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Sustainable Pavement Foundations with Chemically Stabilized Quarry By-Products

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Abstract. Quarry by-products (QB) are an industrial by-product of aggregate quarry processes. They are typically less than ¼ on. (6 mm) in size and consist of coarse, medium, and fine sand particles, and a small clay/silt fraction. Quarry by-products are found abundantly all over the crushed rock extraction facilities in Illinois where they are produced during blasting, crushing, washing, and screening operations. Recent research conducted at the Illinois Center for Transportation (ICT) has evaluated the characteristics of QB materials collected from different quarries across the State of Illinois, and studied potential uses of QB in pavement applications. Because the Unconfined Compressive Strength (UCS) for QB materials was quite low, Portland cement and Class C fly ash chemical admixture stabilizers were used to improve the strength properties of QB materials which resulted in 10 to 30 times increases in laboratory determined UCS compared to virgin unstabilized QB samples. Such significant increases observed in the strength of stabilized QB materials have indicated suitability of QB for sustainable pavement applications. Full-scale test sections were constructed next with chemically stabilized QB base/subbase applications over a subgrade having a California Bearing Ratio (CBR) of 6% to represent medium volume flexible pavement applications. The test sections were evaluated for performance using Accelerated Pavement Testing (APT), which spanned over two years to include effects of harsh winter freeze. Field testing and forensic analysis techniques included Falling Weight Deflectometer (FWD) tests before and after trafficking, hot mix asphalt coring, Dynamic Cone Penetrometer (DCP) profiling of subsurface layers, and trenching to determine actual thicknesses and contribution of each pavement layer to the measured surface rutting. In general, results from APT and forensic analyses indicated satisfactory results and improved rutting performance.

Keywords. Quarry By-products, Pavements, Accelerated Pavement Testing, Field Performance, Sustainability, Chemical Stabilization, Nondestructive Testing, DCP

1. Introduction

Quarry by-products, usually less than 6 mm in size, are produced during quarry operations such as blasting, crushing, screening, and washing. QB are mostly coarse-, medium-, and fine-grained sand particles, with a small fraction of silts and clays. QB can

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exist in aggregate production sites in three distinct types: screenings, pond fines, and baghouse fines [1]. During the crushing stages, QBs are generally carried out in three stages, i.e. primary, secondary, and tertiary crushing [2].

The importance of utilizing aggregate quarry by-products in pavement applications stem from the vast quantities that are produced and remain excessive with many quarries each year. QB stockpiling and disposal is a serious issue facing the aggregate industry as they accumulate in stockpiles and interfere with quarry operations [3]. A report by the Federal Highway Administration estimated the quantity of quarry by-products generated in the United States each year to exceed 159 million metric tons, little of which is being put into use for pavement applications [1]. The same report also estimated that aggregate QB accumulation in the US alone exceeded 3.6 billion metric tons from the 3,000 operating quarries. In the state of Illinois, where this study was conducted, the annual production of crushed stone QB was estimated though a survey conducted among aggregate producers in the state and was found to be as high as 855,000 tons (950,000 US tons) [4]. Research conducted by Kumar and Hudson (1992) showed that stockpiled fines comprised an average of approximately 12% of the total annual aggregate production [5]. More recently, NCHRP Synthesis 435 (volume 4) reported that, depending on the type of rock quarried, QB could make up to 25% of the total aggregates produced [6].

Given these massive quantities, the investigation of successful applications of QB as a sustainable and inexpensive construction alternative for pavements has become imperative. However, only a few number of research studies have been conducted to date to evaluate the use of QB as a geotechnical pavement material in subbase or base applications, and especially the use of QB as an unbound material, which was found to be scarce in literature. NCHRP synthesis 435 (volume 4) being a main source of information on the QB use, summarizes the different QB applications in pavements by the different states in the US [6].

1.1. Laboratory characterization of stabilized QB materials

Based on laboratory testing results, some researchers have utilized chemical stabilization and accordingly recommended specific field applications for QB. According to Kalcheff and Machemehl (1980), the stabilization of QB with cement developed relatively high rigidity with a small amount of Portland cement compared with granular soil-cement stabilization [7]. The use of low-cement content has the advantage of decreasing the shrinkage cracking. Kumar and Hudson (1992) examined the unconfined compressive strength, tensile modulus of elasticity, and Poisson's ratio of cement-treated QB materials [5]. They concluded that stabilizing QB with cement could produce the adequate compressive strength, modulus of elasticity, and tensile strength required for subbase materials. They proposed a base course material additive, flowable fill, under slab granular fill, and cement-stabilized subbase/base layers as possible pavement applications of QB.

Stabilized QB mixes were also evaluated for applications such as flowable fills, soil modification and Self-Consolidating Concrete (SCC). According to the results presented in the study by Wood and Marek (1995), using 3% cement, 8% fly ash, and 89% QB resulted in a flowable fill with adequate performance [8]. Naik et al. (2005) examined the use of QB in SCC and reported that the addition of QB minimized the needed quantity of admixtures without reducing the strength of the SCC [9]. Koganti and Chappidi (2012) reported that using up to 40% QB by weight proved to be beneficial in improving the strength of black cotton expansive soil [10].

