 24 h, and (**h**) specimen in ITS testing rig.

The specimen thickness was determined immediately before testing to account for the curing effects on specimen geometry. The specimens were placed upright between the bearing plates of the testing machine. As shown in Figure 4h, a rig consisting of steel loading strips was used for distributing the vertical load between the specimen and the bearing plates. A deformation was applied to the specimen by forcing the bearing plates together at a constant rate of 50 mm per minute. The maximum load was recorded, and the loading continued until the specimen cracked and the load fell below 10% of the peak load. The machine was then stopped. Subsequently, the specimen was broken apart at the crack for observation. The indirect tensile strength was then computed for the tested specimens as described in Equation (2).

$$\mathrm{ITS}\ (\mathrm{kPa}) = \frac{2000 \times \mathrm{P}}{\pi\, \mathrm{t}\, \mathrm{d}} \tag{2}$$

where P is the peak load measured in *N*, t is the specimen's thickness in mm, and *d* is the diameter of the specimen in mm.

4.2. Resilient Modulus and Permanent Deformation

The UI-FastCell, shown in Figure 5, is a servocontrol repeated loading system consisting of a loading frame and two pneumatic actuators pulsing independently in the axial and radial directions. The device is connected to a control and data acquisition system (CDAS) for user interface and data collection. Lateral confinement is imparted on the specimen by pumping mineral oil into the sides of the triaxial chamber lined with a flexible membrane using the radial pneumatic actuator. The flexible membrane is instrumented with diametric oil-filled linear variable distance transducers (LVDTs) to measure horizontal displacements. The lateral confinement can be programmed to produce a horizontal-to-vertical deviatoric stress ratio greater than unity. Thus, UI-FastCell can produce AASHTO T 307 deviatoric stresses laterally as well as vertically. The vertical deviatoric stress was measured using a vertically mounted load cell on an axial pneumatic actuator, while lateral confinement during vertical pulsing was measured using an instrumented radial pneumatic piston.

As the horizontal and vertical pulsing can be performed independently, the anisotropic resilient behavior of geomaterials can be determined. More details on the UI-FastCell can be found elsewhere [29]. Based on the definitions of vertical resilient modulus (M_R^V) and horizontal resilient modulus (M_R^H), the results were computed using Equations (3) and (4), which is as follows:

$$\mathrm{M_R^V} = \frac{\sigma_\mathrm{d}^\mathrm{V}}{\varepsilon_\mathrm{r}^\mathrm{V}} \tag{3}$$

$$\mathrm{M_R^H} = \frac{\sigma_\mathrm{d}^\mathrm{H}}{\varepsilon_\mathrm{r}^\mathrm{H}} \tag{4}$$

where σ_d^V and σ_d^H are the vertical and horizontal deviator stresses, respectively, and ε_r^V and ε_r^H are the axial and radial recoverable strains, respectively.

