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SUSTAINABLE AGGREGATES PRODUCTION: GREEN APPLICATIONS FOR AGGREGATE BY-PRODUCTS

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16. Abstract

Increased emphasis in the construction industry on sustainability and recycling requires production of aggregate gradations with lower dust (cleaner aggregates) and smaller maximum sizes—hence, increased amount of quarry by-products (QBs). QBs are usually less than 1/4 in. (6 mm) in size. This report provides findings of an industry survey conducted among Illinois aggregate producers on the annual production rate, excess QBs generated, and current application areas of QBs. In addition, a detailed laboratory study was conducted to characterize the engineering properties of QB materials produced in the primary, secondary, and tertiary aggregate production stages from four different quarries operating in the State of Illinois. Since unconfined compressive strength for QB materials was low (less than 11 psi), chemical admixture stabilizers such as Portland cement and Class C fly ash were used to improve the strength properties of QB materials. Significant increases in the strength of stabilized QB materials observed may indicate suitability of QBs for sustainable pavement applications. Recommendations are made on potential strategies to utilize excess fines by incorporating QB materials in pavement construction.

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EXECUTIVE SUMMARY

Increased emphasis in the construction industry on sustainability and recycling requires production of aggregate gradations with lower dust (cleaner aggregates) and smaller maximum sizes—hence, increased amount of quarry by-products (QBs) are also produced. QBs are usually less than 1/4 in. (6 mm) in size. They are the residual deposits from the production of required grades of aggregate and are often stockpiled in excess quantities.

This report provides findings of an industry survey conducted among Illinois aggregate producers on the annual production rate, excess QBs generated, and current application areas of QBs. From the survey results, the current use of QBs in Illinois was found to be limited to applications that utilized low amounts of QBs; therefore, excess amounts of QBs might remain in the stockpiles.

In addition, a detailed laboratory study was conducted to characterize the engineering properties of QB materials produced in the primary, secondary, and tertiary aggregate production stages from four different quarries operating in the State of Illinois. Property tests were conducted for determining aggregate gradation, particle shape characteristics, and mineralogical analysis of the QB samples. Differences in shape and gradation properties of QB materials produced in each crushing stage were observed.

Strength tests, including unconfined compressive strength and direct shear, were also conducted. Because the unconfined compressive strength for QB materials was low (less than 11 psi), chemical admixture stabilizers such as Portland cement and Class C fly ash were used to improve the strength properties of QB materials. In general, 2% cement and 10% Class C fly ash–treated QB materials were 10 to 30 times stronger than the virgin QB samples. Such significant increases in the strength of stabilized QB materials observed may indicate suitability of QBs for sustainable pavement applications.

Some of the recommended applications of QB materials include filling the gaps/voids between large stones as aggregate subgrade on soft subgrades, embankment and/or subgrade/subbase replacement, cement/fly ash–treated subbase (e.g., in inverted pavements), cement/fly ash–stabilized base course, applications of blended QB materials with coarse aggregate fractions of virgin and recycled materials, fine aggregate replacement in 4.75 mm leveling binder asphalt mixes for overlay applications, and asphalt mix design to be plant produced for a 4.75 mm mix and other possible HMA mixes that incorporate a typical QB.

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Nearly 2 billion tons of aggregate are produced every year in the United States with a value of approximately $17.2 billion, contributing an average of $40 billion to the gross domestic product (GDP) of the United States (NSSGA 2014). Of the 2.12 billion tons of aggregate produced in 2009, 1.16 billion tons were crushed aggregates (USGS 2014). According to the U.S. Geological Survey (USGS), production of crushed aggregates in the United States began to decline in 2006 until it reached its minimum in 2009. That was followed by a considerable increase in the production of crushed aggregates from 2009 to 2013. Because of this increase, the USGS has predicted that the amount of crushed aggregates produced will jump to 1.6 billion metric tons in 2020, which is an approximately 20% increase. Sand and gravel production is expected to reach 1.1 billion metric tons, an increase of 14%. These numbers indicate that the demand for crushed aggregates is likely to increase more rapidly than that of the natural aggregates.

Although the production of aggregate contributes significantly to the economy, the by-products resulting from the production processes of aggregates are often considered waste. According to the International Center for Aggregates, the stockpiling and disposal of aggregate by-products is a major problem facing the aggregate industry (Hudson et al. 1997). An increased emphasis in the construction industry on sustainability and recycling encourages the production of aggregate gradations with lower dust and smaller maximum sizes. These new production limitations have “unbalanced” the aggregate production stream, in part because of the demand for cleaner aggregates with smaller top sizes in increased utilization of finer asphalt concrete mixes, resulting in excessive energy use and increased waste fines. Because of these increased energy and disposal costs for aggregate production, the reuse and recycling waste products (e.g., reclaimed asphalt pavement [RAP], recycled asphalt shingles [RAS], and recycled concrete aggregate [RCA]) sometimes exceeds the potential economic and environmental benefits.

The production of crushed aggregates involves quarrying rock by drilling and blasting followed by a series of crushing and screening operations until the desired grade is obtained. Depending on the location and geologic origin, major rock types processed include granite, limestone, dolomite, trap rock, shell, and slate. Aggregate quarry processes such as blasting, crushing, and screening of coarser-grade aggregates produce by-product mineral fine materials commonly known as quarry waste or quarry dust. Quarry waste fines or quarry by-products (QB), as referred in this report, are typically less than 1/4 in. (6 mm) in size and consist of coarse, medium, and fine sand particles, and a clay/silt fraction that is less than a No. 200 sieve (0.075 mm) in size.

Different crusher types are used in primary, secondary, and tertiary aggregate production stages to reduce the sizes of rocks; as a result, the quarry fines produced in those different stages may show differences in properties. According to the findings of Stroup-Gardiner and Wattenberg-Komas (2013) in *NCHRP Synthesis 435* (Volume 4), depending on the type of rock quarried, quarry by-products can be up to 25% of the total aggregate produced. This reflects a high production rate of quarry by-products and indicates the potential for cost-effective and environmentally friendly applications in which QB can be utilized.

Several studies report successful utilization of QB in road base/embankment and flowable fill applications (Kumar and Hudson 1992; McClellan et al. 2002). Kumar and Hudson (1992) also proposed base course material additive, flowable fill, under-slab granular fill, and cement-stabilized subbase/base layer as possible pavement applications of QB. The stabilization of QB with Portland cement develops relatively high rigidity with a small amount of cement compared with granular soil–

cement stabilization. This also has an advantage of decreasing the shrinkage cracking resulting from the low amount of cement used in these applications.

Quarry fines stabilized with cement are also economical and can produce adequate compressive strength, modulus of elasticity, and tensile strength characteristics required for subbase applications (Kumar and Hudson 1992; Kalcheff and Machemehl 1980; Puppala et al. 2008). Puppala et al. (2008) evaluated the use of QB as subbase/base material on expansive subgrade treated with lime. They showed that untreated QB material has moderate swelling; however, it exhibits low strength and low modulus. On the basis of field and laboratory studies, Puppala et al. (2008) concluded that the strength and resilient modulus of cement-treated quarry fines (CQF) are similar to those of sandy material with very few fines. They also suggested that further experimental research be conducted to understand the permanent deformation behavior of cement-treated quarry fines.

Like other materials used in construction, the engineering properties of QB greatly determine their suitability in pavement applications. McClellan et al. (2002) reported engineering backfill as a potential QB material use, which was evaluated based on particle size distribution (gradation), moisture content, and mineralogy of by-products representing a variety of limestone and dolomitic QB. Owing to the natural variability of the parent rock and the different crushing technologies employed, quarry fines often vary in mineralogy (Stokowski 1992). Mineralogical studies such as X-ray diffraction analysis may be used to determine the composition of secondary minerals and quantify the amounts of those minerals that are harmful to any of the anticipated applications. The proper way to determine the properties of quarry by-products is to conduct thorough laboratory characterization, which may include determination of engineering properties as well as chemical and compositional characteristics. Laboratory testing should be conducted even if the quarry by-products are produced from identical rock types using similar technologies (Pitre 2012).

1.2 RESEARCH OBJECTIVE

The project is envisioned to be completed in two phases. The objective of the first phase is to collect information regarding the production of quarry by-products in Illinois, evaluate the physical and engineering properties of aggregate by-products with representative sampling from the quarries in Illinois, and provide recommendations for the potential uses of QB products for the second phase.

The scope of the current study included surveys distributed to selected quarries operating in Illinois, laboratory testing, and preliminary sustainability evaluation. The ultimate goal of this phase is to develop a list of recommended applications to be considered in the second phase of the study.

1.3 RESEARCH APPROACH

The research approach to accomplish the objectives of the current phase of the study included the following tasks:

- Surveys were distributed to the selected quarries in Illinois to evaluate the current status of QB production and accumulation to understand the availability of QB for potential applications. Information was gathered in this task on the sources, types, production techniques, and amounts; and documented properties of quarry by-product fines primarily generated in stone quarries, sand and gravel pits, and recycling facilities that produce aggregates throughout Illinois.

- Representative samples from different crushing stages of aggregate production were collected from four different quarries. Physical and engineering properties of the samples were determined to evaluate potential uses of QB for various highway construction applications.

Gradation and shape characteristics, mineralogy, and strength properties before and after stabilization were determined. Portland cement and Class C fly ash were used as stabilizing agents in investigating the extent of strength gain.

1.4 REPORT ORGANIZATION

The scope of the research study included an industry survey in addition to the evaluation of physical and engineering properties of QB materials. The results from the industry survey are discussed first in this report followed by a description of the QB experimental program and presentation of the laboratory findings. Chapters are organized as follows:

Chapter 2 of this report presents a summary of the literature review. Historical and current uses of QB are presented, followed by general properties of QB from previous research studies. An overview of field applications is provided.

Chapter 3 presents a comprehensive industry survey report compiled from responses to the electronic and hard-copy questionnaires distributed to Illinois aggregate producers in 2013. The results include the overall response collection status and questionnaire response results.

Chapter 4 includes laboratory property testing results and analysis. The scope of laboratory characterization is presented, followed by the results. Various stabilization techniques to improve strength properties of QB materials are presented.

Chapter 5 summarizes the main findings of this study and presents a discussion and recommendation of potential applications. Recommendations are made for potential applications in the second phase of the current study and for future research.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

According to an International Center for Aggregates Research report (Hudson et al. 1997), the stockpiling and disposal of aggregate by-products produced as a result of stone crushing and aggregate production operations are among the major problems facing the stone and aggregate industry. Research conducted in the early 1990s showed that stockpiled fines comprised an average of approximately 12% of the total annual aggregate production of the surveyed companies (Kumar and Hudson 1992). The amount of aggregate by-products produced from rock crushing has increased in response to factors such as the adjusted design specifications for asphalt mixtures, which incorporate very low fines, resulting in changes to crushing/screening processes during aggregate production.

Current Superpave specifications require lower limits for the use of fines in asphalt mixtures. In addition, the growing use of RAP has limited the use of aggregate by-products due to the excess fines resulting from the RAP stockpiles.

Even though some benefits of fine aggregates were demonstrated in the literature for asphalt and concrete paving applications, the use of QB has not become widespread because complete specifications and guidelines are lacking. As a result, quarry fines continue to accumulate in quarries, becoming a major challenge for the aggregate producers.

2.2 COMMON TERMS AND DEFINITIONS

Aggregate quarry processes such as blasting, crushing, and screening of coarser-grade aggregates result in mainline product, as well as by-product mineral fine materials. These by-product fine materials are commonly known as quarry waste or quarry dust. Quarry dust (QD), quarry waste (QW), and quarry fines (QF) are the common terms used to define aggregate by-products representing fine aggregates separated from the mainline products.

The definition and the practical engineering use of the term “fines” vary from one agency to another. Generally, the term “fines” refers to undersized material from a crushing plant, which is subjected to no further processing and that accumulates over time. Materials produced from baghouse installation are good example of fines. Different agencies have adopted different definitions of fines based on size. The general sizes of fine material as defined by different agencies range from 0.25 in. (6.25 mm) and smaller. Baghouse fines are less than a No. 200 sieve size (0.075 mm) and can generally be mixed with plant fines.

Manning (2004) in the United Kingdom defined quarry fines as materials intended to be used as fine aggregate and less than 0.157 in. (4 mm) in size. The same report also defined fines as less than 0.079 in. (2 mm). The reason behind this variation is that fines can generally be defined depending on the application. Therefore, it can be concluded that quarry fines may cover a range of aggregates with maximum sieve sizes of 0.079 to 0.25 in. (2 to 6.25 mm).

2.3 PRODUCTION

The production of crushed stone aggregates starts with blasting of the parent rock and fragmentation; the fragmented rock is then crushed and screened through multiple stages. Crushing of the quarried rock is generally carried out in three stages: primary crushing, secondary crushing, and tertiary crushing (Petavratzi and Wilson 2007). The later stages in aggregate production are washing and stockpiling. In general, quarry by-products are accumulated during aggregate crushing stages and washing operations.

For most practices, quarry by-products produced from the extraction of the limestone or dolomite can be up to 25%, while those produced from the extraction of sandstone/gritstone can be up to 35% (Petavratzi and Wilson 2007; Stroup-Gardiner and Wattenberg-Komas 2013).

Figure 1 is a schematic representation of the different processes involved in aggregate production, as well as the approximate amounts of quarry by-products produced during the various stages of aggregate production. Owing to different sizes of aggregate produced from each crusher and different crusher types (as shown in Figure 1), the amount of fines produced may increase from the primary crusher to the tertiary crusher.

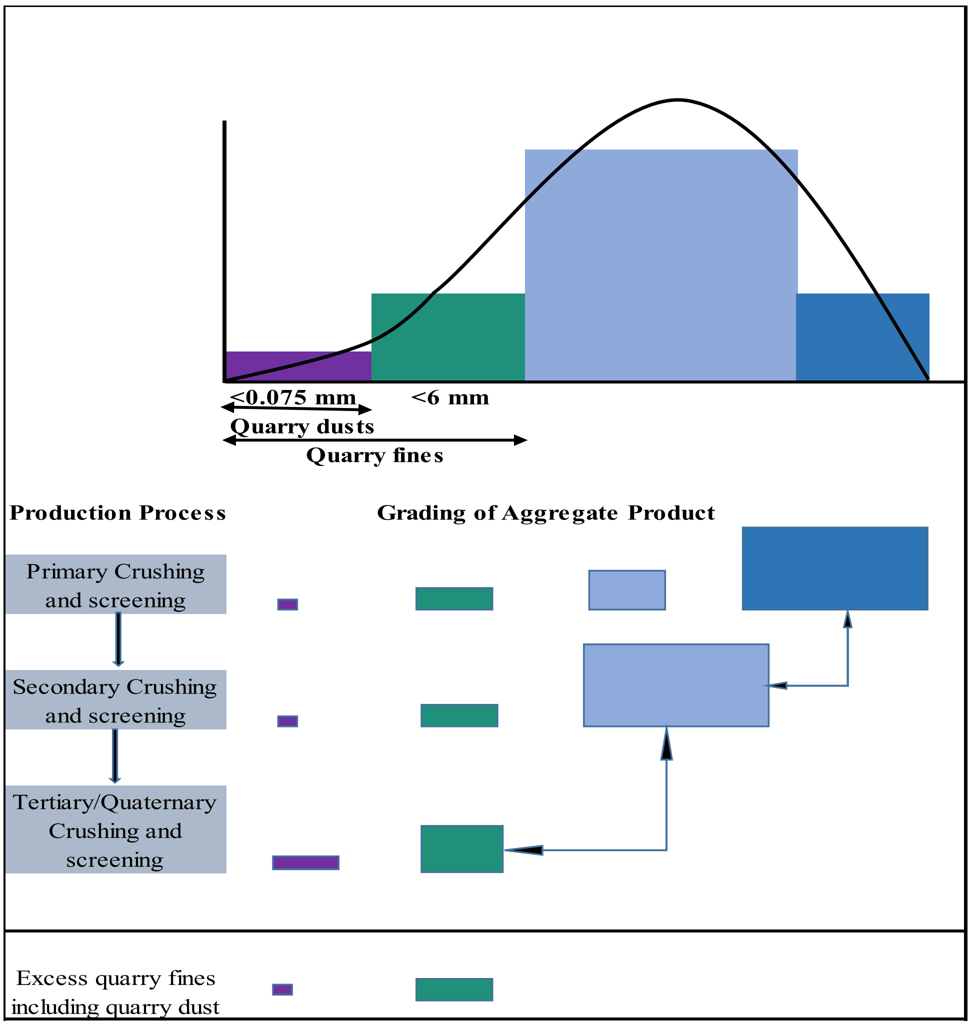


Figure 1. Grading requirements for aggregate product (Petavratzi and Wilson 2007).

According to Tepordei (1992), aggregate production processes result in three types of quarry products: screening fines, pond fines, and baghouse fines. These by-product fines undergo different process during production and therefore possess different physical properties. A detailed description of these by-products follows.

2.3.1 Screening Fines

According to *User Guidelines for Waste and By-Product Materials in Pavement Construction (*FHWA 1998), screenings are less than 4.75 mm (No. 4 sieve). Crushed stone screenings is a generic term to designate the finer fraction of stone products, usually smaller than 5 mm (0.2 in.) in size, which accumulate as a dry or semi-dry by-product after primary and secondary crushing and separation on the 4.75 mm (No. 4 sieve) sieve (Wood and Marek 1995). The size distribution of screenings, their shape, and their physical properties can differ depending on the parent rock's geological source, crushing method, the ratio of reduction, and the coarse aggregate separation method (Wood 1995; Stroup-Gardiner and Wattenberg-Komas 2013).

2.3.2 Baghouse Fines

Baghouse fines are produced in dry plants. Their particle sizes are 0.075 mm (No. 200 sieve) or even finer. Dry plant operations use fines recovery units such as cyclones and baghouses that collect fines from the secondary crusher. This operation is similar to the fines collecting system in hot-mix asphalt plants to recover unwanted dust produced in the drums. Baghouse fines are easy to handle compared with other wastes produced in quarries because they are produced in dry conditions and can be easily stored without further processing. In general, the properties of baghouse fines vary based on the rock type and the producer (Tepordei 1992).

2.3.3 Pond Fines

Usually 90% to 95 % of pond fines are smaller than 0.15 mm (No. 100 sieve), and 80% or more are finer than 0.075 mm (No. 200 sieve). Pond fines, pond slimes, or pond tailing refers to fines produced during the crushed stone aggregate washing process. Washed aggregates frequently have specified uses because washing involves removal of dust, and clay impurities if present. The specified uses of these aggregate products are in Portland cement concrete, railroad ballast, mineral wool, or metallurgical stone (Wood and Marek 1995). Pond fines generally have high moisture contents, ranging from 70% to 80%. Moisture contents can be reduced to 20% to 30% when allowed to naturally dewater for several months.

2.4 ENGINEERING PROPERTIES OF QUARRY BY-PRODUCTS

2.4.1 In Situ Moisture Content

Moisture content of quarry fines depends on characteristics of fines and the production technique. Unlike pond fines, dry screenings do not have high moisture contents. The moisture contents of pond fines are above 20%; however, they may decrease to a range of 5% to 15% during stockpiling. Wood and Marek (1995) have shown that carbonate rock pond or screenings tend to dewater at a slower rate than those from granite, trap rock, or slag. This is because clays are liberated from these sedimentary rocks and become part of the pond screening.