Recent laboratory studies investigated the use of QB (or quarry fines) for pavement applications. Abdullah et al. (2018) conducted workability tests, flexural strength tests, and compressive strength tests on concrete samples with 100% quarry dust used for sand replacement in concrete [11]. The study concluded that concrete samples with 100% QB as fine aggregates produced more sustainable concrete samples with better durability, compressive strength and furnishing properties. The same study reported that concrete samples with QB had higher water absorption and workability at lower water cement ratios. Schankoski et al. (2017) evaluated the rheological properties of fresh cement paste with QB (diabase or gneiss quarry rock powders). They concluded that cement pastes containing QB had lower yield stress and lower viscosity than samples with cement pastes only [12].

Puppala et al. (2008) reported that the addition of 2.3% cement increased the unconfined compressive strength of QB materials to 174 psi (1,200 kPa). They concluded that the strength and resilient modulus of the cement-treated QB were similar to those of sandy materials with very few fines [13]. Mwumvaneza et al. (2015) conducted Unconfined Compressive Strength (UCS) tests on 10% Class ‘C’ fly ash and 2% Portland cement-stabilized QB samples, and they examined that the chemically stabilized QB specimens exhibited up to 30 times strength improvement when compared with untreated QB materials [14].

Finally, in a laboratory study conducted by LaHucik et al. (2016; 2016a), various proportions of cement-treated mixes of QB and Fractionated Reclaimed Asphalt Pavement (FRAP) or virgin coarse aggregates were evaluated [15, 16]. Based on aggregate packing tests conducted with different proportions of QB and FRAP by weight, an optimal blending ratio of 70% QB with 30% FRAP was found to maximize density/minimize void content. LaHucik et al. (2016) also evaluated mix design performances through strength tests (compression/split tension) and modulus tests. Higher cement content increased both the strength and elastic modulus properties of all the tested mixes. Mixtures containing virgin aggregates with QB yielded statistically greater elastic moduli than mixtures with FRAP and QB. Fibers were used as additives in some of the mixtures. From statistical analysis, the fibers did not have a considerable influence on strength or elastic modulus but did provide residual shear capacity across cracks. The QB and FRAP or QB and virgin aggregate mixtures with 3% to 4% cement content exceeded the strength of typical cement-stabilized base materials reported in the literature [15, 16].

1.2. Pavement applications of stabilized QB materials

Only few researchers in the United States have investigated the use of QB as a chemically stabilized base/subbase layer in pavement applications. In a study in Lynn County, Iowa, the use of emulsion-stabilized limestone screening was investigated as a base material [17]. Several test sections with base thicknesses of 4 to 6 in. (100 to 150 mm) and asphalt-cement contents of 2.5%, 3.5%, and 4.5% were inspected. The 4-in. (100-mm) thick base did not produce a satisfactory low cost maintenance roadway, based on periodic crack survey data and structural adequacy assessment using a Road Rater equipment. Thus, the researchers recommended a 6-in. (150-mm) thick emulsion-stabilized QB base with more than 3.5% asphalt cement, topped with 2 in. (50 mm) HMA surface, which could provide a low maintenance roadway [17].

In a study in Arlington, Texas, the use of limestone QB was evaluated as a base material for sections of State Highway 360 [18]. A 36-in. (914-mm) thick layer of quarry fines stabilized with 2.3% cement was used as the base overlain by a 4-in. (102-mm) thick HMA and 8-in. (203-mm) thick Continuously Reinforced Concrete Pavement (CRCP) surface. Field monitoring using horizontal inclinometers showed that the sections experienced low permanent deformation during service. Additionally, the International Roughness Index (IRI) values were measured to be within 32-158 in./mile (0.5-2.5 m/km) after 30 months of service, which is lower than the threshold value of 200 in./mile (3.15 m/km), thus indicating good performance [18].

2. Studied aggregate quarry by-product applications

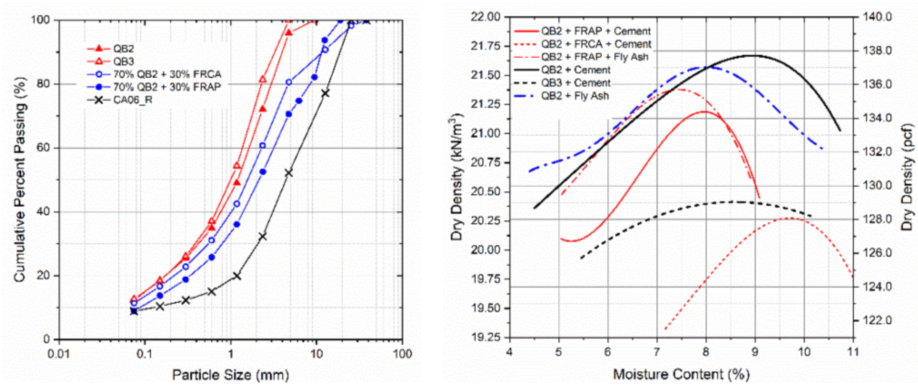
In total, seven pavement test sections investigating bound applications of aggregate quarry by-products were selected for performance evaluation. These applications were selected based on successful previous studies that provided initial evaluations of these applications through laboratory testing [4, 14, 15-16]. In light of the outcomes of these previous research projects, the following set of applications were selected for studying QB usage as chemically-stabilized materials:

- For base course applications, blending QB with coarse aggregate fractions of recycled materials [Fractionated Reclaimed Asphalt Pavements (FRAP) or Fractionated Recycled Concrete Aggregates (FRCA)] and stabilizing the blends with 3% cement or 10% class C fly ash by weight; and
- Using QB as a cement-treated base material; and
- Using QB as a cement or fly ash-treated subbase (i.e. in inverted pavements).

2.1. Materials selection

In total, five aggregate materials were collected to construct the test sections: one virgin aggregate material, two QB materials, and two recycled coarse aggregates. The two QB materials, i.e. QB2 and QB3, were obtained from quarries in Illinois near Thornton and Falling Springs, respectively. The FRAP originated from milling operations for an existing flexible pavement in Illinois, while the FRCA was obtained from a concrete recycling yard in Urbana, Illinois. The CA06_R material was a well-graded dolomite aggregate obtained from a quarry in Fairmont, Illinois and has a grain size distribution conforming to the Illinois Department of Transportation (IDOT) CA06 gradations for base course materials.

The grain size distributions of all aggregate materials and material blends used to construct the test sections are shown in Figure 1(a). Note that for test sections utilizing QB blended with coarse recycled aggregates, a central plant mix of 70% QB2 with 30% FRAP or FRCA by weight was brought to the construction site. The grain size distributions for these blends are shown in Figure 1(a). The Maximum Dry Densities (MDD) and Optimum Moisture Contents (OMC) for all material combinations used to construct the test sections were determined from laboratory testing using the standard compaction effort as per ASTM D698. Figure 1(b) shows the moisture-density relationships for all material combinations used to construct full-scale pavement test sections.



(a) (b)

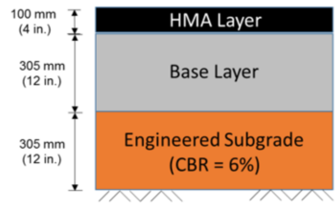
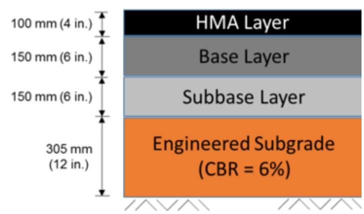
Figure 1. (a) Grain size distribution curves, and (b) moisture-density relationships for the various aggregate material combinations used in construct pavement test sections.

2.2. Details of constructed test sections

The construction of the pavement test sections took place at the accelerated pavement testing facility of Illinois Center for Transportation (ICT). In total, seven test sections were constructed to evaluate chemically stabilized applications of QB in base and subbase layers. All sections were constructed on top of a subgrade soil having an engineered CBR of 6%. The details of these sections are presented in Table 1. All base layers had a nominal design thickness of 12 in. (305 mm). For inverted pavement test sections (i.e. C3S2 and C3S3), the thicknesses of the base and subbase layers were 6 in. (152 mm) each. All test sections were overlain with 4 in. (102 mm) of Hot Mix Asphalt (HMA).

Note that the test sections presented in this paper are part of a larger study aimed to evaluate bound and unbound applications for quarry by-products by constructing 12 flexible pavement test sections and four unsurfaced construction platform sections. Four 'test Cells' (Cell 1S, 1N, 2 and 3), each having four test sections, were constructed for field evaluation. The sections presented in this paper are part of 'Cell 2' and 'Cell 3', which evaluated the performance of seven bound applications of QB and a conventional flexible pavement section. The details for the unbound QB applications evaluated were presented elsewhere [19, 20]. The beginning and end parts of each cell were designed to have 22.5 ft. (6.8 m) long crawler zones where the crawlers of the Accelerated Testing and Loading ASsembly (ATLAS) were placed. The innermost 7.5 ft. (2.3 m) in each crawler area was the speed stabilization zone for the acceleration/deceleration of the wheel to ensure that all test sections were tested at a constant speed of 5 mph (8 km/h). A 10 ft. (3 m) long transition zone was also added at the middle of each cell to minimize any possible influence of changing materials on the APT results.

Table 1. Base and subbase materials constructed in the test sections to study stabilized QB applications.