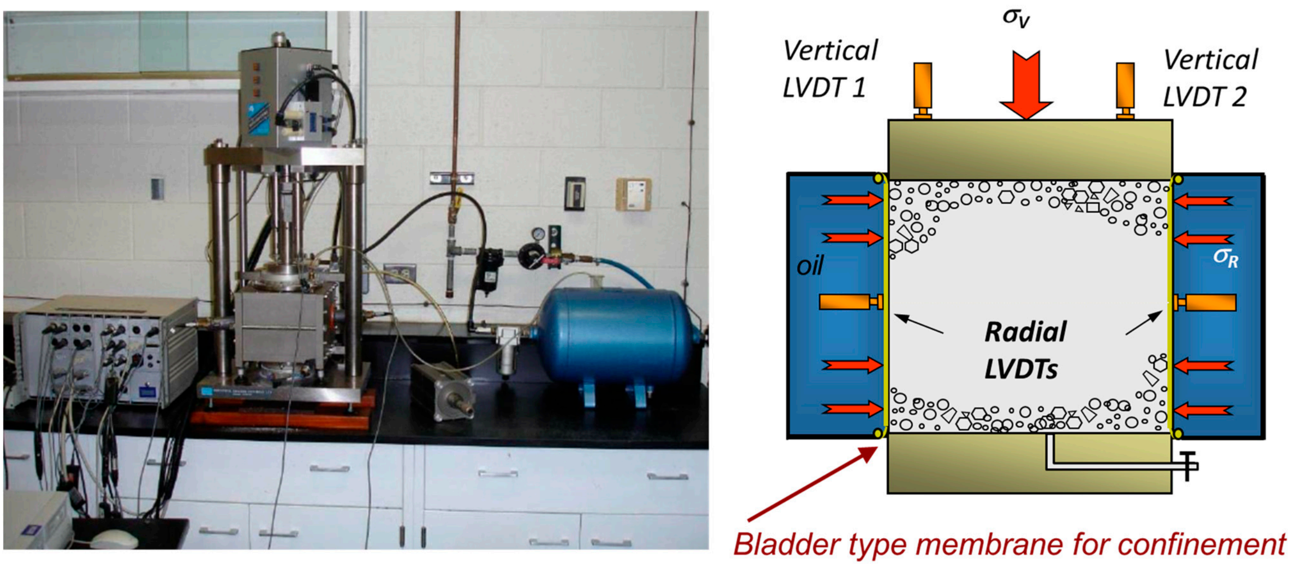

Figure 5. The University of Illinois FastCell (UI-FastCell) device.

Representative blends were prepared for each material studied, and specimens measuring 150 mm in diameter and 150 mm in height were compacted using 75 gyrations in the Superpave gyratory compactor. After compaction, the specimens were air-cured to a constant weight with equilibrium moisture conditions achieved. The specimens were then tested at 25 °C temperature. The specimens were first pulsed in the axial directions and then in the radial directions. The applied stress states for both vertical and horizontal pulsing, measured via the use of AASHTO T 307, are shown in Table 3.

The computed resilient modulus from the test results can be evaluated using the Hicks and Monismith ($k - \theta$) model [30] as described in Equation (5).

$$M_R = k_1 \theta^{k_2} \tag{5}$$

where k_1 and k_2 are material parameters and θ is the bulk stress.

Furthermore, the total accumulated permanent deformation can be evaluated to determine the deformation behavior under repeated loading. In this study, measuring the permanent deformation meant we could gain valuable information about the load bearing and strength characteristics of the tested material. To establish permanent deformation prediction models, permanent deformation was measured up to 1000 cycles. This approach was also expected to provide insight into the relative permanent deformation characteristics of the studied materials.

Table 3. Applied stress states according to AASHTO T 307.

Sequence No.	Confining Pressure, σ_3	Max. Deviatoric Stress, σ_d^V or σ_d^H	No. of Load Applications
	kPa	kPa	
0	103.4	103.4	1000
1	20.7	20.7	100
2	20.7	41.4	100
3	20.7	62.1	100
4	34.5	34.5	100
5	34.5	68.9	100
6	34.5	103.4	100
7	68.9	68.9	100
8	68.9	137.9	100
9	68.9	206.8	100
10	103.4	68.9	100
11	103.4	103.4	100
12	103.4	206.8	100
13	137.9	103.4	100
14	137.9	137.9	100
15	137.9	275.8	100