2.4.2 Swelling Characteristic of Fines

According to the research conducted in by Puppala et al. (2012), a one-dimensional vertical free-swelling test to evaluate swelling characteristics of quarry fines from one site showed a swelling strain up to 6%, per ASTM D698. According to the swelling classification, the sample test was considered a moderately swelling material. This finding was specific to the sample tested in that study, and it therefore cannot be generalized to quarry by-products.

2.4.3 Chemical and Mineralogical Properties

The quality of quarry fines reflects the lithology of the worked material and the processes it has undergone. Different quarries, or activities within the same quarry, may generate a range of quarry fines in relation to particle size and composition. Quarry fines are composed of the same mineral substances as the soil and solid rock from which they are derived, even though changes to their physical and chemical characteristics may have occurred throughout the extraction process. Quarry fines by their nature are usually inert or non-hazardous. Disaggregation, mixing, and moving to other locations; exposure to atmospheric conditions and to surface- or groundwater; segregation; and an increase of surface area caused by particle size reduction may cause physical and chemical transformations with detrimental effects to the environment (Petavratzi and Wilson 2007).

Chemical and mineralogical properties of quarry fines may govern their suitability for various applications. Manning (2004) found that the properties of quarry fines could not be easily predicted because of the natural variability of parent rock and the different crushing technologies employed. The proper way to determine the properties of quarry by-products is to conduct thorough laboratory characterization that may include determination of engineering properties as well chemical and compositional characteristics. Laboratory testing should be conducted even if the quarry by-products are produced from identical rock types using similar technologies (Manning 2004).

According to Dumitru et al. (2001), mineralogical tests such as X-ray diffraction analysis should be conducted to determine the compositions of secondary minerals and to quantify amounts of harmful content that can be detrimental in some applications. Mineralogical tests can also be performed to quantify the amount of harmful clays in quarry by-products. Stokowski (1992) has shown that the finest sizes are enriched in $CaCO_3$, SiO_2, Al_2O_3, and Fe_2O_3 relative to $MgCO_3$. As a result of this finding, quarry by-products have lower specific gravity and are relatively soft because of calcite ($CaCO_3$) and enrichment of clay minerals (SiO_2, Al_2O_3, and Fe_2O_3).

2.4.4 Gradation

Gradation of quarry fines varies depending on the parent rock type quarried. Kalcheff and Machemehl (1980) reported that screenings generally contain freshly fractured faces, have fairly uniform gradation, and contain fewer plastic fines. In their report, Kalcheff and Machemehl (1980) reported average particle size distributions for different types of rocks (Table 1). The particle distributions of screenings from different types of rock follow a similar gradation trend, with particles smaller than sieve No. 200 (0.075 mm) ranging from 6% to 12%.

Table 1. Average Particle Size Distributions of Screenings
from Different Types of Rock (Kalcheff and Machemehl 1980)

Sieve Sizes (mm)	Type of rock						
	Flint	Trachyte	Limestone	Diabase	Granite	Blast furnace slag	Quartzite
	Percentage passing						
3.18	100	100	100	100	100	100	100
2.36	83	82	85	87	86	89	88
1.18	51	52	54	61	60	67	71
0.6	31	33	34	41	42	49	57
0.3	18	22	23	27	28	32	33
0.15	10	13	15	17	19	20	15
0.075	6	8	7	9	12	11	7

2.5 OVERVIEW OF POTENTIAL APPLICATIONS

Kumar and Hudson (1992) showed that through a series of sample evaluations, quarry by-products can generally be divided into six categories based on the percentage passing the No. 200 sieve. Based on the classifications, the authors proposed the following potential paving applications for quarry by-products: base course material additive, flowable fill, under-slab granular fill, and cement-stabilized subbase/base layer.

In the United Kingdom, Petavratzi and Wilson (2007) conducted a study on sustainable aggregates. The purpose of their study was to evaluate the current status of quarry by-products (which includes overburden, quarry fines, and dusts produced during extraction and processing of aggregates).The amount of quarry by-products produced in each stage of aggregate production was quantified in the Petavratzi and Wilson study. In addition, the viable applications and utilization potential (low volume to high volume) of aggregate by-products were discussed. On the basis of their findings, Petavratzi and Wilson concluded that geotechnical and concrete applications consume higher amounts of aggregate by-products.

Similarly, in 2013, Stroup-Gardiner and Wattenberg-Komas (2013) in *NCHRP Synthesis 435* (Volume 4) reported U.S. and worldwide survey findings on the current engineering applications of quarry by-products. The results of the surveys showed that aggregate by-products are commonly used in geotechnical and concrete applications.

Therefore, Section 2.5 of this report focuses on the research that was conducted to evaluate the use of quarry by-products in geotechnical and concrete paving applications.

2.5.1 Base and Subbase Applications

2.5.1.1 Kalcheff and Machemehl (1980)

Stone screenings with or without coarse aggregates have been used as cement-stabilized bases in many applications. According to Kalcheff and Machemehl (1980), stabilization of stone screenings with cement developed relatively high rigidity with a small amount of Portland cement compared with granular soil–cement stabilization. The use of low-cement content has the advantage of decreasing the shrinkage cracking. The data reported by the National Crushed Stone Association laboratory showed that the screenings used in base/subbase should have sufficient amount of fines (smaller than No. 200 sieve). Unwashed screenings with non-deleterious fines are the most suitable for cement stabilization.

2.5.1.2 Kumar and Hudson (1992)

In 1992, Kumar and Hudson examined the unconfined compressive strength, tensile modulus of elasticity, and Poisson’s ratio of cement-treated quarry fines (CQF). Their study concluded that stabilizing quarry fines with cement could produce the adequate compressive strength, modulus of elasticity, and tensile strength required for subbase material. In general, the use of cement-treated quarry fines may require a thicker layer compared with conventional material; however, Kumar and Hudson emphasized, on the basis of their cost analysis, that subbase material using quarry fines can be more economical than a comparable asphalt concrete layer for the equivalent load-carrying capacity. In summary, Kumar and Hudson suggested that fines with cement stabilization in base courses could be used under circumstances such as the following:

- When there is a severe shortage of regular-sized construction aggregates in the area,
- In the case of a low-volume, low-traffic road design with a low budget,

- If the fines are economically transportable (100-mile radius) to the area, or

- If no acceptable soil or gravel is found in the area for soil-lime-fly ash or cement stabilization, or it is not economical to transport.

2.5.1.3 Puppala et al. (2008 and 2012)

Puppala and colleagues conducted laboratory assessment of quarry fines in two consecutive studies. Field performance of quarry fines as base/subbase material on expansive subgrade was evaluated. Laboratory characterization of quarry fines prior to field testing showed that untreated quarry fines material exhibited low strength and low modulus. The liquid limit, plastic limit, and specific gravity of the quarry fines were found to be 21.5%, 11.7% and 2.65, respectively (based on ASTM D4318-00 test methods). A vertical free-swelling strain of around 6% on quarry fines was determined per the ASTM D4546 method. The researchers concluded that the compressive strength of untreated (virgin) quarry fines can be very low (Puppala et al. 2008).

To enhance the engineering properties of this material, 2.3% of cement was used in the field; the results were promising. The addition of 2.3% cement increased the unconfined strength of the untreated quarry fines by almost 12 times. The results showed that, unlike untreated QF, the cemented QF (CQF) behaved as a base material when their resilient modulus was examined. The addition of cement reduced the maximum dry unit weight from 18.7 to 17.9 kN/m^3 (119 to 114 pcf) and increased the optimum moisture content from 11.2% to 13.8%. Moreover, the addition of cement to quarry fines reduced the swelling strain from 6% to almost zero. Table 2 compares the resilient modulus for cement-treated quarry fines with untreated quarry fines at different confining pressures.

Table 2. Maximum Resilient Modulus Values for Cemented Quarry Fines at Different Confining Stresses (Puppala et al. 2008)

Confining Pressure (kPa)	Resilient Modulus MPa (QF)	Resilient Modulus MPa (CQF)
20.7	65	152
34.5	118	216
68.9	228	317
103.4	232	351
137.9	230	369

Puppala et al. (2008) concluded that the strength and resilient modulus of the CQF are similar to those of sandy material with very few fines. The untreated sample of QF exhibited compressive strength of 100 kPa (14.5 psi), while the cement-treated sample had a compressive strength of 1200 kPa (174 psi). The higher strength of CQF was attributed to cementing reactions of the cement and the fine sandy fraction of QF material.

Following the laboratory assessment of quarry fines, field performance tests were conducted with quarry fines used as subbase/base material on expansive subgrade treated with lime (Puppala et al. 2012). Figure 2 shows the cross section of the roadway for which CQF was used as a pavement base to support a new pavement section in Arlington, Texas. Surface deflections of 1.27 mm (0.05 in.) caused by construction irregularities were initially observed. No additional substantial changes in the surface deformation profile were observed during the experimental testing. They concluded the study with recommendation for further testing to evaluate the permanent deformation of cement-treated quarry fines.

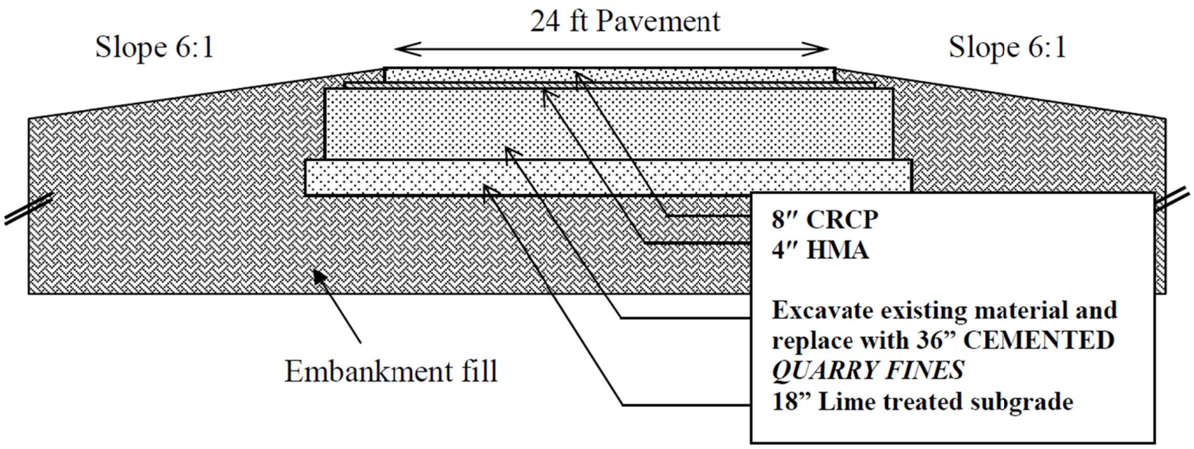


Figure 2. Typical test embankment with CQF as a base material supporting pavement in Arlington, Texas (Puppala et al. 2012).

2.5.2 Mechanical Stabilization of Weak Subgrade with Stone Screenings

2.5.2.1 Kalcheff and Machemehl (1980)

Various crushed stone products have been used throughout the years as supplemental materials to improve a material's load-bearing characteristics (Kalcheff and Machemehl 1980). During highway construction, the subgrade soil must be stable enough to avoid sinkage of the construction equipment. A minimum in situ California bearing ratio (CBR) value of 6 to 8 is required to ensure the safety of construction equipment. Addition of stone screenings to the soils with low in situ CBR values acts as a remedial procedure to increase the CBR of fine-grained soil. The amount of stone screenings required will depend on the soils and the desired CBR.

2.5.3 Ready-Mixed Flowable Fill

2.5.3.1 Kumar and Hudson (1992)

According to Kumar and Hudson (1992), flowable fill, generally known as controlled low-strength material, is a mixture of cement (Type I or Type II), fly ash, sand (100% passing 3/4 in. and 0% to 10% passing No. 200 sieve), and water. Flowable fill is designed as a low-strength, fluid material requiring no subsequent compaction efforts such as vibration or tamping for consolidation. Bearing capacity and stiffness of flowable fill are generally higher than compacted soil and smaller than concrete. The compressive strengths of flowable fill ranges from 20 to 200 psi (137.9 to 1379 kPa) with 40 to 100 psi (275.8 to 689.5 kPa) 28-day strength specified by most states and other agencies. Some of the applications of flowable fill in highway construction include foundation subbase, filling voids under existing concrete pavements, slope stabilization, pipe bending and trench filling, and other types of backfill.

In their report, Kumar and Hudson (1992) showed that with modification of the current standards, quarry fines could be used as part of flowable fill. When stabilized with cement, fly ash, and adequate water, quarry fines can achieve desired consistency with reduction of the overall cost of the mix. That report emphasized that the benefits of using quarry fines was highly dependent on the source of the quarry fines; as a result, the mix ratio of the important parameters in flowable fill varies depending on the quarry fine properties. Some quarry fines may result in a cost-effective flowable mix when replaced completely or partially with sand, while others require increased water and or cement content to obtain specified consistency.

2.5.3.2 Wood and Marek (1995)
Owing to the gradation and fineness of quarry fines, quarry screenings can be used as substitute for more costly natural sand. On the other hand, both baghouse and pond fines are suitable replacement materials for fly ash and have a minor cost increase if extra cement is required. Tennessee Technological University's Department of Civil Engineering, in collaboration with Rogers Group Inc., showed that replacement of natural sand with screenings in the flowable mix provides sufficient compressive strength while reducing cement content. It is possible to use quarry fines with 20% passing a No. 200 sieve in the flowable fill mix and still obtain the desired strength. According to the results presented in the study by Wood and Marek (1995), using 3% cement, 8% fly ash, and 89% quarry fines resulted in a flowable fill with adequate performance.

2.5.4 Partial Replacement of Sand in Concrete

2.5.4.1 Lohani et al. (2012)
Lohani et al. (2012) found that the replacement of sand with quarry dust in concrete improved the properties of the mixture. The quarry dust improved the pozzolanic reaction, micro-aggregate filling, and concrete durability. The researchers concluded that the compressive strength of specimens at the end of 28 days curing increased by 13% and 3.2% for mixes M2 and M3, respectively (M2 and M3 had less than 30% quarry dust, as shown in Figure 3) for 53-grade concrete, compared with the control mix (M1). Strength was reduced by 3.9% and 13.1% for mixes M4 and M5, respectively (M4 and M5 had more than 30% quarry dust). Similarly, for 33-grade concrete, the compressive strength of specimens at the end of 28 days curing increased by 6% and 3.7% for mixes M2 and M3, respectively, but the strength was reduced by 3.3% and 14% for mixes M4 and M5 in comparison with M1.

The study also found that an increase in fines content up to 30% increased the compressive strength of concrete. When the dust content was greater than 30%, the compressive strength decreased gradually. However, the compressive strength of quarry dust concrete continued to increase with age for all percentages of quarry dust contents. The modulus of elasticity slightly increased with an increase in percentage of quarry dust content. The modulus of elasticity at 28 days curing for the control mix (M1) reached 32,617 MPa for 53-grade concrete mix. Mixes M2, M3, M4, and M5 showed a reduction in strength of 1.68%, 5.2%, 8.4%, and 13.7%, respectively, in comparison with M1. Similarly, for 33-grade concrete at 28 days curing, the control mix reached 31,100 MPa. Mixes M2, M3, M4, and M5 showed a reduction in strength of 2.7%, 3.7%, 6.6%, and 11.2%, respectively, in comparison with M1.

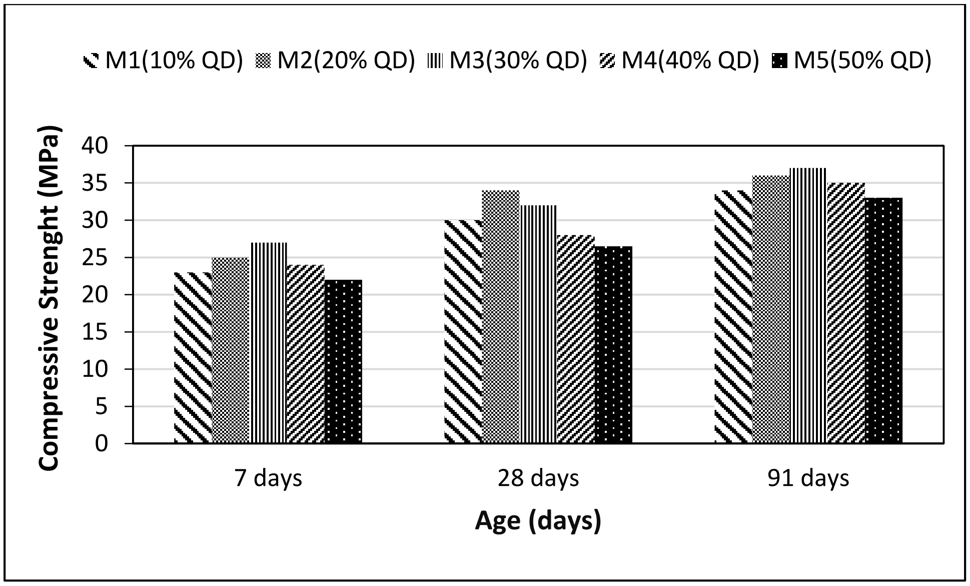


Figure 3. Compressive strength of different mixes with age (Lohani et al. 2012).

2.5.5 Self-Consolidating Concrete

2.5.5.1 Naik et al. (2005)

Naik et al. (2005) examined the use of quarry fines in self-consolidating concrete (SCC). They found that the addition of quarry fines minimized the addition of the admixture without reducing the strength of the SCC. The researchers found that the 28-day strength of concrete made with partial replacement of cement with Class C fly ash combined with partial replacement of sand with quarry fines was equivalent to a conventional mix. The researchers concluded that the use of QB had an advantage of cost savings without affecting overall strength.

2.6 SUMMARY

Quarry dust, quarry waste, quarry fines, and quarry by-products are the common terms used to define aggregate by-products, indicating the fine aggregates separated from mainline quarry products and stockpiled after aggregate production. For many quarries, the definition and the size of fines varies from one agency to another. Generally, the term “quarry fines” refers to undersized materials (typically less than 4.75 mm or 6.35 mm sieve sizes) from crushing stages with no further processing and that accumulate over time.

In general, the studies to characterize QB showed that the strength properties of aggregate by-products are very low. Strength properties of QB can be improved by addition of low-cement contents and moderate amounts of fly ash. The increased strength of treated QB makes them good candidates for various pavement applications such as base/subbase material and stabilization of weak subgrade. Other common applications of QB are flowable fill, partial replacement of sand in concrete, and self-consolidating concrete.

CHAPTER 3: COMPREHENSIVE INDUSTRY SURVEY

To collect data on the types, general characteristics, production volumes, and current applications of QB materials generated in stone quarries, a survey questionnaire was prepared and distributed to aggregate producers operating in the State of Illinois. The survey included questions such as annual production amounts of QB, crushing procedures and equipment used, current applications of excess QB, and tests performed on QB after they are produced. The survey responses were intended to help producers and transportation agencies, as well as researchers, gain knowledge about the general production volumes and procedures of aggregate by-products and better understand potential application areas for local QB utilization.

3.1 DISTRIBUTION PROCESS AND RESPONSE COLLECTION STATUS

In July 2013, a comprehensive survey questionnaire was prepared and sent to crushed stone quarry producers operating throughout Illinois, with the help and oversight of the Specifications Committee of the Illinois Association of Aggregate Producers. Twenty-two aggregate producers responded to the survey, representing about 27% of the producers contacted. Among the 22 aggregate producers who responded, some had multiple quarries operating in the state; therefore, the responses received represent 42 quarries. Also included among the respondents were three of the top five crushed stone producers (ranked according to number of quarries operating in Illinois) that were more likely to experience excess QB problems. Figure 4 shows the locations of the quarries (or producer, if quarry location was not explicitly provided) that responded to the survey questionnaire. It can be seen that the respondents covered the State of Illinois from north to south and from west to east, with the majority of them located in northern part of the state.