Section ID	Description	Pavement cross sections
C2S1	A blend of 70% QB2 and 30% Fractionated Reclaimed Asphalt Pavements (FRAP) by weight, mixed with 3% Type I cement by weight.	 All test sections (except C3S2and C3S3)
C2S2	A blend of 70% QB2 and 30% Fractionated Recycled Concrete Aggregates (FRCA) by weight, mixed with 3% Type I cement by weight.	
C2S3	A blend of 70% QB2 and 30% FRAP by weight, mixed with 10% Class 'C' fly ash by weight.	
C2S4	A Blend of QB2 and 3% Type I cement by weight.	
C3S1	A Blend of QB3 and 3% Type I cement by weight.	 C3S2 and C3S3
C3S2	Subbase layer: A Blend of QB2 and 3% Type I cement by weight. Base layer: CA06_R (A dense-graded unbound dolomite aggregate layer conforming to the CA06 aggregate gradation band of the Illinois Department of Transportation)	
C3S3	Subbase layer: A Blend of QB2 and 10% Class 'C' fly ash by weight. Base layer: CA06_R	

2.3. Construction of test sections

The top 12 in. (305 mm) portion of the in situ subgrade at the full-scale testing site was prepared and engineered to a CBR of 6% by an iterative procedure. The desired CBR was achieved through the adjustment of the soil's moisture content and compaction levels. A moisture content of 12% and a dry density of 19.1 kN/m3 (121.6 pcf) resulted in the targeted CBR of 6%. The details for the iterative procedure utilized for engineering the subgrade was presented elsewhere [19, 20]. Qamhia et al. (2019) presented the achieved subgrade CBR at the various measuring points [21].

QB2 blends with FRAP and FRCA for test sections C2S1, C2S2, and C2S3 were plant-mixed in a local asphalt plant and then delivered to the construction site. To ensure proper setting and curing of the test sections, a maximum of two hours was allowed between mixing with the stabilizing agent and compaction. For the purpose of this project, where relatively small road sections were constructed with each material, the construction procedure involved the following steps: (1) stockpiles of known volumes of the QB materials or QB blends with FRAP/FRCA were dry-mixed using the bucket of a backhoe to ensure the consistencies of targeted moisture contents and particle size distributions, (2) moisture samples were collected to measure the in situ moisture contents, and calculate the dry weights of the stockpiles accordingly, (3) the stabilizing agent (3% cement or 10% fly ash, by weight) was added and mixed several times, for uniformity, using a backhoe bucket, (4) additional moisture was added, as needed, to adjust the moisture content to the optimum moisture content, and the blends were further mixed to uniformly distribute the moisture and the stabilizing agent, (5) the mixes were placed and tilled several times for mixing uniformity using a soil tiller, then compacted using a smooth-drum vibratory roller. The test sections were typically constructed and compacted in 152-mm (6-in.) lifts. Construction steps involved in constructing the chemically stabilized layers are presented in Figure 2. Note that the use of a pugmill mixer or a single shaft travelling mixer is recommended to achieve better blending for a larger scale construction.

Figure 2. Construction steps of chemically stabilized test sections studying QB applications.

Finally, the HMA structural layer was paved in two equal 50-mm (2-in.) thick layers. The same mix design was used for both layers. The mix design had an asphalt binder with a Performance Grade of PG 64-22 and a 9.5-mm (0.375-in.) nominal aggregate size.

3. Performance monitoring and evaluation

3.1. Accelerated pavement testing conditions

The constructed test sections were monitored for performance through accelerated pavement testing (APT). Heavy vehicle loads were applied using the Accelerated

Transportation Loading ASsembly (ATLAS). A super-single tire (455/55R22.5) was used to traffic the test sections. The first number (455) refers to the tire width from wall to wall in mm, the second number (55) corresponds to the side wall height expressed as a percentage of tire width, and the third number (22.5) is the rim diameter in inches.

A constant unidirectional wheel load of 10 kip (44.5 kN), a tire pressure of 110 psi (760 kPa), and a constant speed of 5 mph (8 km/h) were assigned to load the constructed sections, and to evaluate their rutting potential. Channelized wheel loading was applied with no wander considered. Once the test sections were done receiving 100,000 wheel passes at the above listed standard load/pressure, the wheel load was increased to 14 kips (62.3 kN) and the tire pressure was increased to 125 psi (862 kPa), and additional 35,000 passes were applied at these increased load/pressure levels.

3.2. Surface rutting accumulation and subgrade pressures

Performance monitoring was accomplished by periodic surface profile measurements after a certain number of passes. The transverse surface rut profile measurements for the HMA-surfaced test sections were measured using an automated laser profiler. Transverse rut measurements at the two measuring points in each test section were taken up to a distance of 16 in. (405 mm) on each side of the centerline of the wheel path. At each measuring point, a total of six 31.9 in. (810 mm) lateral scans were performed at 0.2 in. (5 mm) spacing, and the rut depth was reported as the average rutting of the centermost 11.8 in (300 mm) of the wheel path from the six measurements.