5. Results

5.1. Tensile Strength and Moisture Susceptibility

In accordance with the Asphalt Academy's Technical Guideline 2 [5], the Indirect Tensile Strength (ITS) and Tensile Strength Ratio (TSR) results were used to perform a comparative assessment of the different EAM blends. Laboratory ITS and TSR testing results are compiled in Figures 6 and 7. The testing was performed on duplicate specimens with an average absolute indirect tensile strength variance of 8.95 kPa. The ITS_{Dry} of the EAMs containing crushed limestone and varying percentages of FRAP was found to increase linearly with the increase in FRAP content. Given that the EAMs containing FRAP and QB exhibit an ITS_{Dry} in the range of 60–100 kPa, the mixtures are deemed suitable for traffic levels below 1 million ESAL, as per the Asphalt Academy's TG2. Additionally, there was a notable increase in the tensile strength of the EAMs with the inclusion of FRAP and QB materials. This can be attributed to the FRAP surface being partially coated with the residual RAP binder allowing for better cohesion between aggregate particles when stabilized with emulsion. Moreover, FRAP aggregates become relatively more angular during pavement milling and the subsequent aggregate production process. This leads to a better interlock and enhanced emulsion aggregate interface development, resulting in improved tensile strength. On the other hand, the ITS_{Wet} was observed to be highest for 50R-0QB and the lowest for 25R-0QB. However, it should be noted that the ITS_{Wet} values of 0R-0QB (control) and 25R-0QB were observed to be similar. Aside from 25R-0QB, EAMs containing FRAP and QB passed the minimum 50% TSR requirements set out in the Asphalt Academy's TG2. The TSR requirement checks whether an EAM layer will experience a reduction in strength when subjected to moisture intrusion. Furthermore, it is worth noting that 30R-70QB exhibited the highest values of ITS and TSR. The high strength of 30R-70QB can be attributed to the fact that it achieved the highest packing density in the aggregate matrix, as previously demonstrated by LaHucik et al. [28].

5.2. Anisotropic Moduli and Permanent Deformation Characterizations

The results from resilient modulus testing using UI-FastCell are compiled in Figures 8–12. Permanent deformation behavior is shown in Figure 13. The overall response of the EAMs follow the typical trends observed in previous studies [11,31]. Figures 8 and 10 show that both the vertical and horizontal resilient moduli values of 50R-0QB mixture are the highest. Additionally, there is a noticeable reduction in the vertical resilient modulus of the mixture containing 25% FRAP (25R-0QB). In particular, the trends regarding the vertical resilient modulus of mixtures containing only FRAP closely follow the observations made by the authors of studies similar to this one [13,32]. Based on our observations and regarding the $k - \theta$ material parameter k_1, a significant increase in vertical resilient modulus was noted for 50R-0QB over the control 0R-0QB mixture. However, as observed with the ITS_{Wet} values, 25R-0QB showed a reduction in vertical resilient modulus over the control 0R-0QB. Contrary to the trend observed in ITS results, 30R-70QB showed a decrease in both vertical and horizontal resilient moduli over the control 0R-0QB.

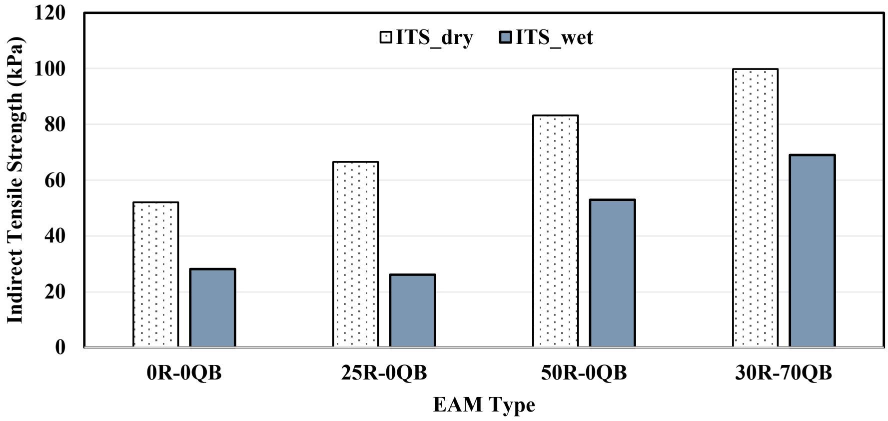

Figure 6. Effect of blend constituent composition on the Indirect Tensile Strength (ITS) of the EAMs.