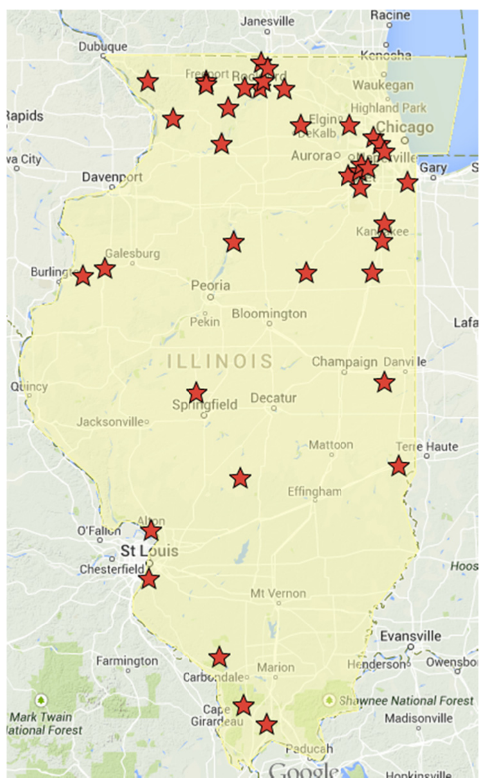


Figure 4. Locations of survey respondents.

3.2 SURVEY RESULTS

This section contains a detailed presentation of the survey results, including each question asked in the survey questionnaire as well as statistics of the responses. Quarry by-products are defined in the questionnaire as “typically less than 1/4 in. in size.”

3.2.1 Quarry Deposit Type

Quarry deposit type collected from the survey is shown in Figure 5. The total number of responses to this question was 42. According to the survey results, only four of the respondents indicated an underground type of deposit (representing less than 10%), while the remaining 38 respondents indicated surficial type of deposit.

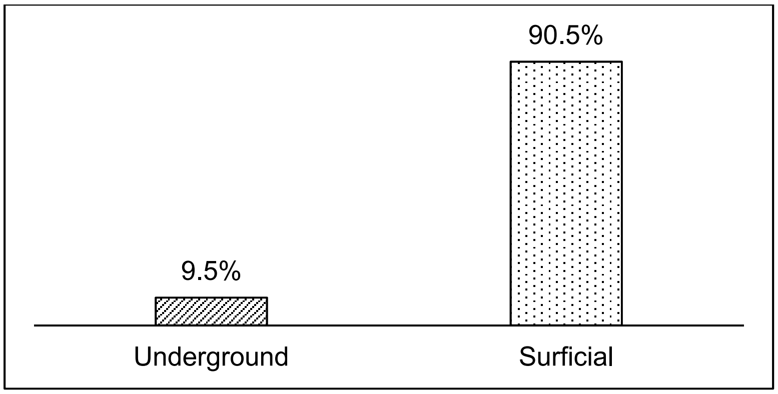


Figure 5. Quarry deposit type.

3.2.2 Annual Production of Quarry By-Products

Thirty-eight respondents, representing 90% of total respondents, are producing QB. Figure 6 shows the typical annual tonnage of QB produced. Among the quarries that produce quarry fines, 55% have a typical annual amount of QB greater than 100,000 U.S. short tons, 26% between 25,000 and 100,000 tons, and 19% less than 25,000 tons. Respondents listed various crushers they use in aggregate production stage: impactor crusher, jaw crusher, cone crusher, vertical shaft impactor crusher, gyratory crusher, and roller crusher. The responses showed no clear relation between crusher type and QB amount.

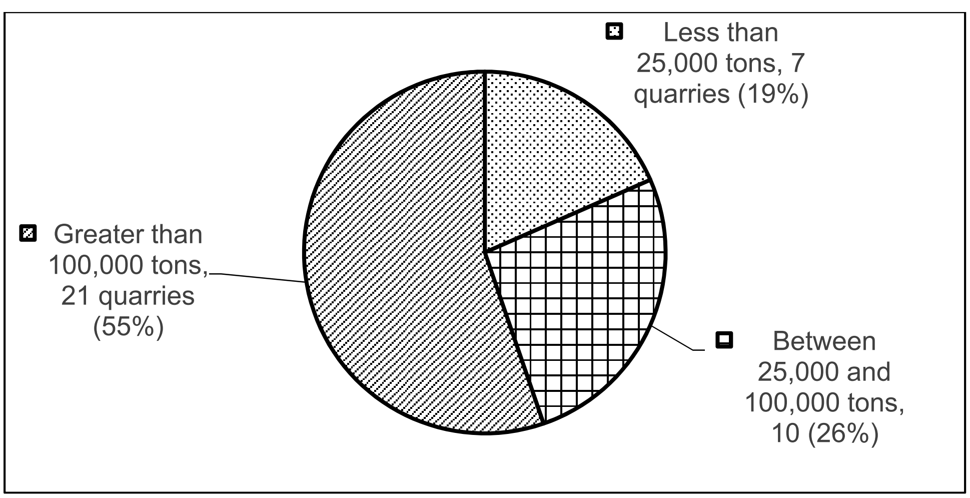


Figure 6. Typical annual tonnage (U.S. short tons) of QB produced.

3.2.3 Production of QB at Different Crushing Stages

Respondents were asked to indicate all of the different crushing/screening stages during which QB are produced in their facility. Most of the aggregate producers have up to three crushing/screening stages: primary, secondary, and tertiary. Depending on the practices in quarry operations and current production methods, the stages in which QB are produced can vary. The percentage of respondents producing QB in each crushing/screening stage is shown in Figure 7. Most of the responses indicated more than one stage. Thirty-four respondents, which represent almost 90%, indicated that the secondary crushing stage can produce QB. Twenty-four respondents, slightly more than 60%, indicated that the primary crushing stage can also produce QB. Moreover, 21% of respondents indicated that up to four, or even five, stages in their quarry are producing QB.

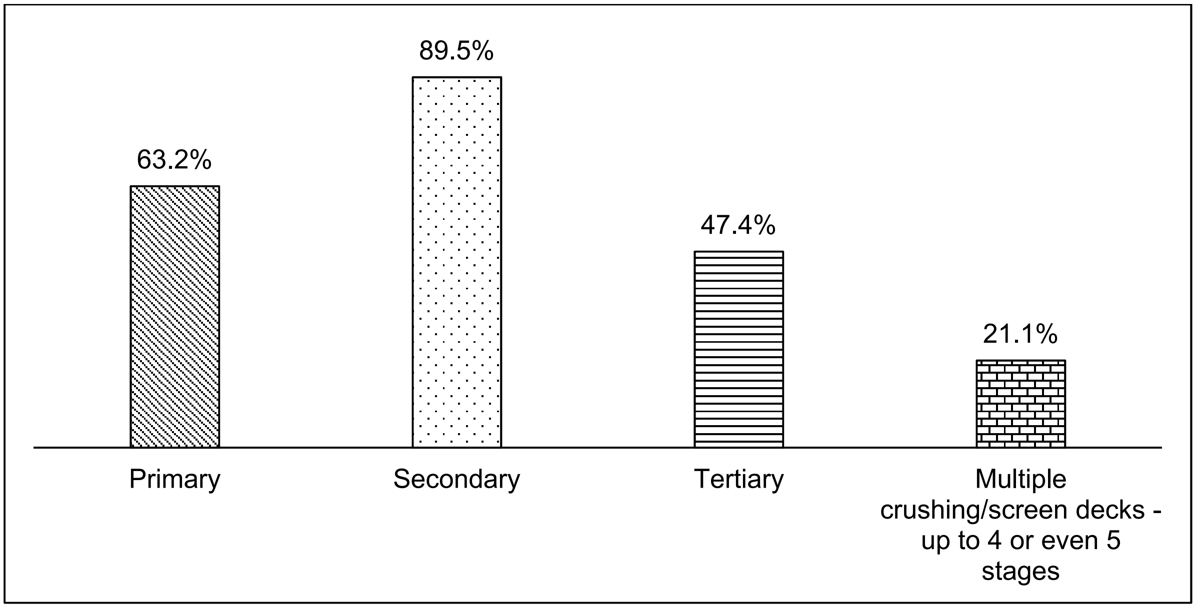


Figure 7. Percentage of respondents producing QB in each crushing/screening stage.

Only 14 respondents sample QB from different stages and/or run property tests. Some quarries test all products off the production belts. Some quarries indicated that intermediate belt cut samples are routinely pulled in an effort to understand various crusher aperture settings. Some pay particular attention for QB produced in tertiary crusher.

Thirty-three of the quarries surveyed (78% of respondents) have excess fines that are currently not utilized in a calendar year. The approximate amounts of excess fines produced in a year are shown in Figure 8. Six respondents indicated that more than 100,000 U.S. short tons of QB were not fully used each year. Fourteen respondents indicated that more than 25,000 tons of QB were in the excess category. It can be seen that the excess QB produced each year can be as high as, or even greater than, 950,000 tons from the 20 quarries responding to the questionnaire. Respondent quarries that did not report excess fines indicated that they did not produce large quantities of fines and that available fines were sold as agricultural lime (known as aglime) or other products for agricultural applications.

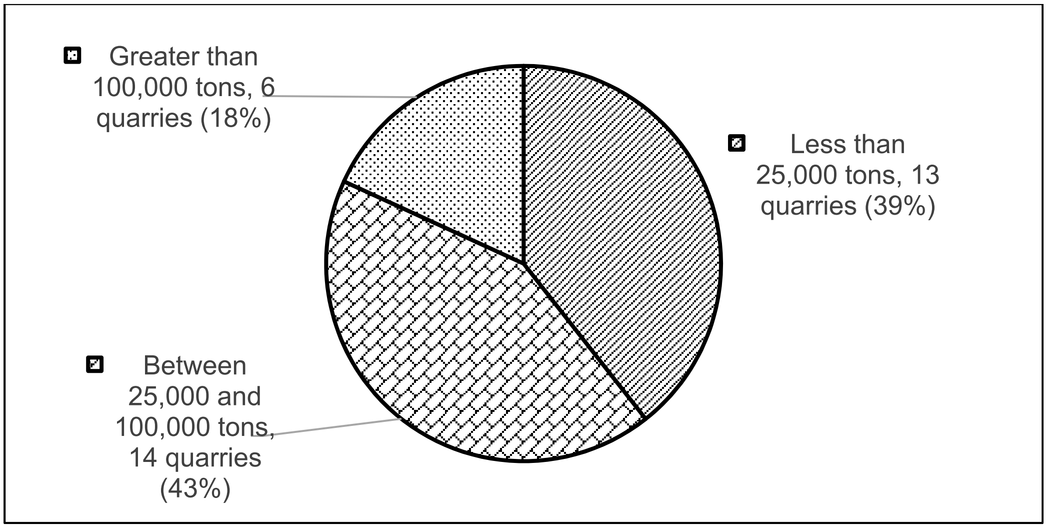


Figure 8. Annual tonnage (U.S. short tons) of excess QB (not sold/used).

Twenty-one of the quarries surveyed (55% of respondents) had a stockpile of excess QB in or near their facility at the time they responded. The approximate amounts of the excess QB stockpiled are shown in Figure 9 . Five quarries indicated having more than 500,000 tons of QB stockpiled nearby. Nine quarries indicated having more than 100,000 tons of QB stockpiled. Altogether, more than 3,475,000 tons of QB were stockpiled at the time the survey was conducted. Compared with the annual amount of excess QB, it can be seen that excess QB are accumulated over years, which further implied that handling and stockpiling may be a potential problem for these quarries.

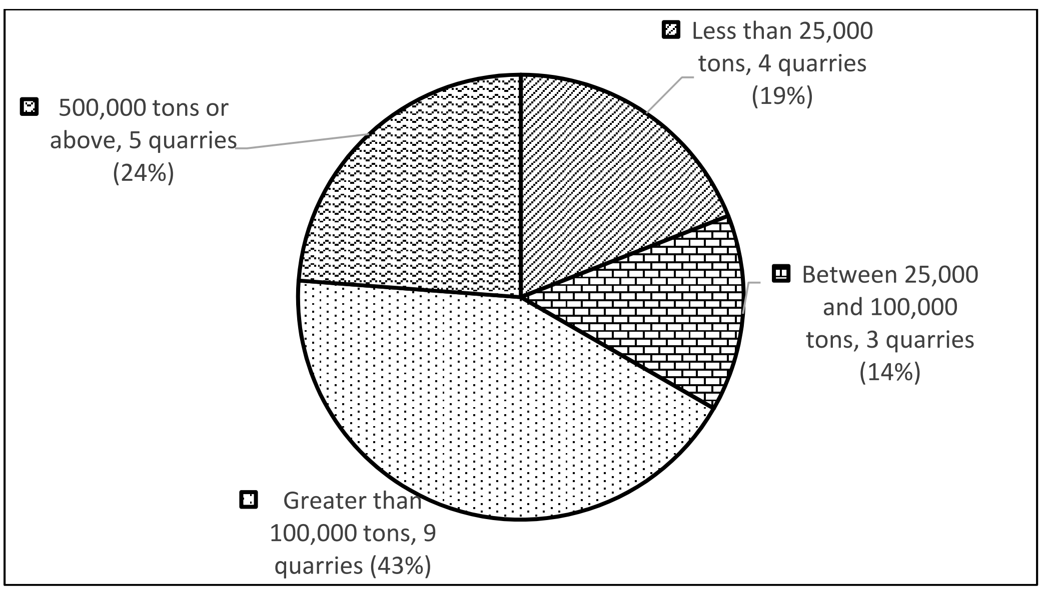


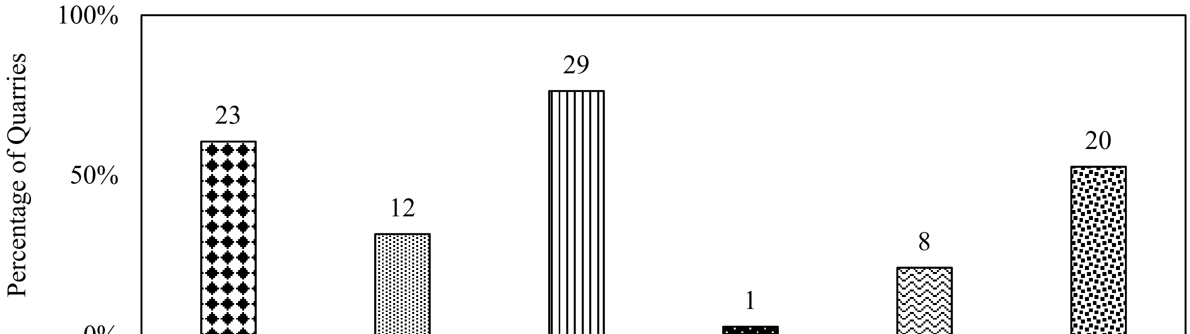
Figure 9. Approximate amounts of the excess QB stockpiled.

3.2.4 Characterization Methods for Quarry By-Products

The survey results also included information about percentages of quarries that performed each test on quarry fines, such as (1) pH, 58% of respondents; (2) chemical composition, 56%; (3) grain size distribution, 53%; (4) Atterberg limits, 36%; (5) petrographic analysis, 14%; (6) X-ray diffraction, 14%; and (7) specific gravity and absorption, less than 10%.

3.2.5 Utilization of Quarry By-Products

Regarding the current utilization of QB, several application areas were reported in the survey. The results collected from 38 survey respondents are presented in Figure 10, indicating the use percentages for each application. The most common application is aglime, which is beneficial to plants when added to soil; other common uses are trench backfill, earth fill, fine filler for concrete, and quarry fines in hot-mix asphalt production.



	Trench backfill	Earth fill application	Aglime	Aggregate Subgrade	Fine aggregate/filler for concrete	Other (such as for limestone cement, HMA, etc.)
Percentage	60.5%	31.6%	76.3%	2.6%	21.1%	52.6%

The total number of respondents was 38. Numerals above the chart bars indicate the number of quarries utilizing QB for that application.

Figure 10. Utilization percentages for different QB applications.

3.3 SUMMARY

In July 2013, a comprehensive survey questionnaire was prepared and sent to crushed stone quarries operating throughout Illinois. Twenty-two aggregate producers responded to the survey, representing about 27% of the producers contacted. Among the 22 aggregate producers who responded, some had multiple quarries operating in the state; therefore, the responses received represent 42 quarries.

Based on the survey results, it is clear that large amounts of QB are generated through the crushing/screening stages and that a substantial portion of these QB is not currently being used. It can be seen that the excess QB produced each year can be as high as, or even greater than, 950,000 U.S. short tons from the 20 quarries responding to the questionnaire.

In addition, because of the yearly accumulation of unsold/unused QB, excess QB stored in stockpiles from quarries surveyed were more than 3,475,000 U.S. short tons, based on the survey results. Hence, it would be of value to find potential application areas in pavements for these by-product materials. Such applications would help in utilizing excess and unused fines accumulating in stockpiles while improving sustainability of pavements and reducing the cost of pavement construction by replacing virgin materials by quarry by-products.

CHAPTER 4: LABORATORY PROPERTY TESTING, RESULTS, AND ANALYSES

4.1 SCOPE OF LABORATORY TESTING

A detailed laboratory test matrix was developed to determine physical and engineering properties of the collected QB samples from various quarries communicated with during the survey. The objective of the experimental program is to establish a framework to evaluate applicability of QB for various pavement applications. This chapter summarizes sampling, experimental program, and results.

4.1.1 Selected Quarry Locations

Aggregate by-product samples were obtained from four quarries in the State of Illinois, as shown in Figure 11. All four of the quarries generate large quantities of QB annually and are located across the State of Illinois. Samples from different quarries allow evaluating variability in engineering properties of QB from different geological locations and production techniques to better represent QB from Illinois.

Two batches of QB samples were collected from Quarry 1 near the Chicago area and were sampled within a 5-month period—the first in December 2013 (batch #1) and the second in April 2014 (batch #2). Collecting two batches of materials allowed evaluating any variability in the engineering properties of QB materials sampled at different times. It should be noted that because of the limited amounts of material received as part of first batch, not all characterization tests could be conducted on that batch. Accordingly, there are some variations in the experiments applied for both of the batches. Detailed experiments conducted on each batch can be found in Section 4.1.3.

After the first round of the experimental program was completed for the samples collected from Quarry 1, additional samples were collected from other quarries to evaluate variability of the major properties of QB sampled from various quarries. Only one batch of samples was collected from each quarry in December 2014.

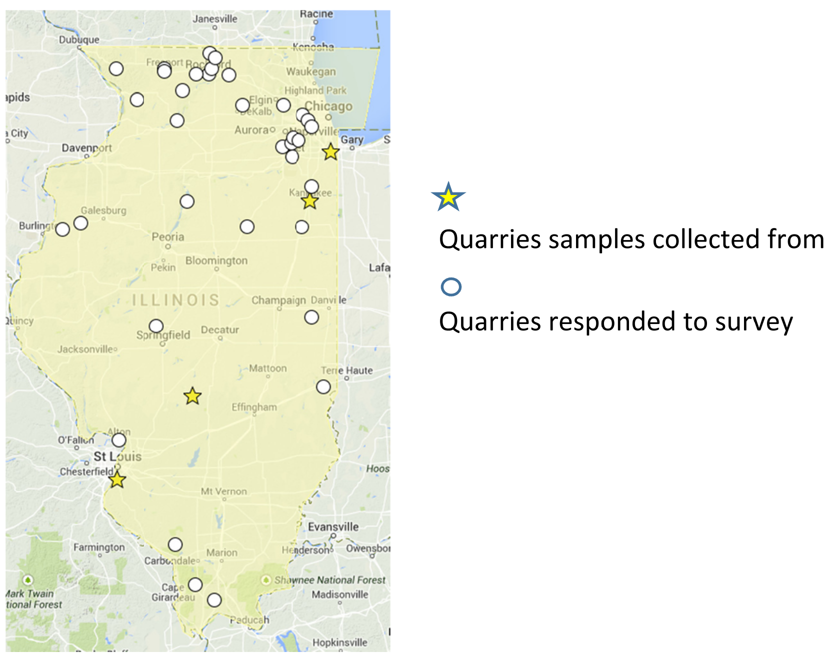


Figure 11. Location of four quarries for sample collection.