Comparisons of maximum wheel path rutting progressions of the test sections intended to study chemically stabilized layer applications of QB, are made in Figure 3. Overall, for the stabilized sections, the two sections chemically stabilized with 10% class ‘C’ fly ash (C2S3 and C3S3) consistently accumulated higher rut amounts and showed higher rates of rutting progression at the increased load level when compared to the other test sections chemically stabilized with 3% Portland cement. For the two sections, intended to study the effect of QB source, i.e. C2S4 with cement-stabilized QB2 base and C3S1 with cement-stabilized QB3 base, the trends of rutting progression were similar, indicating little effect of the source of QB on performance. Further, satisfactory rut performance was achieved for C3S2 inverted test section with a cement-stabilized QB subbase. The best performances with the lowest rut amounts were obtained for C2S1 and C2S2 having stabilized base courses of the QB blends with FRAP/FRCA, and the highest rutting accumulation was observed for C3S3 with a fly ash-stabilized QB subbase.

Three of the test sections with stabilized QB applications, namely C2S1, C2S4, and C3S2, had soil pressure cells installed on top of the subgrade to measure the vertical stress on top of the subgrade. A comparison of the measured wheel load deviator stresses on top of the subgrade for these test sections is presented in Figure 4. These test sections with stiff chemically stabilized QB base/subbase layers consistently recorded low pressures on top of the subgrade, indicating negligible subgrade rutting; which was also validated from the trenches which showed no signs of subgrade rutting. Note that a conventional test section with the same layer thicknesses and subgrade properties had significantly higher measured vertical pressures on top of subgrade of around 9 psi (61 kPa). Clearly, the stiffer stabilized base materials are changing the mechanism of stress distribution in the pavement structure, allocating a higher share of the load to the stiffer base/subbase layers, and thus reducing subgrade pressures and subgrade rutting potential.

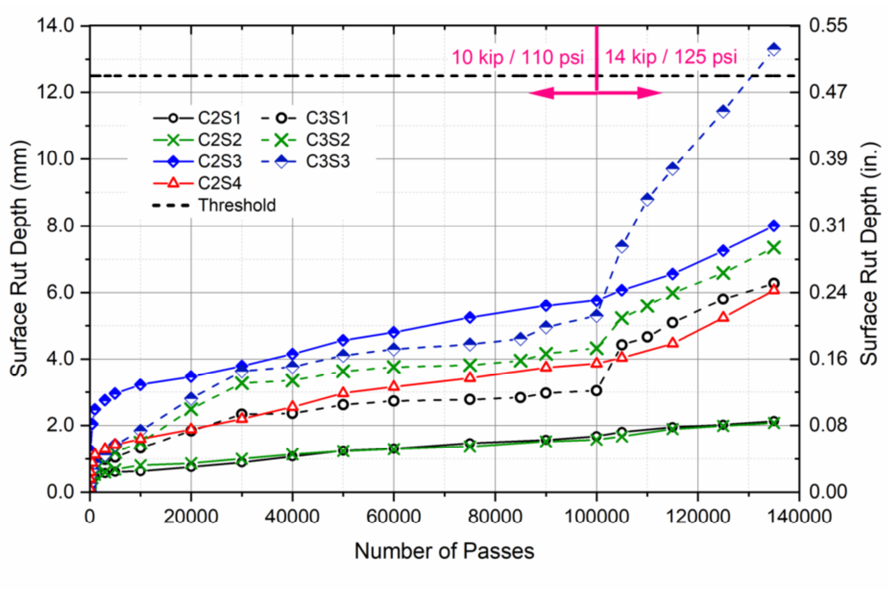


Figure 3. Wheel path maximum rut progression in test sections utilizing QB applications.

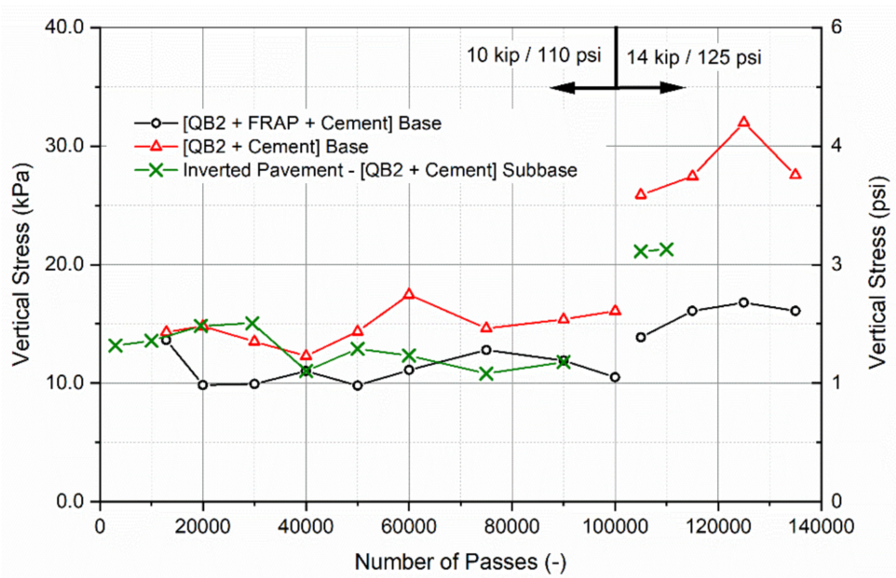


Figure 4. Vertical stress measured on top of subgrade using the installed pressure cell sensors.