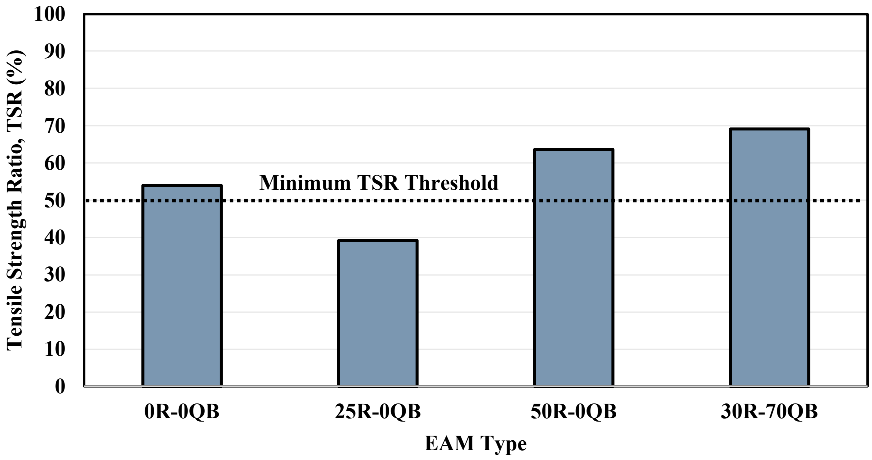

Figure 7. Effect of blend composition on the Tensile Strength Ratio (TSR) of the EAMs.

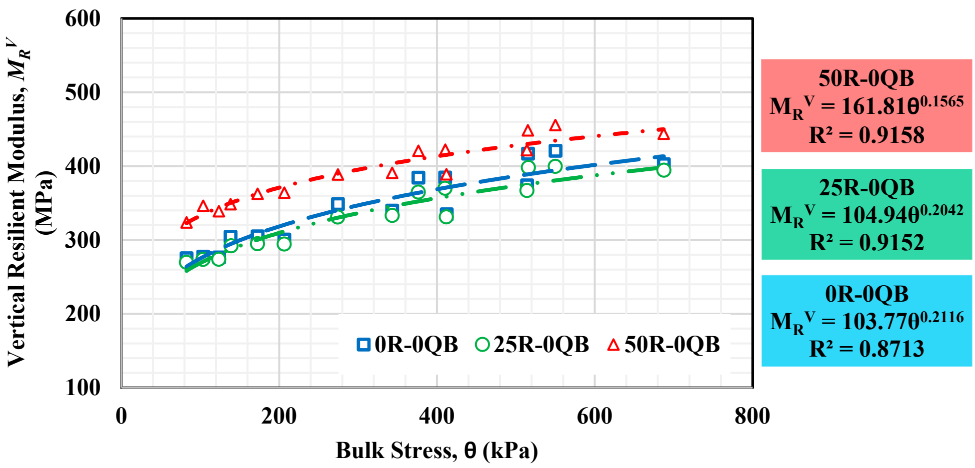

Figure 8. Effect of variation in FRAP on vertical resilient modulus (M_R^V).