4.1.2 Sampling from Different Crushing Stages

In general, the materials were sampled from three main crushing/screening stages—primary, secondary, and tertiary—when they were available during active aggregate production. All the crusher types used by Quarry 1 were compression crushers. Secondary and tertiary production stages use cone compression crushers, and primary crushing is done with a gyratory compression crusher. Crusher types used by Quarries 2, 3 and 4 were not known.

Because only two main crushing/screening stages were utilized on site for Quarries 3 and 4, samples were collected from the primary and tertiary stages. Figure 12 shows the complete set of samples collected for laboratory testing.

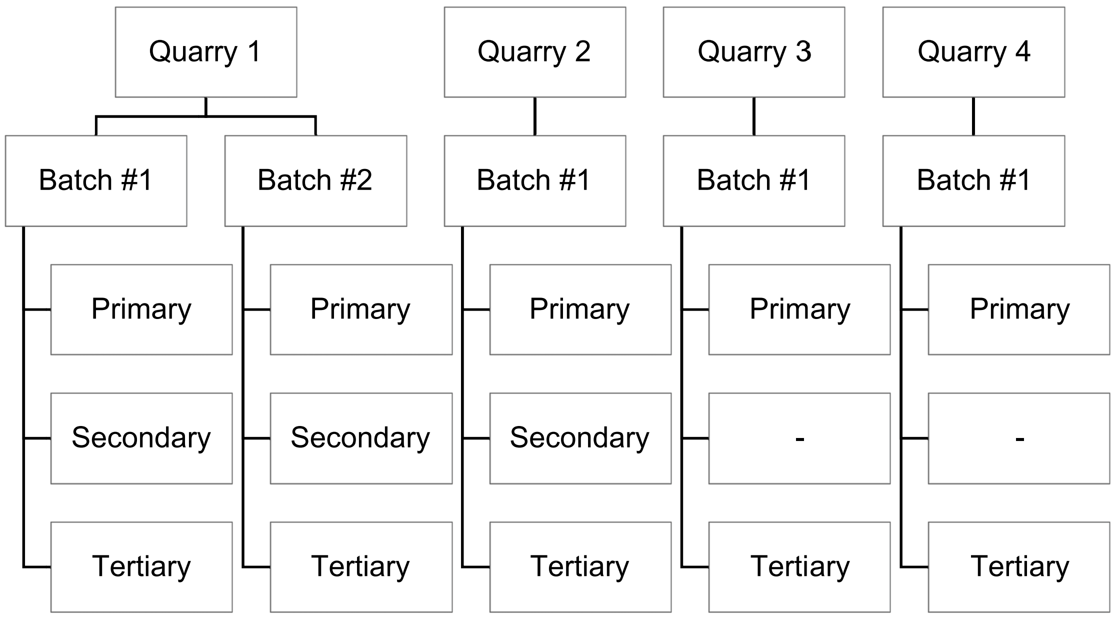


Figure 12. Laboratory testing sample sets.

Figure 13 shows pictures of the samples collected from the first batch at Quarry 1, from the primary crushing stage, secondary crushing stage, and tertiary crushing stage. The materials from the primary stage appeared coarser and more rounded in shape. Materials from the secondary and tertiary stages looked similar, with finer size and flatter and more elongated shape.

(a) (b) (c)

Figure 13. Samples collected from Quarry 1 first batch:
(a) primary stage, (b) secondary stage, (c) tertiary stage.

4.1.3 Experimental Program

The scope of the experimental program included gradation, moisture density relationship, and strength characteristics of QB samples collected inform the crushing stages shown previously in Figure 12. In addition to sieve analysis and imaging-based aggregate shape property testing, modified methylene blue (MMB), moisture density, Atterberg limits, unconfined compressive strength (UCS), and direct shear tests were conducted on the QB samples collected from the Quarry1. X-ray diffraction test results were provided for the Quarry 1 samples. Chemical oxide compositions of QB samples obtained from X-ray diffraction were used to determine adequacy for admixture treatment.

The scope of the experimental program for the samples collected from Quarries 2, 3, and 4 was limited to the major engineering properties—sieve analysis, MMB, Atterberg limits, moisture density, and UCS.

A summary of the experimental framework is illustrated in Figure 14. In addition to the experiments listed for virgin QB samples, chemical admixture-treated samples were evaluated by the standard Proctor test and UCS test. Both Portland cement and Class C fly ash were considered as chemical admixtures to treat QB samples for strength gains.

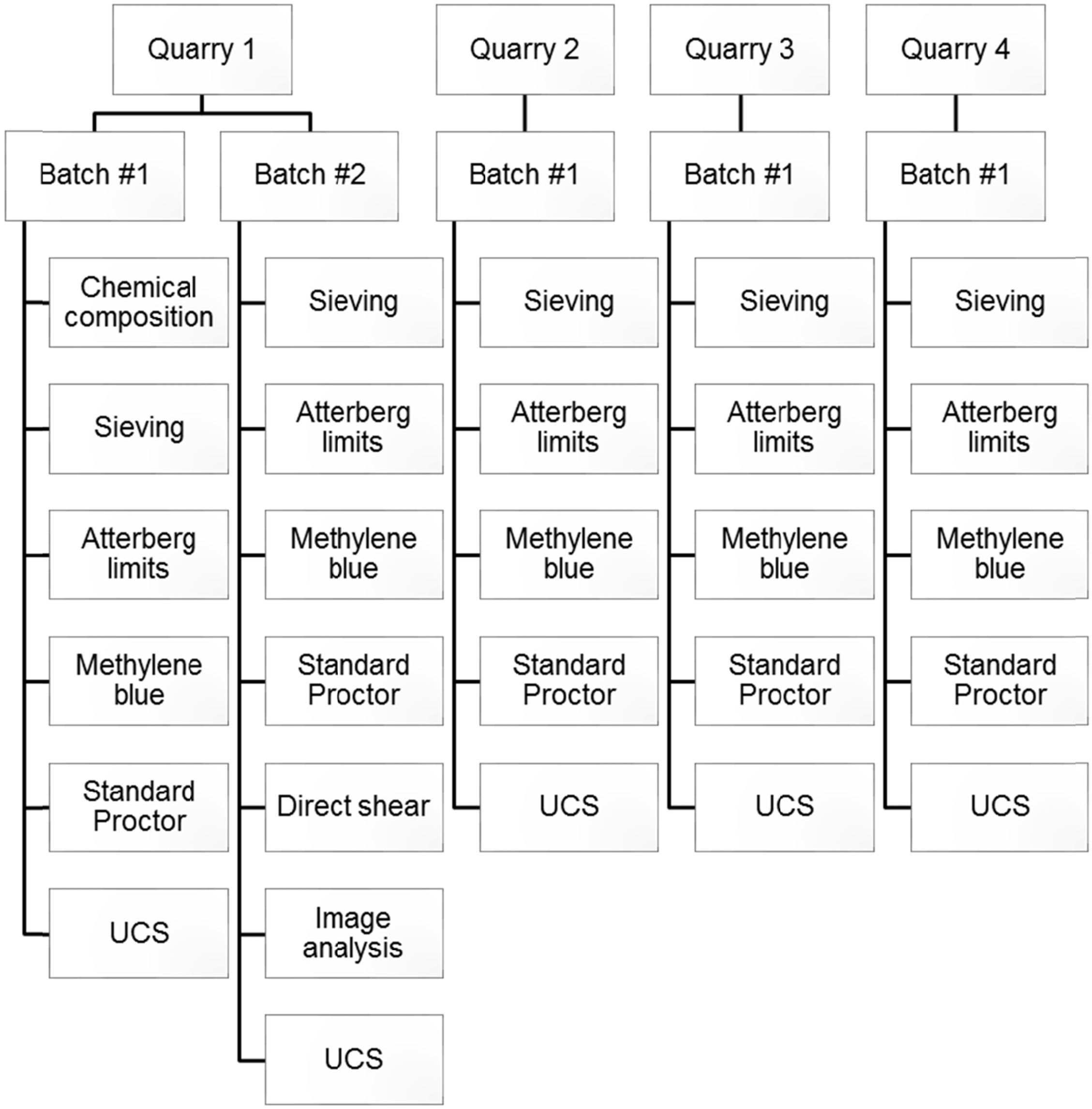


Figure 14. Experimental program for the QB samples collected from Quarries 1–4.

4.2 LABORATORY CHARACTERIZATION OF UNTREATED QUARRY BY-PRODUCT

4.2.1 Chemical Composition

Table 3 presents X-ray diffraction results of the aggregate by-product compositions for the quarry by-product samples obtained from Quarry1. As shown in the table, calcium and magnesium carbonates are the major components of the aggregate by-products, indicating that the by-products were obtained from dolomitic-type parent rocks. As expected, there were no substantial differences in the oxide compositions of the aggregate by-products from the three crushing stages. The secondary and tertiary crusher by-products were similar in mineralogy. Compared with the secondary and tertiary crusher by-products, the primary crusher QB samples exhibited only a slight difference in chemical composition.

Table 3. Summary of Mineralogical Composition of Quarry By-Products Sampled from Quarry 1

Crushing Stage	$CaCO_3$	$MgCO_3$	SiO_2	Al_2O_3	Fe_2O_3	Mn_2O_3	SO_3	K_2O	P_2O_5	Total
Primary	49.65	38.47	8.56	1.46	0.80	0.04	0.33	0.64	0.04	99.99
Secondary	50.27	40.52	6.62	1.05	0.66	0.04	0.20	0.53	0.04	99.93
Tertiary	50.38	40.47	6.63	1.03	0.65	0.04	0.20	0.52	0.04	99.97

4.2.2 Harmful Clay Content

Clay contents of the aggregate by-products were determined from a modified methylene blue (MMB) test. The test was used for a quick assessment of the amount of harmful clay in the fines portion of the aggregates (Pitre 2012). The main components of the MMB test kit are scale, methylene blue test solution, testing tubes, syringes, calorimeter, and adjustable micro-pipette (Figure 15).

Figure 15. Methylene blue test kit.

Table 4 presents the results obtained for samples collected from each quarry. In general, harmful clay content comprised less than approximately 3% of fines in the QB samples. There was some variation between quarries and within quarries. For the two batches collected from Quarry 1, almost similar clay content was observed, and an average was taken to represent the clay content for those samples. The harmful clay content of Quarry 1 samples was lower than that of the samples collected from other quarries.

In general, slightly higher clay content was observed in quarry by-products from the primary crushing stage except at Quarry 3, where higher clay content was observed from samples collected during the tertiary crushing stage. The higher clay content in aggregate by-products from the primary crushing stage is possibly the result of weathered rock or overburden material, which are more likely to be found in the quarried rocks in the primary crusher.

Table 4. Harmful Clay Content in Aggregate By-Products Sampled from Quarries 1–4

Quarry	Crushing Stage	Clay Content (%)
1	Primary	1.24*
	Secondary	0.57*
	Tertiary	0.28*
2	Primary	2.40
	Secondary	2.30
	Tertiary	2.00
3	Primary	2.70
	Tertiary	3.20
4	Primary	3.20
	Tertiary	3.10

*Represents the average of the first- and second-batch samples.

4.2.3 Grain Size Distribution

Particle size distribution is of significant importance because of its major influence on the performances of bound and aggregate pavement layers. Owing to the variety of parent rock types and the different crushers and technology used in the various aggregate production stages, the particle shape and size of aggregate by-products may differ from one another. To quantify these differences, grain size distribution was determined using sieve analysis. Quarry by-products were compared based on the quarry locations and crushing stages.

Dry sieve analysis was conducted on all quarry by-products; the results are summarized in Table 5. The table shows the particle size distributions of aggregate by-products determined according to the ASTM D422 method. Gradation results are shown for samples from each quarry and different crushing stages. The aggregate by-products from Quarries 1, 2, and 3 have a nominal maximum size of 4.75 mm (No. 4 sieve). About 2% of the aggregate by-products sampled from Quarry 4 and the tertiary crusher were found to be slightly larger than 4.75 mm (0.19 in.). The amount of particles finer than 0.075 mm (No. 200 sieve) ranges from 7% to 15% for all quarry samples.

Table 5. Particle Size Distributions of Aggregate By-Products for Quarries 1–4

	Quarry_1[a]			**Quarry_2**			**Quarry_3**		**Quarry_4**	
	Primary	**Secondary**	**Tertiary**	**Primary**	**Secondary**	**Tertiary**	**Primary**	**Tertiary**	**Primary**	**Tertiary**
Sieve Size (mm)	**Percentage Passing**									
9.5	100	100	100	100	100	100	100	100	100	100
4.75	100	100	100	100	100	100	100	100	100	98
2.36	76	66	74	81	79	84	61	96	79	75
1.18	52	43	47	55	54	54	40	71	58	52
0.6	34	29	31	34	40	37	28	52	44	39
0.3	21	21	22	22	29	27	19	37	33	30
0.15	15	15	16	15	20	20	11	24	22	21
0.075	10	10	11	10	13	15	7	15	13	14

[a]: Averages of the two batches.

To illustrate the general trend in the gradation of aggregate by-products, the particle size distribution for all aggregate by-products are presented in a gradation plot in Figure 16. That figure shows that all the aggregate by-products follow well-graded types of gradation except for the aggregate by-products from the tertiary production stage from Quarry 3. Detailed gradation comparison between batches and crushing stages, as well as from the various quarries, can be found in Appendix A.

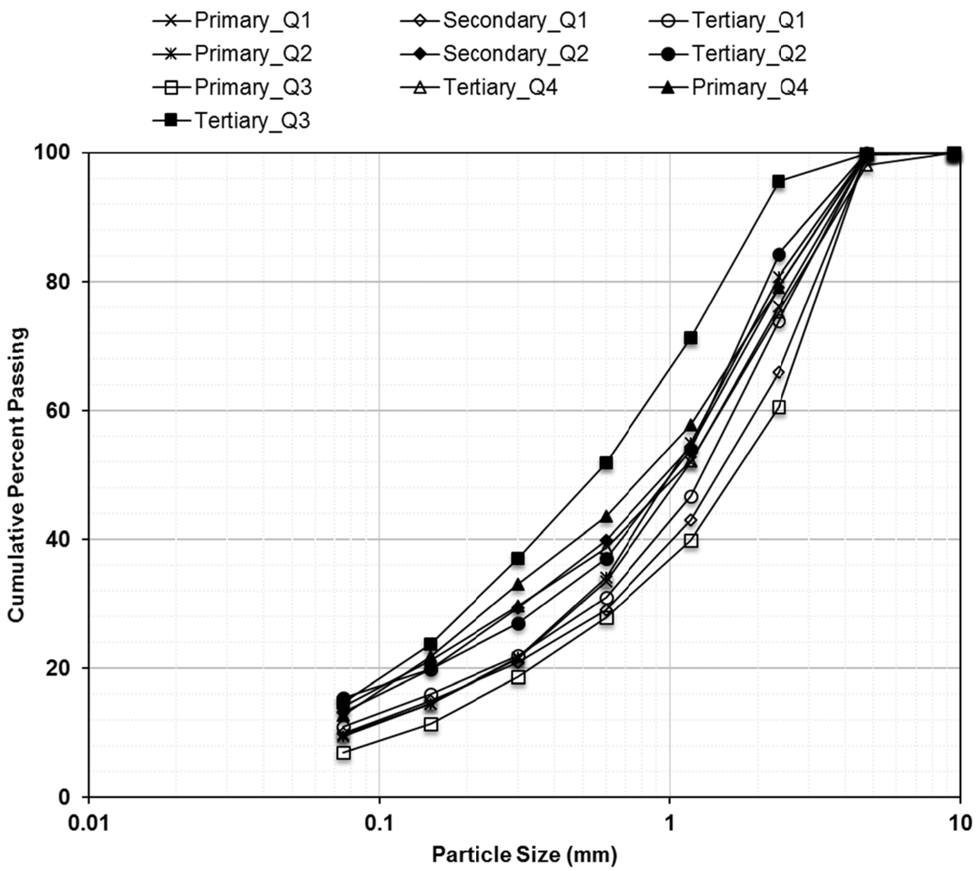


Figure 16. Gradation bands for aggregate by-products for all quarry locations.

Fineness modulus (FM) was also used to quantify the differences in the gradations and particle size distributions of quarry by-products. Fineness modulus is defined mathematically as the sum of cumulative percentages retained on the standard sieves. It is generally used to determine the coarseness and fineness of aggregates. As summarized in Table 6, the FM varied from 2.86 to 4.05.

Based on the FM values and gradation charts, it was concluded that the samples from Quarries 1, 2, and 4 had similar gradation characteristics between different crushing stages. Major differences between crushing stages were observed only with the samples collected from Quarry 3.

In general, aggregate by-products from the primary crushing stage had a higher FM value than that of the samples collected from the subsequent crushing stages for all quarries considered. This implies that primary crusher samples are coarser than the samples from the crushing stages. The aggregate by-products collected from the tertiary crushing stage of Quarry 3 showed the lowest value of FM among all of samples collected, as shown in Table 6, which also shows the differences observed in the FM values. Detailed gradation charts for all samples collected can be found in Appendix A.

Table 6. Fineness Modulus of Samples Collected from Quarries 1–4 at Different Crushing Stages

Quarry	Crushing Stage	Fineness Modulus
1	Primary	4.05*
	Secondary	4.29*
	Tertiary	4.29*
2	Primary	3.92
	Secondary	3.70
	Tertiary	3.69
3	Primary	4.64
	Tertiary	2.86
4	Primary	3.53
	Tertiary	3.81

*Represents the average of the first- and second-batch samples.

The results for the two batches collected from the Quarry 1 are also presented separately in order to illustrate the differences in batches collected at different times. For two batches of aggregate by-products sampled at different times from the same quarry, there was only a slight discrepancy in the general trends of the particle size distribution curves. The gradations of the QB samples were compared based on the production stages and the batch numbers. Accordingly, the FM modulus for each batch was calculated and tabulated, as shown in Table 7.

For both batches, aggregate by-products from the secondary and tertiary crushing stages showed very small differences in FM values. This implies that the particle size distributions of aggregate by-products from the secondary and tertiary crushing stages were almost similar.

Table 7. Fineness Modulus for the Two Sample Batches Collected from Quarry 1

	Primary	Secondary	Tertiary
Batch #1	4.31	4.42	4.30
Batch #2	3.80	4.15	4.27

4.2.4 Atterberg Limits

Atterberg limit tests were performed in accordance with the ASTM D4318-10 method. All QB samples from the four quarries and from different crushing stages were nonplastic, which indicates that QB samples had very low water-holding capacity.