3.3. Falling Weight Deflectometer Test Results and Interpretations

FWD tests were conducted by dropping three different load levels at each measuring point to induce variable stress states in pavement layers, and detect the surface deflections from seven geophones that are set 12 in. (305 mm) apart; including a center geophone directly under the load drop location. The complete data covering all deflection basins from the conducted tests are presented elsewhere [19, 20].

Figure 5 shows the FWD deflections from the load dropped geophones (D_o - D_3), spaced 12 in. (305 mm) apart. For each individual test section, the trends for the progression of rutting and FWD deflections are matching (i.e. typically greater maximum ruts were accumulated in the wheel path at the sections where higher FWD deflections were recorded). For sections with a cement-stabilized QB base material (i.e. C2S1, C2S2, C2S4, and C3S1), the measured FWD deflections were lower than those in section C2S3 with a fly ash-stabilized QB/FRAP base and inverted pavement section C3S2 with a cement-stabilized subbase, largely due to a higher stiffness of the pavement structure due to the chemically stabilized QB base. For section C3S3 with a fly ash-stabilized subbase, significantly higher deflections were measured, indicating a weaker pavement structure. The engineered subgrade stiffness was also likely similar in sections C2S1 - C3S2 according to the similar shapes of the deflection basins. The higher sensor deflections measured for sensors D_2 and D_3 in C3S3 were an indication of a weaker engineered subgrade for this section.

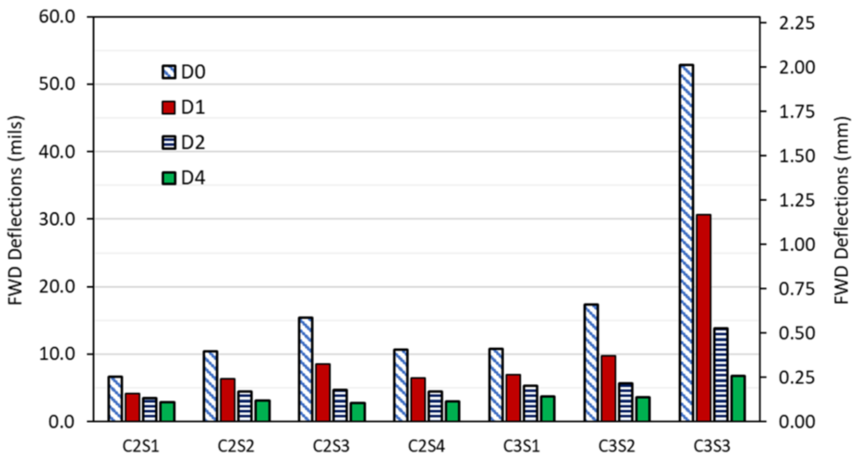


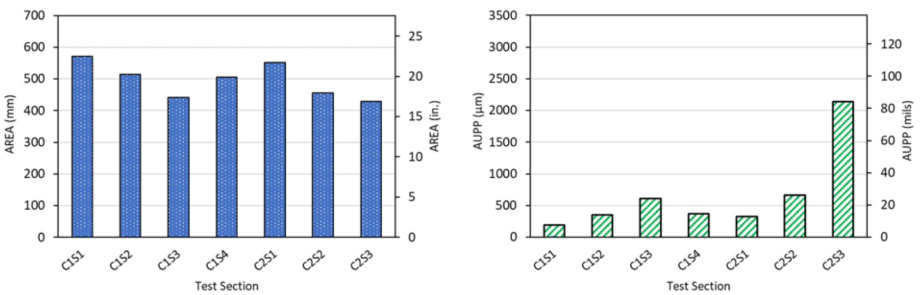
Figure 5. Recorded FWD deflections for sensors D_0 – D_3.

Based on the FWD sensor deflections, the AREA parameter and the Area Under Pavement Profile (AUPP) were calculated. AREA parameter, measured in units of inches (mm), calculates the area of deflection basin over a radial distance of 36 in. (914 mm) from the center of the load plate, normalized with respect to D_0 sensor deflection. AUPP, measured in units of mils (µm), calculates the area beneath the deflection basin over a radial distance of 36 in. (914 mm) from the center of the load plate. These parameters are calculated using the following equations:

$$AREA = \frac{6[D_0+2D_1+2D_2+D_3]}{D_0} \tag{1}$$

$$AUPP = \frac{5D_0-2D_1-2D_2-D_3}{2} \tag{2}$$

The AREA parameter combines multiple measured deflections into one value and thus minimizes the contribution of malfunctioning sensors, if any [22]. The AUPP deflection basin parameter is complementary in definition to the AREA profile, and a lower AUPP is typically indicative of a higher pavement stiffness and better integrity. Higher AREA values generally indicate better structural integrity. From the results shown in Figure 6, the constructed pavement test sections with bound bases/subbases, the calculated AREA values and the measured surface ruts from field evaluation all follow the same trends; sections with higher AREA values accumulated the least rut depths. Note that FWD deflections are resilient, and they relate to pavement responses directly, but do not directly relate to performance trends. In most cases, however, FWD deflections and rut accumulations followed similar trends. Similarly, the AUPP values follow the trends of surface rut accumulations.