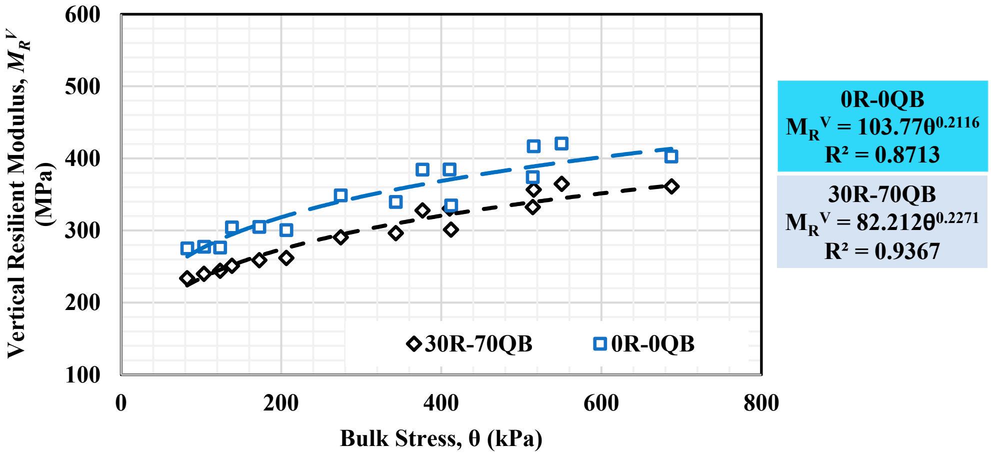

Figure 9. Vertical resilient modulus (M_R^V) for 30R-70QB.

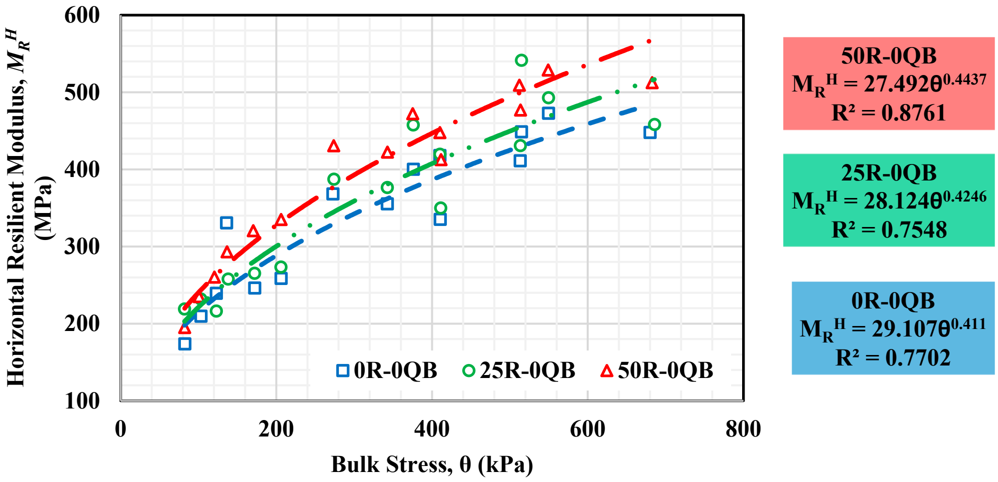

Figure 10. Effect of variation in FRAP on horizontal resilient modulus (M_R^H).

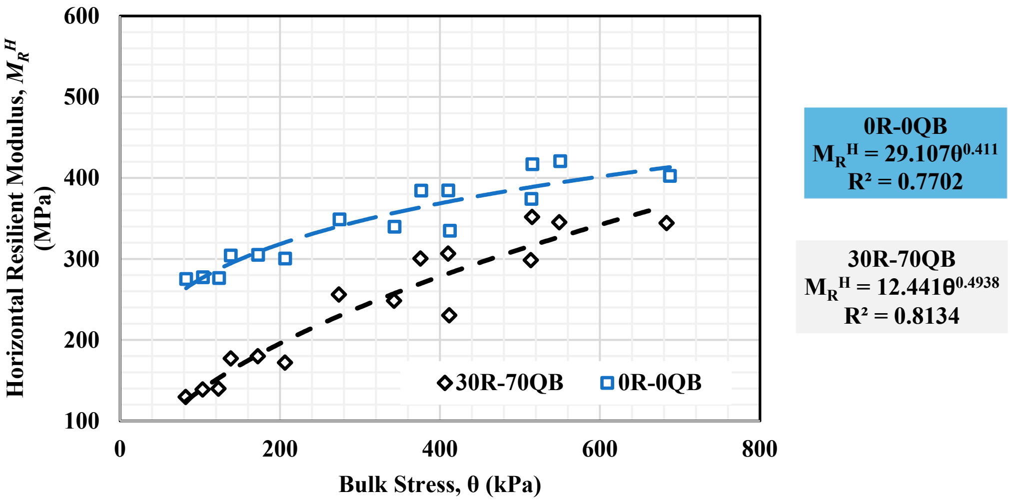

Figure 11. Horizontal resilient modulus (M_R^H) for 30R-70QB.