Liquid limits were 14.0%, 13.1%, and 13.3% for the primary, secondary, and tertiary crusher materials from Quarry 1, respectively. The liquid limits of QB samples from the samples collected at other quarries could not be determined because, after several trials at successively higher water contents, the soil pat continued to slide in the cup and the number of blows required to close the groove was always less than 25.

4.2.5 Soil Classification

The first batch of QB samples from the primary, secondary, and tertiary crushing stages at Quarry 1 had coefficients of curvature (c_c) of 2.4, 3.3, and 4.2 and uniformity coefficients (c_u) of 15, 30, and 37.5, respectively. Materials from the second batch of QB samples had c_c of 2.0, 2.1, and 2.9 and c_u of 22, 25, and 26, respectively.

On the basis of the AASHTO Soil Classification System, all the QB samples were classified as A-2-4, which represented silty gravel and sand. On the basis of the Unified Soil Classification System (USCS), the QB samples from the first batch from Quarry 1 were classified as well-graded silty sand (SW-SM), poorly graded silty sand (SP-SM), and silty sand (SM), for the primary, secondary, and tertiary crushing stages, respectively. The second-batch QB samples from Quarry 1 were all classified as SW-SM. Similarly, all QB samples from the other three quarries and different crushing stages were classified according to USCS.

It can be seen in Table 8 that both samples from the primary crushing stages at Quarry 2 and Quarry 3 were classified as SW-SM, and the samples from the secondary and tertiary crushing stages from the two quarries were classified as SM, indicating a higher amount of fine materials passing No. 200 sieve were produced from the secondary and tertiary crushing stages. But that was not the case for QB samples from Quarry 4, which were all classified as SM, with more than 12% of the fines passing No. 200 sieve.

Table 8. USCS Classifications of all QB Samples

Quarry Number	Crushing Stage	Batch #1	Batch #2
1	Primary	SW-SM	SW-SM
	Secondary	SP-SM	SW-SM
	Tertiary	SM	SW-SM
2	Primary	SW-SM	—
	Secondary	SM	—
	Tertiary	SM	—
3	Primary	SW-SM	—
	Tertiary	SM	—
4	Primary	SM	—
	Tertiary	SM	—

4.2.6 Image Analysis and Aggregate Shape, Texture, and Angularity

Aggregate particle shape, texture, and angularity have been recognized as influencing the engineering behavior of unbound aggregates. The aggregate image analysis system, Enhanced University of Illinois Aggregate Image Analyzer (E-UIAIA), used in this study is an improvement over the older version because it is equipped with three high-resolution (1292 × 964 pixels) charge-coupled device, progressive-scan color cameras to capture three orthogonal views (front, top, and side) of individual particles to establish the morphological indices of aggregate particle shape, texture, and angularity. More details on the features of the E-UIAIA can be found elsewhere (Moaveni et al. 2013). Figure 17 shows the E-UIAIA and an example of the three orthogonal views of a particle captured by the camera system.

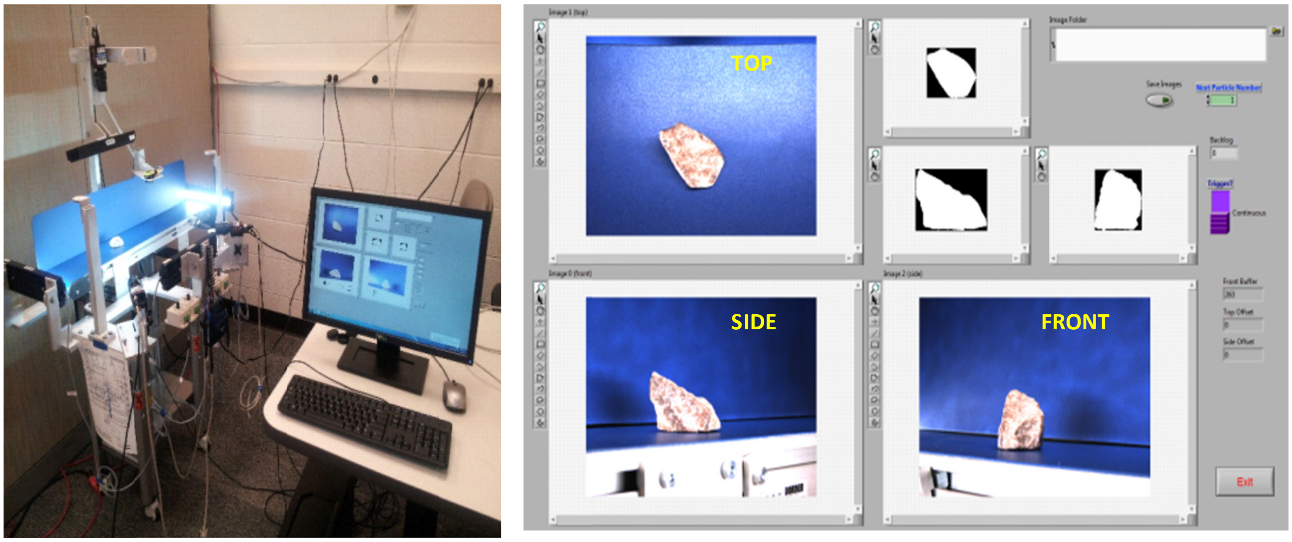


Figure 17. E-UIAIA and the particle front, top and side views captured. (Moaveni et al. 2013)

The flat and elongated (F&E) ratio and angularity index (AI) were the key indices—measured with the E-UIAIA—for determining physical properties of QB. Image-based analysis to determine particle shape properties was conducted only for Quarry 1 samples because the experiments conducted later on samples from Quarries 2, 3, and 4 were more focused on sample classification and strength testing for potential application.

Approximately 100 particles retained on the No.8 (2.38 mm) sieve were scanned for each material from the second batch of Quarry 1 to determine trends in particle shape. Average AI values for QB materials from the primary, secondary, and tertiary crushers were 497, 550, and 542 cumulative degrees, respectively. QB samples from the primary crusher had the lowest AI value indicating the least angular particles. The samples from the secondary crusher had slightly higher value than the samples from the tertiary crusher.

These findings supported the visual assessment that primary QB samples are often rounder and that QB from the secondary crusher were more angular. Average F&E ratios for QB materials from the primary, secondary, and tertiary crushers were 2.3, 3.2, and 3.3, respectively.

Another trend observed was that QB from the primary crusher had the lowest F&E ratio and that QB from the secondary and tertiary crushers had very close F&E ratios. These findings indicated that particles from the primary crusher were more cubical and therefore may have better resistance to breakage.

4.2.7 Standard Proctor Test

In accordance with ASTM D698, the moisture density compaction characteristics of the virgin QB samples were evaluated from the four quarries sampled in this study; the results are summarized in Table 9. For all aggregate by-products from different quarry locations, the optimum moisture content (OMC) from standard Proctor tests ranged from 7.9% to 10.4%, whereas the maximum dry density ranged from 129.7 to 142.1 pcf (20.4 to 22.3kN/m^3). In general, the maximum dry density and OMC varied from one quarry location to another. While there was no unique trend for the variation of OMC, for all quarry locations, higher maximum dry density values were observed in aggregate by-products from the primary crushing stages. Detailed moisture density curves for each material can be found in Appendix B.

Table 9. Summary of Optimum Moisture Content and Maximum Dry Density for Virgin Aggregate By-Products

Virgin Aggregate By-Products			
Quarry	Crushing Stage	Optimum Moisture (%)	Maximum Dry Density (pcf)
1	Primary*	9.0	142.1
	Secondary*	8.6	138.6
	Tertiary*	10.4	133.9
2	Primary	9.1	135.3
	Secondary	10.1	132.0
	Tertiary	8.6	135.4
3	Primary	9.7	133.0
	Tertiary	9.2	129.7
4	Primary	7.9	136.3
	Tertiary	8.7	133.8

*Moisture density conducted on the first batch

4.2.8 Direct Shear Test

To determine shear strength properties of QB samples, direct shear tests were conducted on samples from batch 2 of Quarry 1 using an automated pneumatic direct shear testing device, following the ASTM D3080 method. The tests were performed on square prismatic specimens 4 in. in size with a thickness of 1 in., at shear rate of 0.005 in. /min.

Figure 18 shows a representative sample prepared for the direct shear test. All the QB specimens were conditioned for a minimum of 3 hours at their optimum moisture contents and compacted to 95% of their maximum densities, per the standard Proctor test results discussed in the previous section. Because of a lack of material from the first batch, the direct shear tests were conducted only on QB samples from the second batch under three normal stress conditions: 0, 15, and 20 psi. Two test repetitions were conducted at each normal stress.

The results for all 18 direct shear tests performed are presented in Figure 19(a), which shows the relationships observed between the normal stress and the maximum shear stress; the R^2 values are greater than 0.8. The friction angles obtained for all the primary, secondary, and tertiary crusher QB samples are near 59°. This relatively high value may relate to the proper compaction and confinement conditions of the specimens.

To assess the behavior of QB materials during the shearing phase, the applied shear force and vertical displacement obtained during testing were studied with the horizontal displacements measured. Figure 19(b) shows typical test results obtained under 10 psi normal stress applied. Note that the three QB materials have similar responses to shearing. The shear stress increased with shear displacement until the maximum peak failure condition and then gradually decreased. Dilative characteristics of the samples from the three crushing stage were similar with some reduction in the tertiary stage.

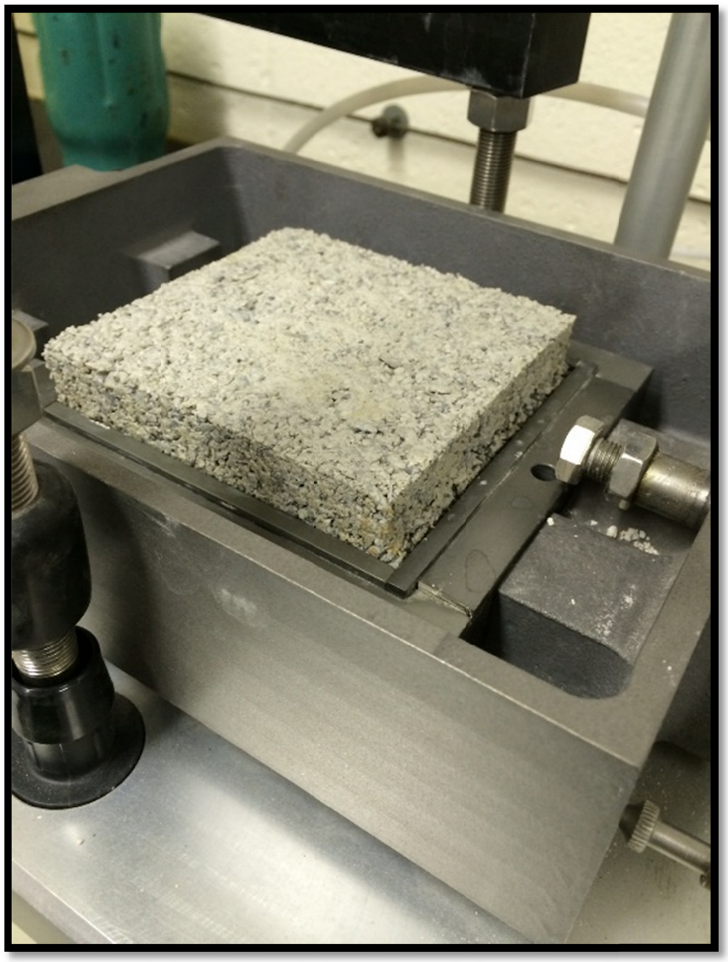
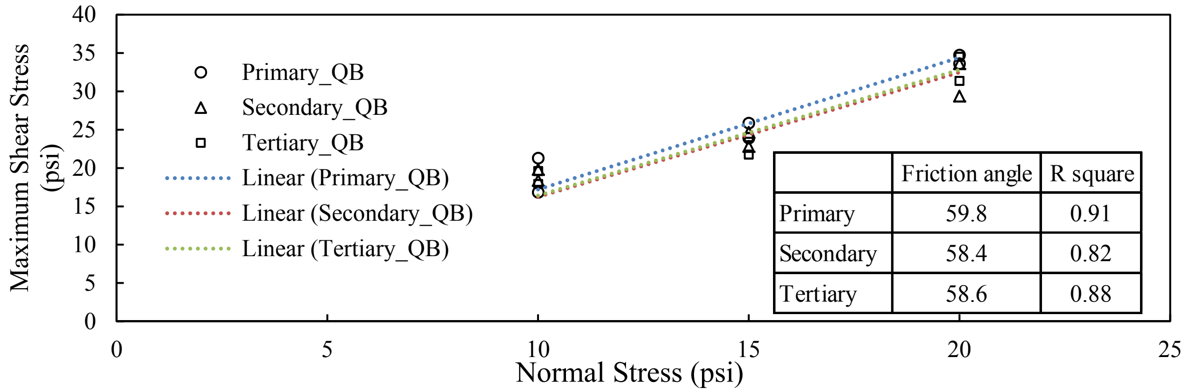


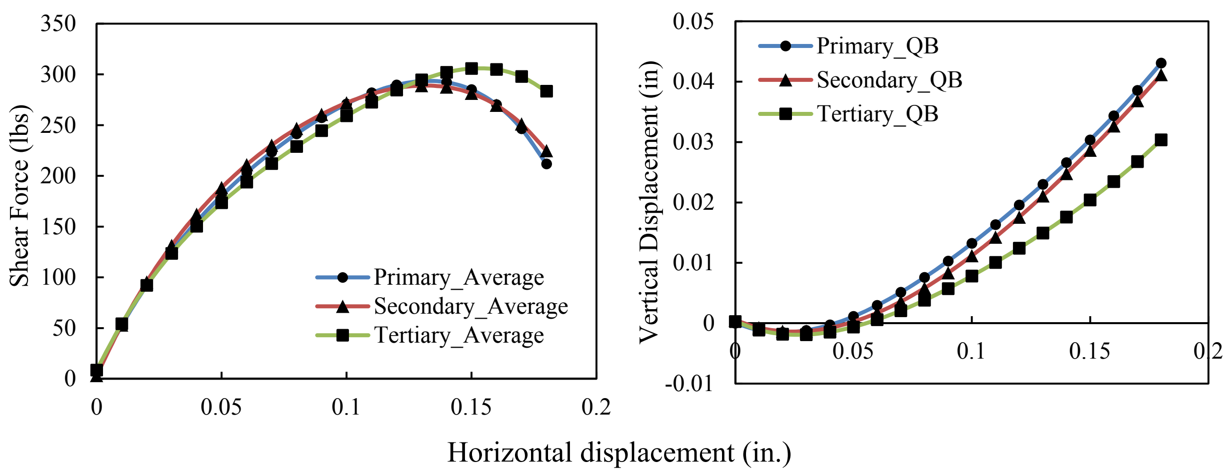
Figure 18. A sample prepared for the direct shear test.

4.2.9 Unconfined Compressive Strength Test

To better evaluate the strength of QB samples under more critical unconfined conditions, unconfined compressive strength (UCS) tests were performed on QB samples from all four quarries. The maximum dry density and the optimum moisture content data obtained from the moisture density characteristics of virgin materials were used to prepared samples for testing. Four samples from Quarry 1, 2.8 in. diameter by 5.6 in. high, were prepared for conducting the UCS tests for each QB material, in accordance with the ASTM D2166 method. Because of the limited amount of batch #1 materials received, only one sample was tested for each of the primary, secondary, and tertiary production stages, but three samples were tested for each production stage from batch #2. The UCS values decreased from the primary crusher QB (average value of 10.5 psi) to the secondary crusher QB (8.8 psi) to the tertiary crusher QB, which exhibited the lowest UCS value (3.3 psi).



(a)



(b)

Figure 19. Direct shear test results: (a) maximum shear stress under different normal stresses; (b) shear force and vertical displacement varying with horizontal displacement at 10 psi normal stress.

Two samples from each of the other three quarries were prepared for UCS tests for each QB material from different crushing stages, in accordance with the ASTM D2155 method. For samples from Quarry 2, the UCS values decreased from the primary crusher QB (average value of 8.9 psi) to the secondary crusher QB (4.4 psi) but then increased for the tertiary crusher QB (6.4 psi). For samples from Quarry 3, the UCS values decreased from the primary crusher QB (average value of 5.0 psi) to the tertiary crusher QB (2.9 psi). For samples from Quarry 4, the UCS values for both crushing stages were the same with an average value of 8.1 psi.

In Figure 20, UCS values were plotted with the maximum densities obtained from the standard Proctor tests. In that figure, it can be seen that all QB samples generally exhibited low UCS values—less than 14 psi. In addition, there is a clear relationship between UCS and the maximum dry density obtained. For samples from the same quarry source, the higher maximum dry density, the larger the UCS it achieves. This emphasizes the importance of good compaction in the field if QB samples are to be used in future applications.

Overall, the compressive strength values of the QB materials were low, indicating the need for improvement through stabilization depending on the strength requirements for various highway construction applications. The trials with two commonly used stabilizing agents will be discussed in the next section.

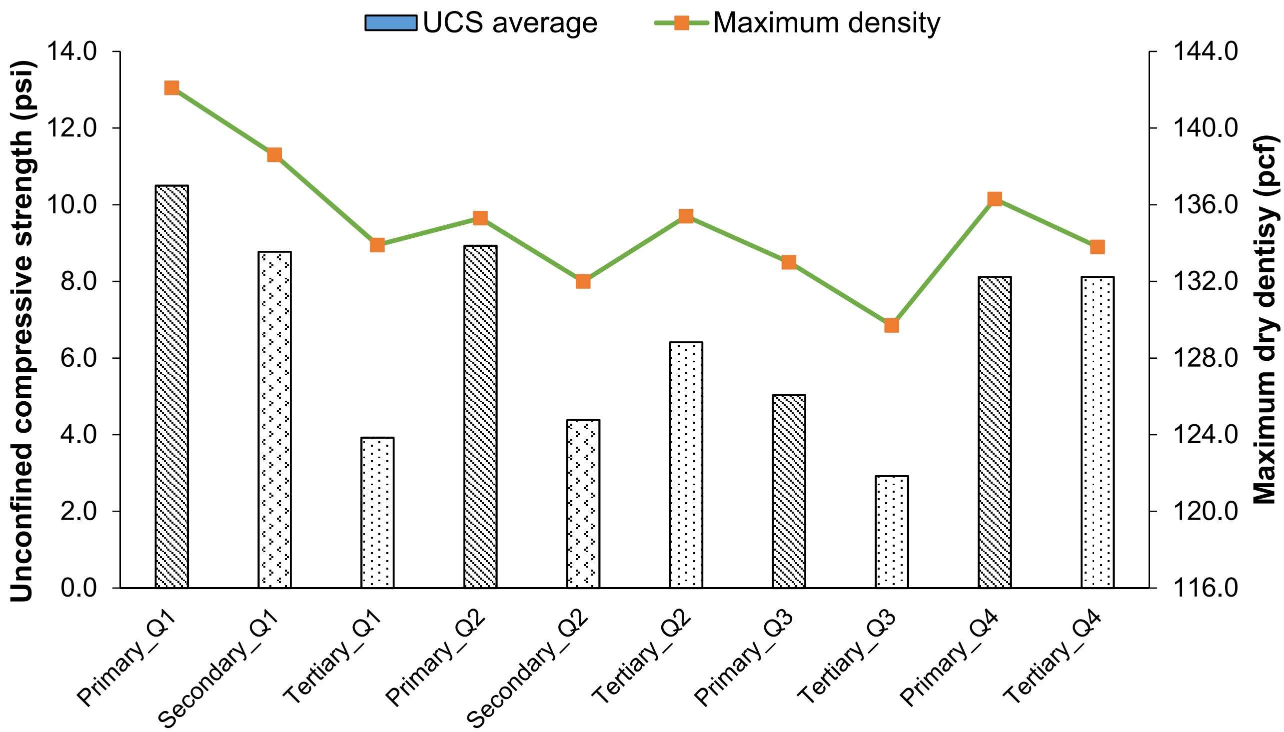


Figure 20. Unconfined compressive strengths and maximum dry densities obtained for virgin QB materials (Q1 through Q4 refer to Quarry 1 through Quarry 4).