(a) (b)

Figure 6. FWD deflection basin parameters: (a) AREA parameter, and (b) AUPP.

3.4. Subsurface layer DCP profiling

Following HMA coring, DCP testing was conducted into the underlying base and subbase layers of all test sections. The DCP tests were conducted directly in the center of the wheel path through the holes of the cored HMA. All DCP tests were conducted in dry weather conditions after several days/few weeks of no rain. The results for all test sections are summarized in Figure 7, which shows the number of DCP drops normalized for 1 in. (25 mm) of penetration. Higher numbers correlate with higher shear strength characteristics of the stiffer subsurface layers since DCP results produce shear strength profiles. For example, it took 852 DCP hammer drops for penetrating 12.25 in. (311 mm) into the C2S1 cement-stabilized QB/FRAP blend, i.e. 70 DCP drops per 1 in. (25 mm) of penetration.

The strength profiles of the subsurface pavement base/subbase layers were found to correlate well with performance trends, where sections accumulating the least rutting had the highest number of DCP drops per 1 in. (25 mm). In particular, C2S1 and C2S2 with blends of QB with FRAP/FRCA accumulated the least rutting, and had the strongest DCP profiles.

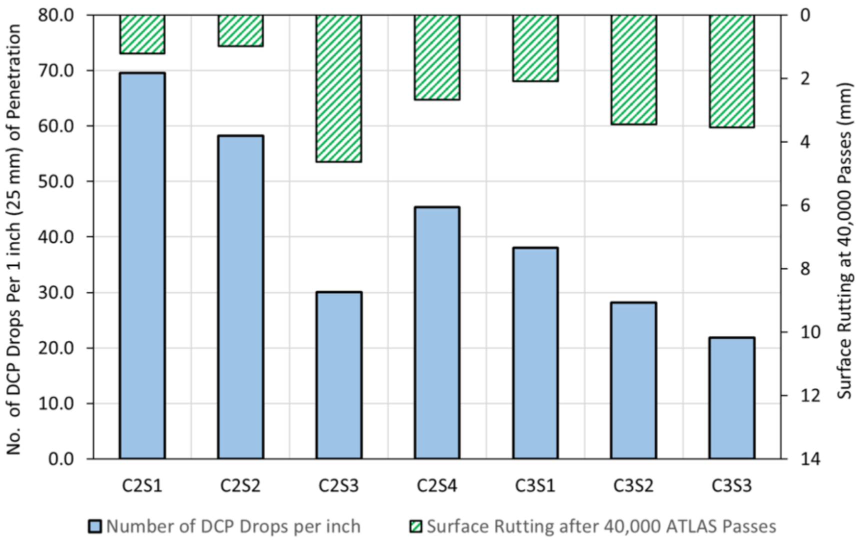


Figure 7. DCP penetration rates in base and subbase closely match with rutting progression trends.

3.5. Unconfined compressive strength tests for stabilized test sections

Following trenching of the test sections, some of the stabilized materials were recovered in intact pieces that were large enough to extract laboratory samples for Unconfined Compressive Strength (UCS) testing. Earlier on, attempts to extract and test cores of the stabilized base/subbase layers from the wheel path were not successful as the materials eroded with the presence of water from the coring process. In another attempt, a dry coring technique was employed to extract cylinders from the stabilized base and subbase layers for UCS testing. However, the lightly cemented layers eroded under the drilling action, producing fine fragments that clogged the coring bit; creating high friction and preventing the recovery of fully intact cores.

Test cubes, 3 in. (76 mm) in size, were saw-cut in the laboratory from the recovered intact blocks cut using a dry-sawing process. The size of the test cubes were 4 times the nominal maximum aggregate size (NMAS) for the FRAP course aggregate particles used in C2S1 and C2S3 test sections (NMAS of FRAP was 0.75 in. or 19 mm), thus conforming with ASTM recommendations for sample size. For C2S2 with QB/FRCA blends, 95% of the material blend was smaller than ¾ in. (19 mm) in accordance with the combined QB/FRCA gradation.