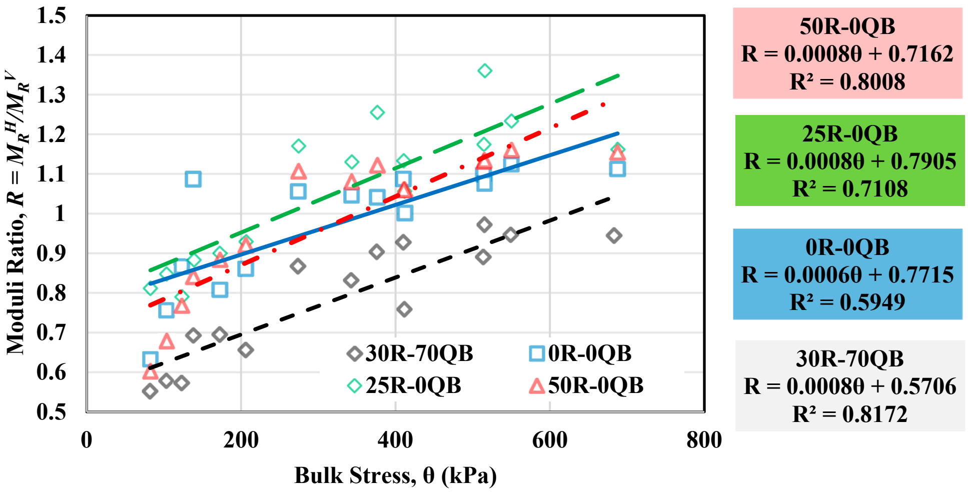

Figure 12. Effect of EAM blend composition on ${M_R}^H/{M_R}^V$.

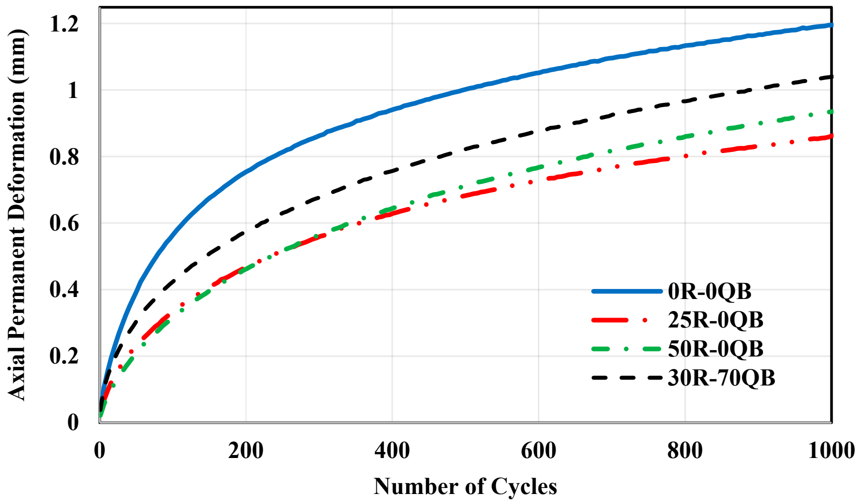

Figure 13. Effect of EAM blend composition on permanent deformation.

The horizontal-to-vertical resilient moduli ratio is considered to be an indicator of suitability for pavement base course and shear strength properties of the material [11,22,29]. Based on Figure 12, the higher slope and offset of the horizontal-to-vertical resilient moduli ratio line for mixtures containing FRAP compared to the control indicates an improved response to moving wheel loads. There is a notable reduction in moduli ratio for 30R-70QB over the control. However, it should be noted that the EAMs prepared via the partial replacement of crushed limestone with FRAP (25R-0QB and 50R-0QB) showed a better response to repeated loading at high bulk stress states ($\theta > 400$ kPa) compared to the control EAM (0R-0QB). Additionally, an anisotropic moduli ratio greater than unity implies that the EAMs have a higher resistance to stress state reversal. Such a moduli ratio alludes to an equal or greater number of aggregate contact points in the horizontal direction compared to the vertical direction. This results in lower compressibility or higher stiffness in the horizontal direction during stress state reversals under a moving wheel load, which is desirable [29,33].