4.3 STABILIZATION OF QUARRY BY-PRODUCTS

4.3.1 Selection of Stabilizers

To increase the strength properties of the QB samples, chemical stabilizers were chosen. While chemical stabilization of soil and aggregates improves their physical and engineering properties, this process depends heavily on the chemical reaction between soil/aggregates and the stabilizers. It is therefore important to choose the right stabilizers to effectively improve the strength. The rationale behind the selection of stabilizers is to obtain maximum strength gain with lowest cost and environmental impact.

According to the summary of literature provided in Chapter 2, stabilization using low-cement contents appeared to be a cost-effective alternative successfully used in stabilizing quarry by-products. In addition, lower cement content has the benefit of reducing shrinkage potential of cemented materials.

Two-percent Type I Portland cement by weight of oven-dry aggregate by-products was used as the stabilizer in this study. The second choice was fly ash, a by-product of a different industry. Like cement, Class C fly ash possesses cementitious and pozzolanic properties that do not depend on the reaction with clay particles to develop strength. The percentage of Class C fly ash used in this study varied from 5% to 10% to improve the strength properties of aggregate by-products.

4.3.2 Standard Proctor Test on the Stabilized Materials

To increase the strength properties of the aggregate by-product samples, 2% Portland cement, 5% and 10% Class C (self-cementing) fly ash, were used as stabilizers. The Class C fly ash material conformed to ASTM C618 and AASHTO M295 standards. The compaction curves were determined per the ASTM D558 method for the aggregate by-product samples treated with both stabilizers. The compaction curves are provided in Appendix B.

The optimum moisture contents and maximum dry densities determined are listed in Table 10. Owing to more effective results obtained by 10% Class C fly ash, 5% Class C fly ash was used only with the QB samples from the first batch in the Quarry 1.

As shown in Table 10, the optimum moisture content for 2% cement-treated quarry by-products ranged from 6.6% to 9.9% and 7% to 8.3% for 10% Class C fly ash–treated aggregate by-products. There was no clear trend on how optimum moisture content and maximum density changed with quarry location and crushing stages.

In general, smaller values of optimum moisture content and higher values of maximum dry density were observed for 10% Class C fly ash–treated QB than for 2% cement-treated QB. Such a difference in the characteristics of aggregate by-products stabilized with Portland cement and Class C fly ash was attributed to the differing amounts of free lime each stabilizer contributed during the flocculation and agglomeration of the treated QB samples.

Table 10. Summary of Optimum Moisture Contents and Maximum Dry Densities for (a) 2% Treated; and (b) 10% Class C Fly Ash–Treated Quarry By-Products

(a) 2% Cement-Treated By-Products			
Quarry	Crushing Stage	Optimum Moisture (%)	Maximum Dry Density (pcf)
1	Primary	9.6	137.9
	Secondary	9.2	135.9
	Tertiary	9.9	135.4
2	Primary	7.8	135.7
	Secondary	7.8	132.8
	Tertiary	8.4	136.0
3	Primary	9.4	131.2
	Tertiary	9.1	133.0
4	Primary	6.6	135.4
	Tertiary	8.7	132.8

(b)		10% Class C Fly Ash (Batch #2)		5% Class C Fly Ash QB (Batch #1)	
Quarry	Crushing Stage	Optimum Moisture (%)	Maximum Dry Density (pcf)	Optimum Moisture (%)	Maximum Dry Density (pcf)
1	Primary	7.0	143.0	8	139.5
	Secondary	8.3	140.1	8.6	138.6
	Tertiary	8.0	141.2	8.6	135.6
2	Primary	7.8	134.4	—	—
	Secondary	7.7	136.3	—	—
	Tertiary	8.0	134.6	—	—
3	Primary	8.2	133.9	—	—
	Tertiary	7.8	133.1	—	—
4	Primary	7.2	139.0	—	—
	Tertiary	7.8	135.6	—	—

4.3.3 Unconfined Compressive Strength Test

Unconfined compressive strength (UCS) tests were also conducted on the QB in admixture-treated condition to evaluate the benefits of chemical admixture treatment and to show how treated samples of weak soils can be improved to achieve the desired strength.

The maximum dry density and the optimum moisture content data obtained from the moisture density characteristics of treated aggregate by-products were used to prepare the samples for the UCS tests. For samples from Quarry 1, two test repetitions were carried out per ASTM D1632 and ASTM D1633 for each of the 2% cement-treated materials. Because of the shortage of materials from the first batch of QB samples from Quarry 1, the 5% and 10% Class C fly ash stabilization was used with only the second batch of QB materials. Three repetitions were performed for each sample with Class C fly ash treatment.

Significant strength increases were found after treating QB specimens with all stabilizers. Later on, to verify the effectiveness of the cement and Class C fly ash treatments, more samples were collected from Quarries 2, 3, and 4. For those samples, two specimens from each crushing stage were prepared and tested. All the samples treated with admixtures were cured for 7 days at room temperature at 100% humidity. Before UCS testing, all stabilized samples were soaked for 4 hours to evaluate effects of a harsh, moist environment on strength properties.

Sample preparation and testing procedures for treated QB are shown in Figure 21.

Figure 21. Photos showing sample preparation and testing for treated QB.

Table 11 lists the summary UCS values obtained for all of the QB samples collected from the four quarries at different crushing stages. Detailed UCS values measured from the QB samples can be found in Appendix C.

It can be seen from the average of measured UCS that with proper admixture treatment, significant improvement of strength properties can be achieved. Virgin (untreated) aggregate by-products have very low UCS values, with an average of less than 11 psi.

Class C fly ash at 5% treatment was applied to Quarry 1 samples only. Strength increases of up to ten times were observed in those samples. When 10 % Class fly ash was used, strength gains were approximately 20 to 30 times the strength of the original untreated samples. The highest strength values with 10% fly ash were observed in Quarry 1 samples (more than 300 psi), whereas other quarry samples had relatively lower strength values of around 200 psi, except for the Quarry 2 tertiary crusher sample and Quarry 3 primary crusher sample.

On average, the 2% cement-treated specimens prepared for each of the QB crushing categories from each quarry had relatively consistent high UCS values above 200 psi. Virgin QB samples were strengthened by more than 20 times the initial strength by adding 2% cement. Approximately equivalent gains were achieved by 2% cement and 10% Class C fly ash treatment of QB samples.

Table 11. Average UCS for Virgin QB Materials and Treated QB Materials with 2% Cement, and 5% and 10% Class C Fly Ash

Quarry	Crushing Stage	Average UCS (psi)			
		Virgin	2% cement-treated	5% Class C fly ash–treated	10% Class C fly ash–treated
1	Primary	10.50	202	105	332
	Secondary	8.78	213	155	334
	Tertiary	3.93	205	114	343
2	Primary	8.93	254	—	202
	Secondary	4.38	270	—	193
	Tertiary	6.41	218	—	153
3	Primary	5.03	183	—	101
	Tertiary	2.92	215	—	205
4	Primary	8.12	389	—	297
	Tertiary	8.12	287	—	234

Despite the fact that both 2% cement-treated materials and 10% Class C fly ash–treated materials can reach significantly similar high strength values compared with virgin materials, differences were observed in some samples.

Figure 22 shows that 10% Class C fly ash treatment resulted in the highest strength gains for all the QB samples from Quarry 1 compared with other samples with the same fly ash and cement treatment for the same quarry samples. However, for samples from the other quarries, 10% Class C fly ash treatment was less effective than the 2% cement treatment. One possible reason is that materials with 10% Class C fly ash treatment from Quarry 1 achieved higher maximum dry density than achieved by the 2% cement treatment, while materials from the other quarries with the two treatments did not show such large difference in maximum dry density (see Figure 23). Higher density indicates better compaction with 10% fly ash to achieve more effective lime reaction, which led to higher compressive strengths after a 7-day curing period compared with the UCS values of the 2% cement-treated samples.

Accordingly, strength of QB from the same quarry is directly related to the density achieved for six out of the ten materials. For example, materials with 10% Class C fly ash treatment from Quarry 1 achieved higher maximum dry density than achieved by the 2% cement treatment, which resulted in higher compressive strength of Class C fly ash–treated materials. Similarly, materials from Quarry 2 primary and tertiary crushers treated with 2% cement achieved higher maximum dry densities and higher compressive strengths when compared with those treated with 10% Class C fly ash. Also, Quarry 3 tertiary crusher materials treated with 2% cement and 10% Class C fly ash achieved approximately the same maximum dry density and compressive strength characteristics.

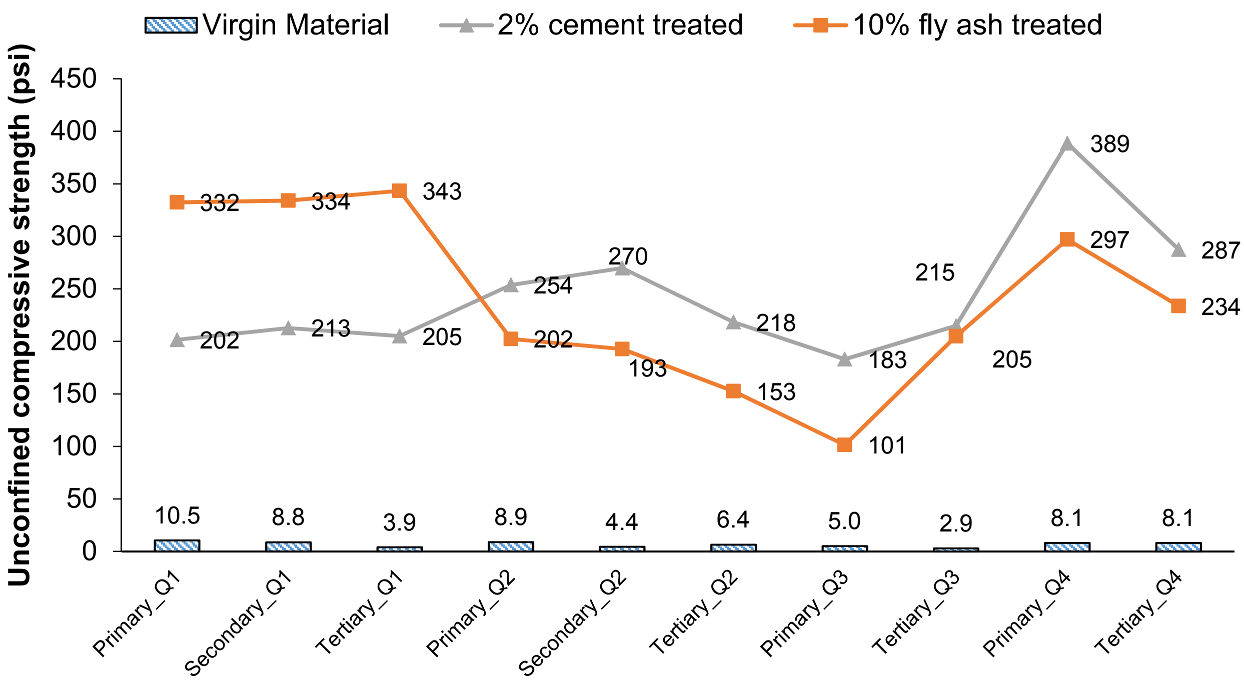


Figure 22. Average unconfined compressive strengths for virgin, 2% cement, and 10% Class C fly ash–treated QB materials.

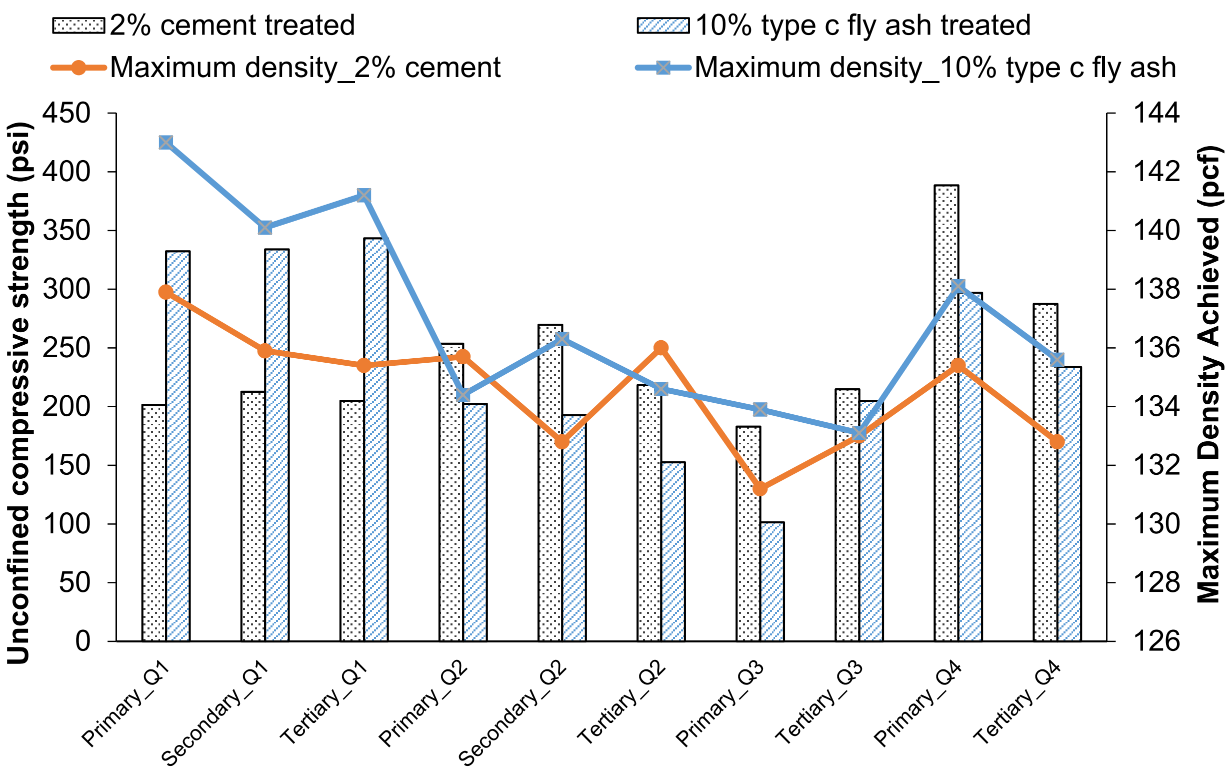


Figure 23. Average unconfined compressive strengths and maximum dry densities obtained for 2% cement-treated and 10% Class C fly ash–treated QB materials.

However, for the other four materials tested (from the secondary crusher at Quarry 2, the primary crusher at Quarry 3, and the primary and tertiary crushers at Quarry 4), achieved maximum dry density trends did not correlate well with the compressive strength characteristics. One possible reason could be related to gradation and particle packing effects.

To address the gradation and particle packing concerns, recent work at the University of Illinois has also focused on investigating the effect of cement and Class C fly ash–stabilized QB gradation on the unconfined compressive strength. The QBs from Quarry 3 were size separated and engineered to match certain gradation curves that are power exponents of the ratio of the sieve size to the maximum particle size according to the Fuller curve (also known as the Talbot equation). To compare the gradation and packing effect, densities and moisture contents for each engineered gradation were set the same as maximum density and optimum water content for the original gradation obtained in the lab. Densities achieved were 132.1 pcf and 133.5 pcf for cement and fly ash–stabilized QB samples, respectively. Water contents targeted were 9.25% and 8.0% for cement and fly–ash stabilized QB samples, respectively. Two replicates were tested for each engineered gradation. Accordingly, stabilized QB samples from Quarry 3 had varying strength properties at different engineered gradations. The engineered gradation with the power term “n” equals to 0.45 led to the highest shear strength characteristics for both the 2% cement and 10% Class C fly ash treatment (see Figures 24 and 25).

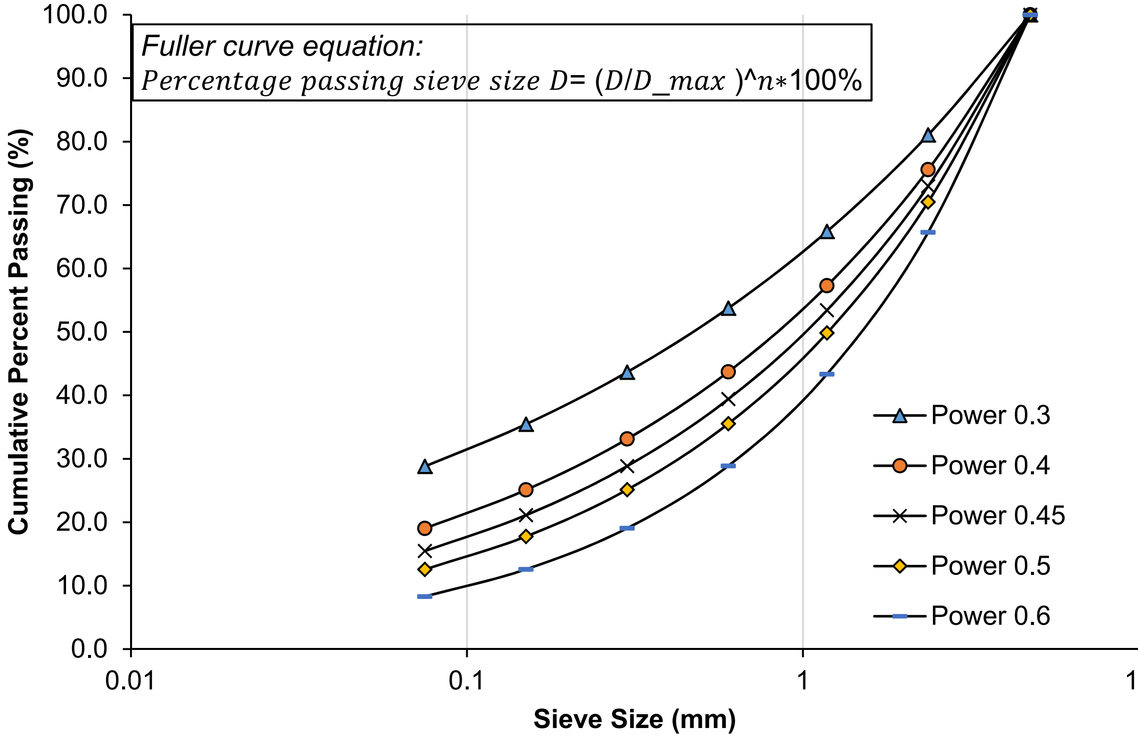


Figure 24. Engineered gradations of stabilized QB samples from Quarry 3 generated according to Fuller power curve (Talbot equation).