Three test cubes were prepared and tested for each stabilized test section in Cell 2, as well as for stabilized QB3 base in C3S1 and the stabilized subbase layers in C3S2 and C3S3. Prior to testing, the cubes were capped using a sulfuric compound to ensure more uniform loading distribution, and then tested for unconfined compressive strength at a rate of 0.04 in./minute (1 mm/minute). Figure 8 summarizes the UCS results for the different mechanically stabilized QB combinations and compares the achieved field UCS of the tested cubes. Since only three cubes were tested for each test section, which is insufficient for conducting statistical analyses, the minimum, average, and maximum cube strengths are shown. Also shown in Figure 8 are the UCS for the laboratory tested cylinders. Note that for concrete specimens, it is generally agreed that cube strengths are 18-30% higher than cylinders with a 2:1 aspect ratio of height: diameter [23, 24].

On average, the highest UCS was achieved for the QB2 with 3% cement combination (C2S4 and C3S2), which was significantly higher than the USCS for laboratory cylinders, followed by cement-stabilized QB/FRCA and QB/FRAP (C2S2 and C2S1), respectively. The lowest strength was achieved for the fly ash-stabilized QB2/FRAP combination, which was the only combination that achieved a lower average UCS than the laboratory cylinders. Note that the reported strength values for the field cubes can be considered to represent the UCS for the recovered intact blocks. The presence of internal cracks resulting from trenching and handling might have contributed to lower strength. Generally, the strength values of these cubes are expected to be on the higher end since they were extracted from the intact blocks recovered after trenching, while the weaker parts of the stabilized pavement layers would not be found intact. A discussion of the UCS of laboratory prepared cylinders with the different material combinations was presented elsewhere [19-21].

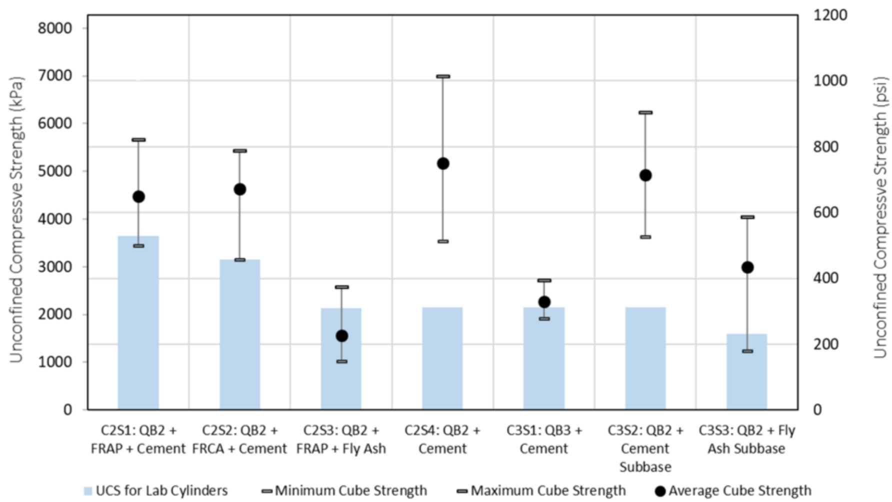


Figure 8. Unconfined compressive strength (UCS) values of stabilized QB material combinations retrieved from field test sections.

4. Summary and conclusions

This paper presented research findings from a study conducted at the Illinois Center for Transportation (ICT) to investigate sustainable bound applications for Quarry By-products (QB) in base and subbase layers. Three categories of chemically stabilized QB applications were selected and tested for field performance: (1) Blending QB with coarse aggregate fractions of reclaimed asphalt pavement (FRAP) and recycled concrete aggregates (FRCA); (2) using QB as a cement-treated base material; and (3) using QB as a cement or fly ash-treated subbase material in inverted pavements.

Satisfactory rutting performance trends were achieved for all chemically stabilized QB layer applications. No fatigue cracking was observed in any of the test sections with chemically stabilized QB applications. QB blends with FRCA or FRAP and cement had higher and statistically different unconfined compressive strengths from laboratory tests. They also showed the most satisfactory rutting performance trends, with the lowest Falling Weight Deflectometer (FWD) deflections, and the highest number of drops per inch (25.4 mm) of penetration by Dynamic Cone Penetrometer (DCP) from field testing. Sections stabilized with fly ash had somewhat inferior and more variable performance trends when compared to the cement-stabilized sections. Test sections that utilized two different sources of QB for the cement-stabilized base application (i.e. QB2 and QB3) did not show any significant difference in performance, which is in agreement with the laboratory unconfined compressive strength test results.

The performance monitoring of the stabilized test sections before and after trafficking with accelerated pavement testing in general indicated relatively low FWD deflections for the stabilized test sections utilizing QB applications. Additionally, measured wheel load stresses from pressure cells installed on top of the subgrade indicated relatively low subgrade pressures of around 2 psi (14 kPa) recorded for the three cement-stabilized base/subbase test sections, and thus low subgrade rutting potential. Further, inverted pavement sections (C3S2 and C3S3) showed satisfactory performance. In particular, C3S2 with a cement-stabilized QB subbase resulted in better performance demonstrating the suitability of using cement-stabilized QB in inverted pavement applications.

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