The permanent deformation (PD) behavior of the EAMs is presented in Figure 13. The PD tests were conducted at a confinement pressure of $\sigma_3 = 103.4$ kPa and a deviatoric stress of $\sigma_d = 103.4$ kPa. The lowest plastic deformation was observed in EAMs containing FRAP (25R-0QB and 50R-0QB) followed by the FRAP and QB blend (30R-70QB). We also observed that the inclusion of 25% FRAP resulted in the lowest level of permanent deformation accumulation, and this result aligns with the findings of a previous study conducted by

Ullah and Tanyu [13]. Additionally, the EAM blend containing 100% crushed limestone aggregate as a replacement (30R-70QB) accumulated less permanent deformation compared to the control EAM blend (0R-0QB). This could have positive implications for the future in-place full-depth recycling of aggregate base layers constructed using QB and FRAP. Past studies have described the influence of stress state (σ_3/σ_1) [34], RAP binder content and type [35], and moisture conditions on PD [13] trends of unbound aggregate mixtures containing RAP. Additionally, researchers [31,32,36] have described the sensitivity of the strength and performance characteristics of EAMs due to aforementioned factors. Therefore, further research should be undertaken to determine moisture susceptibility, the effects of stress state, and RAP binder type and content on the strength characteristics of EAMs containing FRAP and QB.

6. Conclusions

The present study demonstrated the feasibility of including recycled and waste aggregate by-products in emulsion aggregate mixtures (EAMs) for pavement base layer applications. A practical mixture design and characterization methodology was adopted, and the mixtures were evaluated using standard and advanced laboratory tests that considered indirect tensile strength (ITS), resilient modulus (M_R), and permanent deformation (PD). Four different EAMs were evaluated with varying percentages of fractionated reclaimed asphalt pavement (FRAP) (0%, 25%, and 50%) and quarry by-product (QB) fines of 0 or 70%. Based on the results of our study, the following observations and conclusions can be made:

- An increase in FRAP content resulted in an increase in the strength and moisture resistance of the bituminous EAMs. The EAM containing FRAP and QB (30R-70QB) exhibited the highest ITS_{Dry} and ITS_{Wet} values. These observations indicate a superior FRAP and QB aggregate interlock and compatibility with emulsion stabilization compared to crushed limestone.
- EAMs containing 50% or more FRAP content satisfied Asphalt Academy's Tensile Strength Ratio (TSR) requirements, indicating sufficient moisture resistance under moisture intrusion.
- An appreciable increase in vertical resilient modulus was observed with the inclusion of 50% FRAP content in EAMs (50R-0QB). In addition, the introduction of FRAP material (25R-0QB, and 50R-0QB) increased the stiffness of EAMs for base layer applications.
- The higher anisotropic moduli ratios of the blends revealed that the EAMs prepared using FRAP (25R-0QB, and 50R-0QB) were less susceptible to deformation under principal stress reversals under a moving wheel load.
- Moreover, a significant reduction in permanent deformation of about 22% was observed in EAMs containing FRAP (50R-0QB and 25R-0QB) compared to the control mixture.

The present study focused on assessing the effects of including waste aggregates and recycled materials on the strength and performance aspects of EAMs under laboratory conditions. Before field implementation, we recommended that future research focuses on conducting comprehensive laboratory freeze–thaw resistance evaluations of selected EAMs. Such a study could help ensure a successful laboratory-to-field transfer of knowledge. In addition, a wider range of aggregate types in RAP and emulsion sources should be investigated.

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