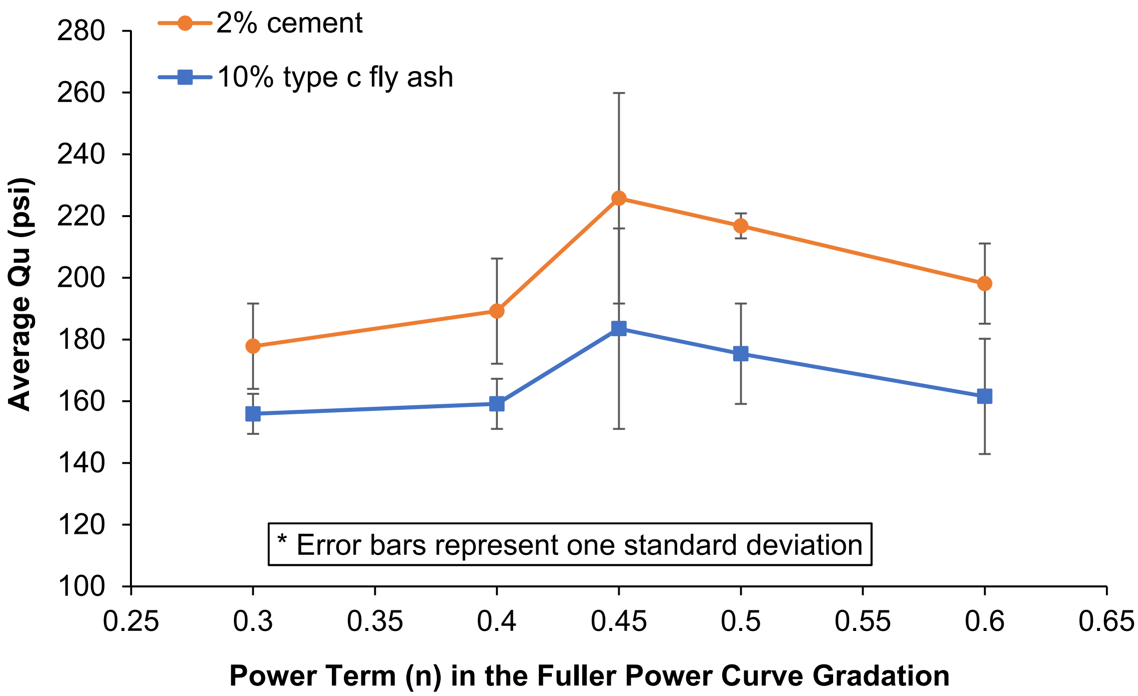


Figure 25. Unconfined compressive strength properties of stabilized QB materials at different engineered gradations according to Fuller power curve (Talbot equation).

The original QB gradations were checked with the engineered gradations for the “n” power values of 0.3, 0.4, 0.45, 0.5, and 0.6. The range of power value (n) found for the original QB gradations is summarized in Table 12. For example, the gradation of QB from primary crusher from Quarry 1 lies between gradation curves of n = 0.4 and 0.6. As stated previously, four out of the ten materials (i.e., the secondary crusher from Quarry 2, primary crusher from Quarry 3, and the primary and tertiary crushers from Quarry 4), did not exhibit strong correlations between density and strength. For the QB material from the Quarry 3 primary crusher, this can be explained because the QB gradation curve is close to n = 0.6 power curve, as listed in Table 12. Therefore, possible explanations for a lower strength of the fly ash–treated materials are no sufficient packing and relatively larger particle sizes diminishing the effectiveness of the fly ash reaction with QB particles. In addition, the secondary crusher QB material from Quarry 2 had higher strength compared with the primary crusher and tertiary crusher QB materials even though the secondary crusher QB material had the lowest density achieved. One possible reason for this finding is better packing of the secondary crusher QB materials from Quarry 2 because its gradation is very close to the n = 0.45 maximum density gradation curve.

Table 12. Original QB Sample Gradations Compared with Power Curve Engineered Gradations

Quarry	Crushing Stage	Range of Engineered Gradation Power (n); see Figure 23
1	Primary	0.4-0.6
	Secondary	0.45-0.6
	Tertiary	0.45-0.6
2	Primary	0.3-0.6
	Secondary	0.3-0.45 (very close to 0.45 curve)
	Tertiary	0.3-0.45 (close to 0.45 curve)
3	Primary	close to 0.6 curve
	Tertiary	0.3-0.45
4	Primary	0.3-0.5 (close to 0.4 curve)
	Tertiary	close to 0.45 curve

For the unstabilized QB, it appears that density is the main factor dominating the strength of QB such that high densities correlate to high UCS values for all four quarry materials. On the other hand, for stabilized QB materials, density is only one of many factors that may control strength. Other dominating factors might include gradation, particle shape and angularity, and the uniformity of distribution of the stabilizers within the soil, as well as the effectiveness of stabilizer.

Effectiveness of a stabilizer is indicated by an improvement in the stiffness and strength characteristics of unbound aggregates. Note that QB materials from Quarry 1 were tested and characterized for engineering properties first; the rest of the QB materials from the other 3 quarries were tested ten months later. Class C fly ash has a shelf life that depends on storage conditions, and the effectiveness of fly ash is reduced with time as it hydrates in damp conditions. This may explain the reduction in the strength gains with three of the QB materials tested afterward. Thus, it is expected that fly ash was highly reactive when QB materials from Quarry 1 were tested, and the strength gains with 10% Class C fly ash were possibly higher than those for the 2% cement-treated samples, as well as for the other QB materials stabilized with 10% Class C fly ash.

It was shown on the basis of the UCS measurements that 2% cement, 5% Class C fly ash, and 10% Class C fly ash are all potential stabilizers that can be used with the aggregate by-products for strength improvement. However, given that fly ash is a by-product of coal-burning plants, the use of the Class C fly ash as an admixture for treating aggregate by-products can be a more cost-effective and sustainable pavement application.

4.4 SUMMARY

To evaluate the engineering properties of QB materials, samples were collected from four quarries. The impact of variability within the quarries and between the quarries' crushing/screening stages on physical and engineering properties was evaluated.

An experimental program using X-ray diffraction, modified methylene blue (MMB), sieve analysis, particle shape image analysis, moisture density, Atterberg limits, unconfined compressive strength (UCS), and direct shear testing was conducted to investigate the feasibility of using QB in pavement applications.

In addition, QB samples treated with Portland cement and Class C fly ash were evaluated based on the moisture density and UCS tests to determine their strength gain compared with the virgin QB materials.

On the basis of the results of laboratory testing, the following conclusions are offered:

1. The QB samples obtained from all quarry locations were essentially nonplastic.

2. According to the grain size distribution charts, the QB samples were silt and sand-sized particles. In two batches collected from the same quarry, there were observable differences in the UCS (untreated) values and the gradations of the QB samples obtained from the primary, secondary, and tertiary crushing stages. The changes in gradation characteristics could make QB samples either well-graded or poorly graded silty sand soil classifications.

3. An enhanced aggregate image analyzer was utilized to quantify QB particle shape properties for particle sizes retained on a No. 8 (2.38 mm) sieve. For materials from Quarry 1, QB particles collected from the primary crusher were more rounded and cubical in shape than the quarry fines collected from the other crushers.

4. The results from the standard Proctor moisture density tests showed that for all the virgin (untreated) and admixture-treated QB materials, maximum dry densities were in the range of 129.7 to 143 pcf (20.4 to 22.5 kN/m^3), and the optimum moisture contents were in the range of 6.6% to 10.4%. In general, the maximum dry density and optimum moisture content (OMC) of untreated aggregate by-products varied from one quarry to another. While no unique trend was found in the variation of OMC, higher maximum dry density values were observed in aggregate by-products from the primary crushing stages. On the other hand, the OMC and maximum dry density of the treated aggregate by-products were highly dependent on the type of stabilizer used. Compared with cement-stabilized QB, higher maximum density values and lower OMC were observed for Class C fly ash–treated by-products.

5. For Quarry 1, materials from the three crushing stages showed similar trends in shear strength characteristics. A rather high friction angle of approximately 59° was obtained for all QB samples tested in a direct shear apparatus under adequate confinement.

6. All QB materials from the four quarries with different geological locations in the State of Illinois exhibited low UCS values. Moreover, the UCS values were found to be directly related to the maximum dry density achieved during the standard Proctor test. For each QB material, the higher the achieved maximum dry density, the higher the UCS value. This finding emphasizes the importance of proper compaction in the field when utilizing QB materials.

7. Significant increases in UCS values were achieved for the stabilizers tested (2% Portland cement, 5% Class C fly ash, and 10% Class C fly ash). The 2% cement and 10% Class C fly ash–treated materials were able to achieve at least 100 psi (689.5 kPa) strength. The strength properties of the stabilized QB materials could be influenced by gradation, particle packing or density, particle shape and angularity as well as the uniformity of distribution of the stabilizers.

CHAPTER 5: SUMMARY OF FINDINGS AND RECOMMENDATIONS

5.1 FINDINGS AND CONCLUSIONS

This report presents findings of the Illinois Center for Transportation (ICT) project R27-125 study on quarry by-products (QBs) at the University of Illinois at Urbana-Champaign. The objectives of this project were to document aggregate by-product production trends in Illinois, to determine the material properties of aggregate by-products through laboratory testing and materials characterization, and to evaluate the feasibility of using QBs in various pavement applications.

An industry survey conducted among crushed stone producers operating throughout Illinois indicated that current uses of QB are limited to applications that utilize low amounts of QB; therefore, excess amounts of QB might remain in the stockpiles.

Aggregate by-products from four quarries were collected, and several laboratory tests (i.e., X-ray diffraction, modified methylene blue, sieve analysis, particle shape image analysis, moisture density, Atterberg limits, unconfined compressive strength [UCS], and direct shear) were performed to explore the feasibility of using increased quantities of QB in sustainable and beneficial pavement applications.

The laboratory tests were also conducted to evaluate the effect of sampling stages on QB properties and distinguished QB samples collected from primary, secondary, and tertiary crushing stages. The overall strength properties of QBs from all the four quarries were found to be low. Accordingly, chemical admixture stabilization alternatives using Portland cement and Class C fly ash were studied as a means to improve the strength and durability characteristics of QBs. For that evaluation, moisture density, shear strength, and UCS tests were conducted on treated QB samples. The addition of cement and fly ash considerably increased the strength properties.

On the basis of the research findings, the following conclusions can be drawn:

1. The amounts of QBs produced each year were as high as 950,000 U.S. short tons (based on information from the 20 quarries that responded to the questionnaire). In addition, QBs in the excess category stored in stockpiles from the quarries surveyed were more 3,475,000 tons in total.

2. On the basis of the Unified Soil Classification System (USCS), the QB samples collected from four different quarries in Illinois were determined to be primarily silt and sand-sized particles. There were observable differences in the gradations of the QB samples from the primary, secondary, and tertiary crushing stages as collected from the same quarry (Quarry 1) in two batches. The changes in gradation characteristics could make QB samples either well-graded or poorly graded and reflected the differences in the overall very low UCS (untreated) values for QBs.

3. The QB samples obtained from all quarry locations were essentially nonplastic.

4. The Enhanced University of Illinois Aggregate Image Analyzer (E-UIAIA) was utilized to quantify QB particle shape properties for grain sizes retained on the No. 8 sieve. For materials from Quarry 1, QB particles collected from the primary crusher were more rounded and cubical in shape compared with the quarry fines collected from the secondary and tertiary crushers.

5. On the basis of the results of standard Proctor moisture density tests, all the virgin (unstabilized) and admixture-treated QB materials were found to have maximum dry densities

in the range of 129.7 to 143 pcf and optimum moisture contents (OMCs) in the range of 6.6% to 10.4%. In general, the maximum dry density and OMC values of untreated aggregate by-products varied from one quarry to another. While there was no unique trend noted for the variation of OMCs, higher maximum dry density values were typically observed in aggregate by-products from the primary crushing stages. The optimum moisture content and maximum dry density values of the treated aggregate by-products were highly dependent on the type of stabilizer used. Compared with 2% cement-treated QB samples, higher maximum density and lower optimum moisture content values were obtained for the Class C fly ash–treated Quarry 1 by-products.

6. QB samples from the three crushing stages showed similar trends in shear strength characteristics. In general, all the samples obtained from the four quarries with different geological locations in Illinois exhibited low UCS values (less than 11 psi). The UCS results were directly proportional to the maximum dry densities obtained from standard Proctor tests.

7. Significant increases in UCS values were achieved for QB samples treated with stabilizers (i.e., 2% Portland cement, 5% Class C fly ash, and 10% Class C fly ash). On the basis of the strength gains observed, it was determined that the use of the 10% Class C fly ash could be the most effective, considering both the environmental and economic aspects of aggregate by-product stabilization. The 10% Class C fly ash–treated materials could achieve UCS values as high as 340 psi and no lower than 100 psi for all the QBs tested.

5.2 RECOMMENDATIONS FOR FUTURE RESEARCH

The laboratory assessment and property testing of QB provided good results regarding the increased strength of QB. While the gain in UCS values is promising, a full suite of strength, modulus, and deformation characteristics of treated QB is recommended for fully characterizing engineering behavior of the treated QB materials in future sustainable pavement applications.

Moreover, the life-cycle cost analysis and life-cycle analysis and benefits associated with use of QB should be evaluated. Even though the environmental impact of aggregate production is relatively small compared with that of other sectors, aggregate production provides achievable opportunities to improve sustainability of aggregate production and efficiency by utilization of quarry by-products. Better utilization of quarry by-products (which constitute an average of 8% to 10% of total aggregate production) will immediately have an impact, reducing primary energy demand and greenhouse gas emissions. Therefore, reliable and representative inventory data should be collected to perform environmental assessment of aggregate production and investigate potential utilization of quarry by-products in the future.

This research study produced potential strategies to utilize excess fines by incorporating quarry by-products (QB) in construction. A second phase of this research project is recommended, with the following suggested tasks:

1. Construct full-scale pavement test sections using the most promising applications of QB materials, including

    i. QB to fill the gaps/voids between large stones as aggregate subgrade on soft subgrades;

    ii. embankment and/or subgrade/subbase replacement;

iii. cement or fly ash–treated subbase (e.g., in inverted pavements);

iv. cement or fly ash–treated QB for use as a base;

v. QB to be blended with coarse aggregate fractions of virgin and recycled materials and other additives, such as fibers, etc., for use as a subbase/base;

vi. fine aggregate replacement in 4.75 mm leveling binder asphalt mixes for overlay applications; and

vii. asphalt mix design to be plant produced for a 4.75 mm mix and other possible HMA mixes that incorporate a typical QB.

2. Test and monitor the full-scale pavement sections utilizing the above-described QB applications and check against current mechanistic analysis based pavement design requirements and the resulting satisfactory field performance from the accelerated pavement testing.

Draft specifications will be produced for the QB uses that show the highest potential in the field testing.

The alternatives to be recommended for beneficial QB utilization are expected to have an immediate impact for sustainable construction practices in the State of Illinois by reducing total energy consumption and greenhouse gas emissions per ton of aggregate production and resulting in significant savings on IDOT construction projects.

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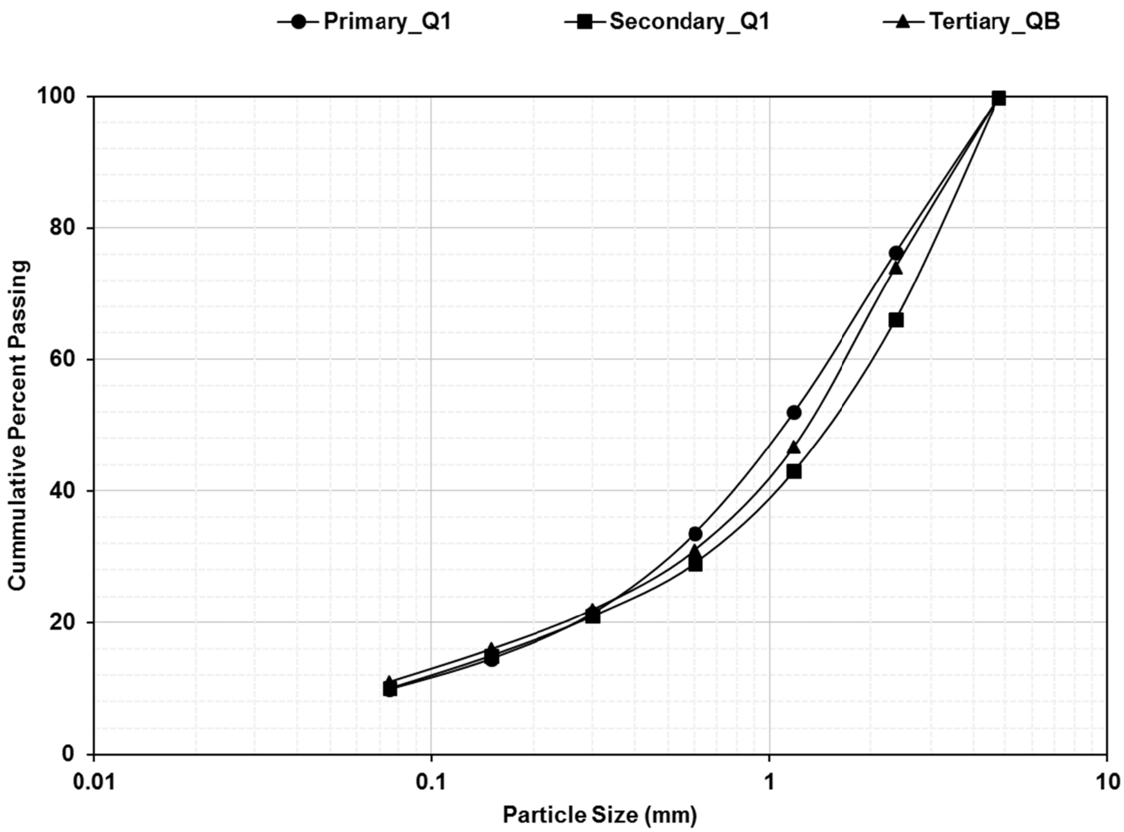
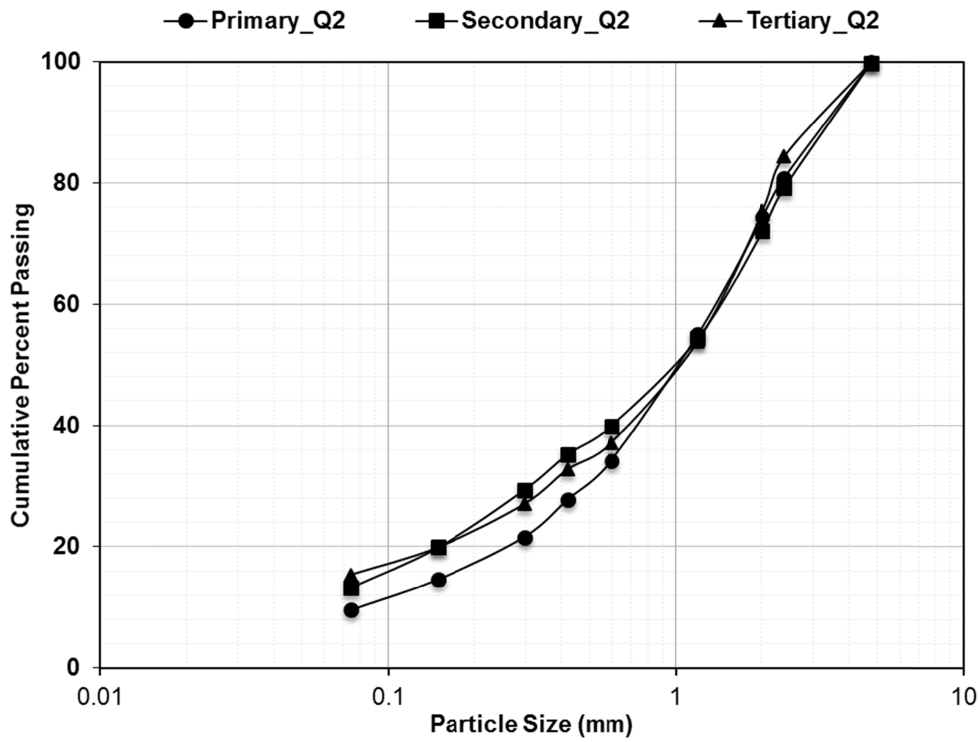
APPENDIX A

A-1 QB GRADATIONS FROM DIFFERENT CRUSHING STAGES WITHIN THE SAME QUARRY

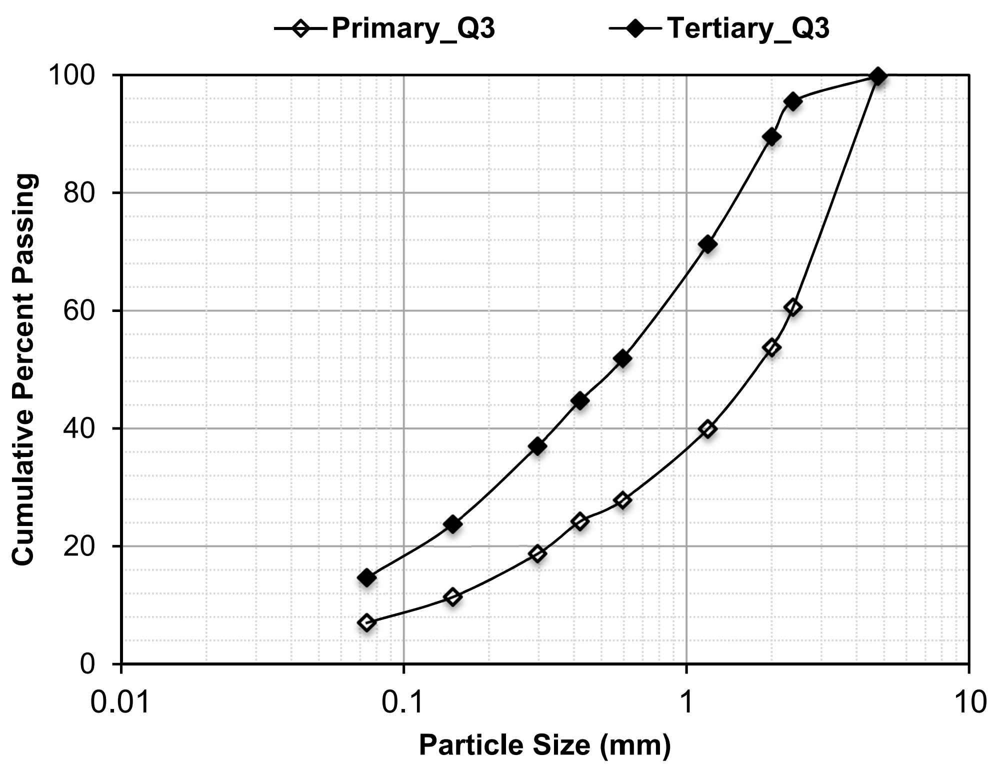
A-1-1 QB from Quarry 1



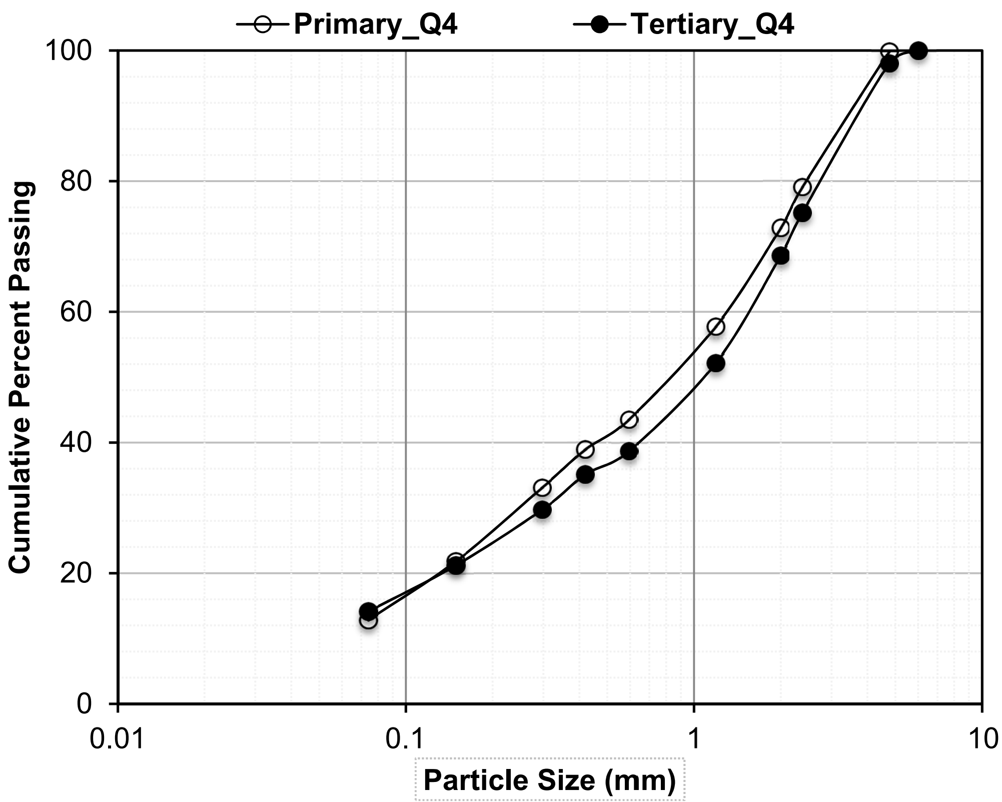
A-1-2 QB from Quarry 2



A-1-3 QB from Quarry 3

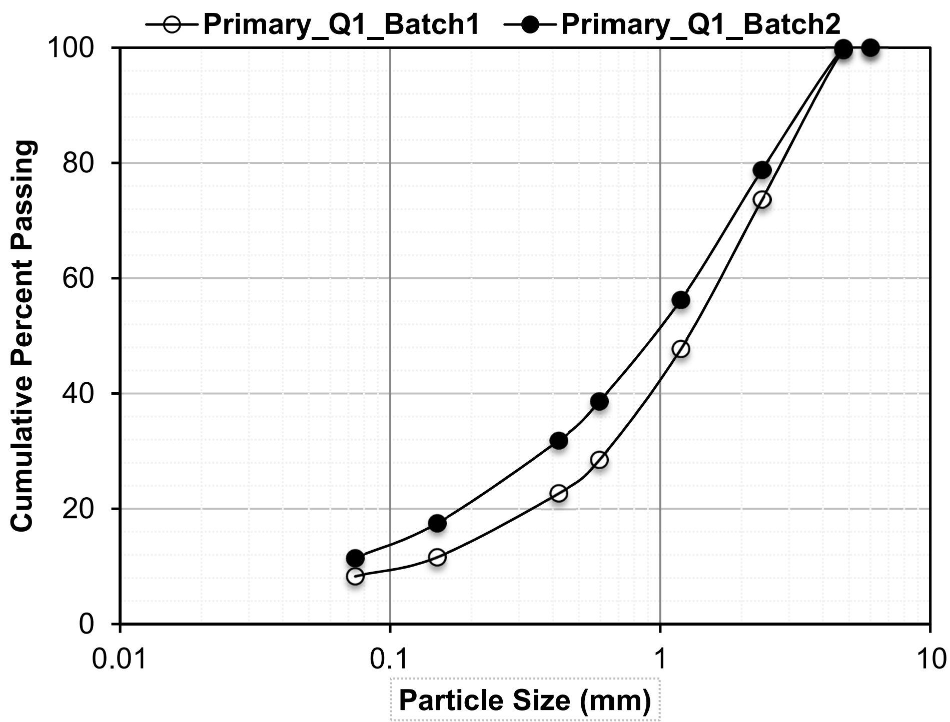


A-1-4 QB from Quarry 4

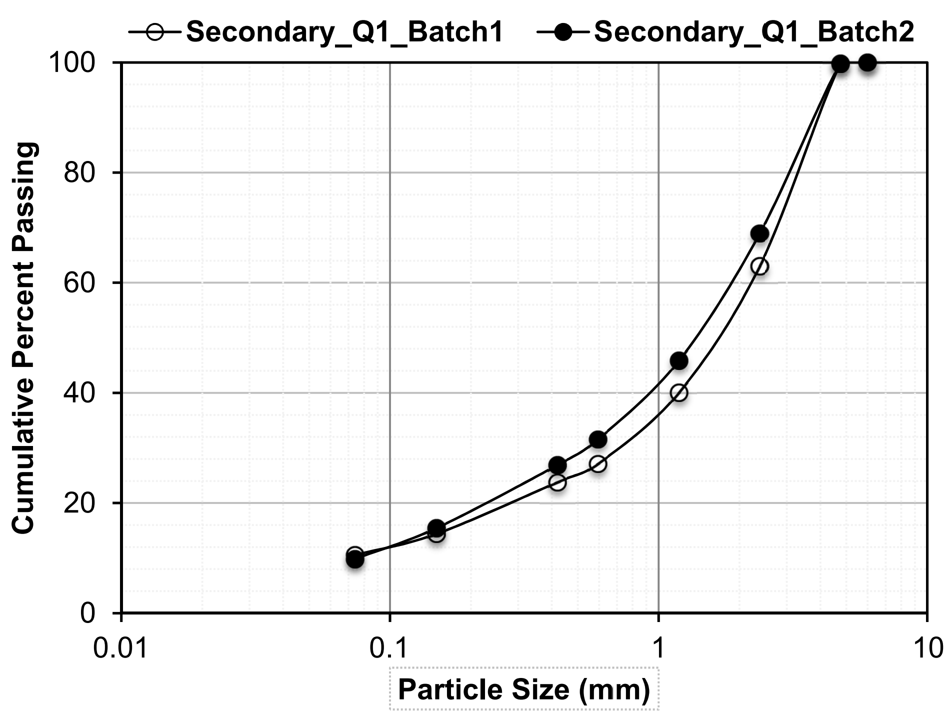


A-2 QB GRADATIONS FROM DIFFERENT BATCHES IN QUARRY 1

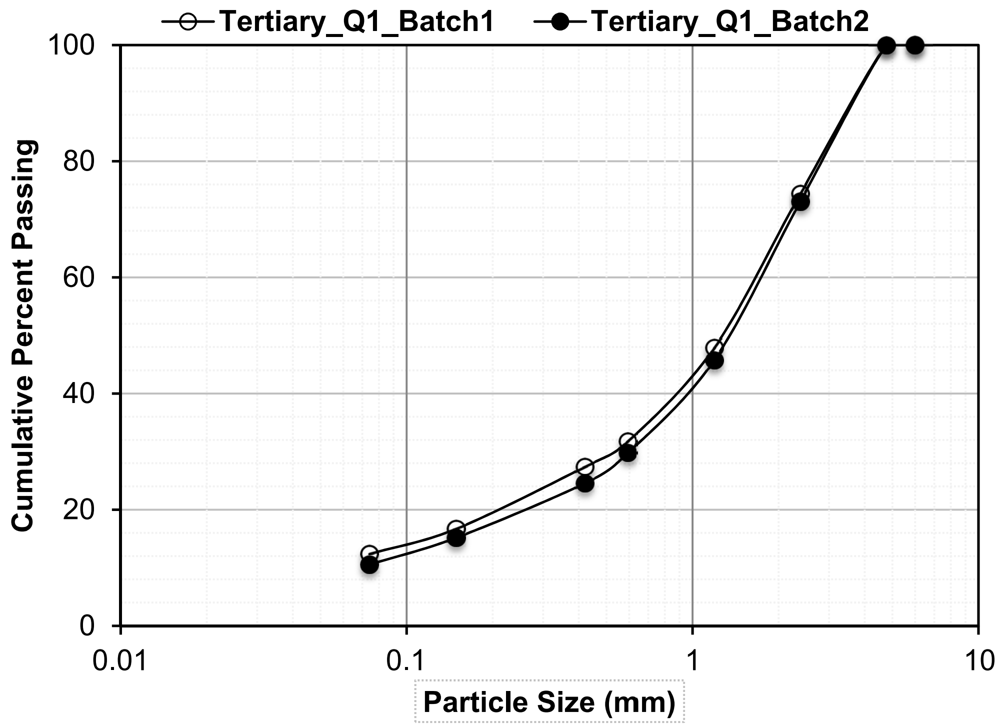
A-2-1 QB from Primary Crusher



A-2-2 QB from Secondary Crusher

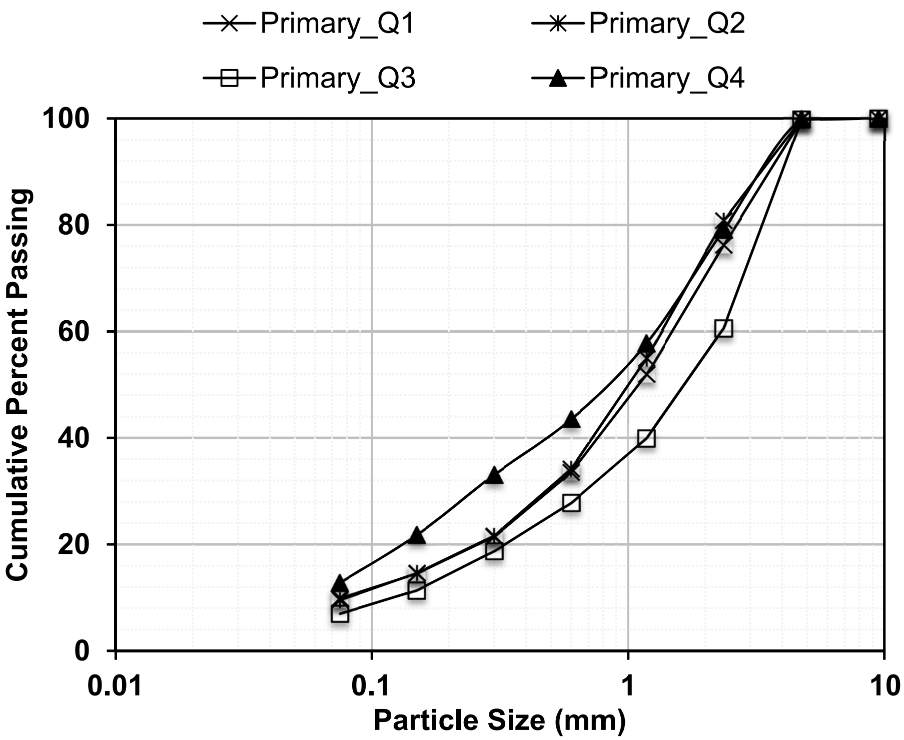


A-2-3 QB from Tertiary Crusher

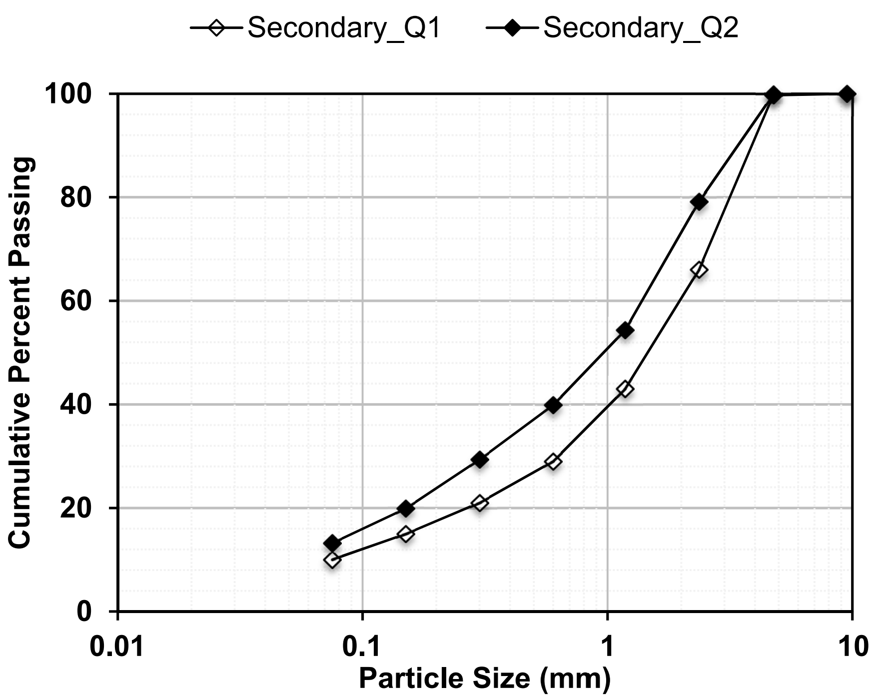


A-3 QB GRADATIONS FROM SIMILAR CRUSHING STAGES WITHIN DIFFERENT QUARRIES

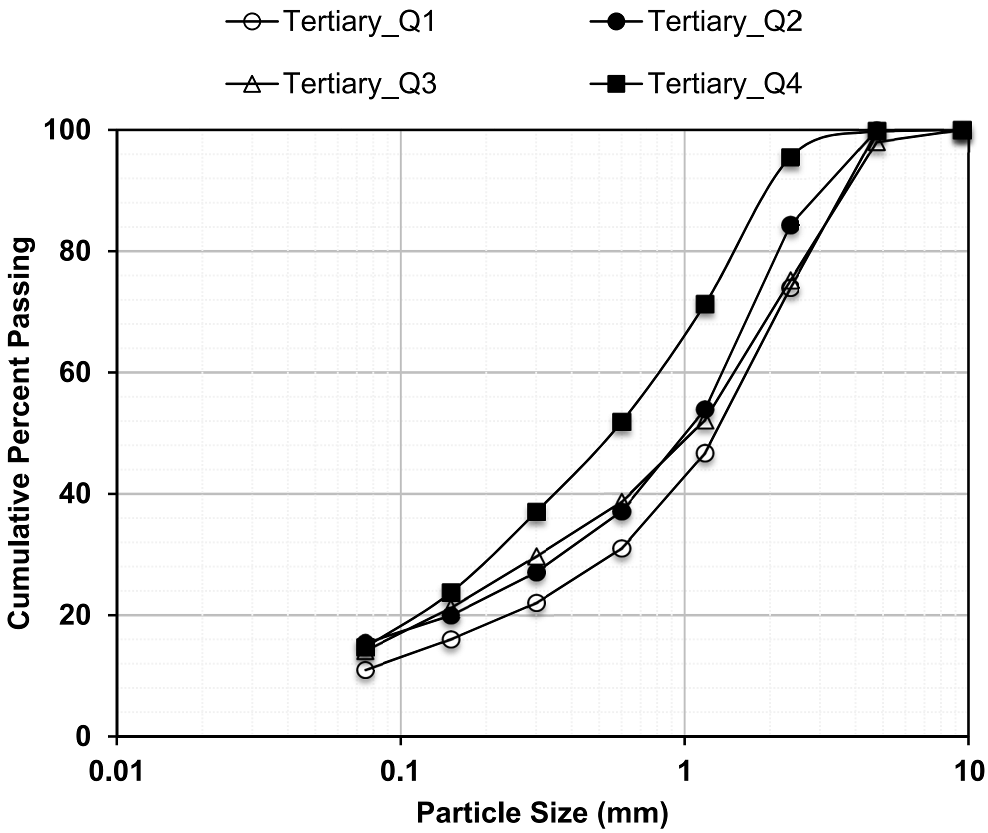
A-3-1 QB from Primary Crushing Stage



A-3-2 QB from Secondary Crushing Stage



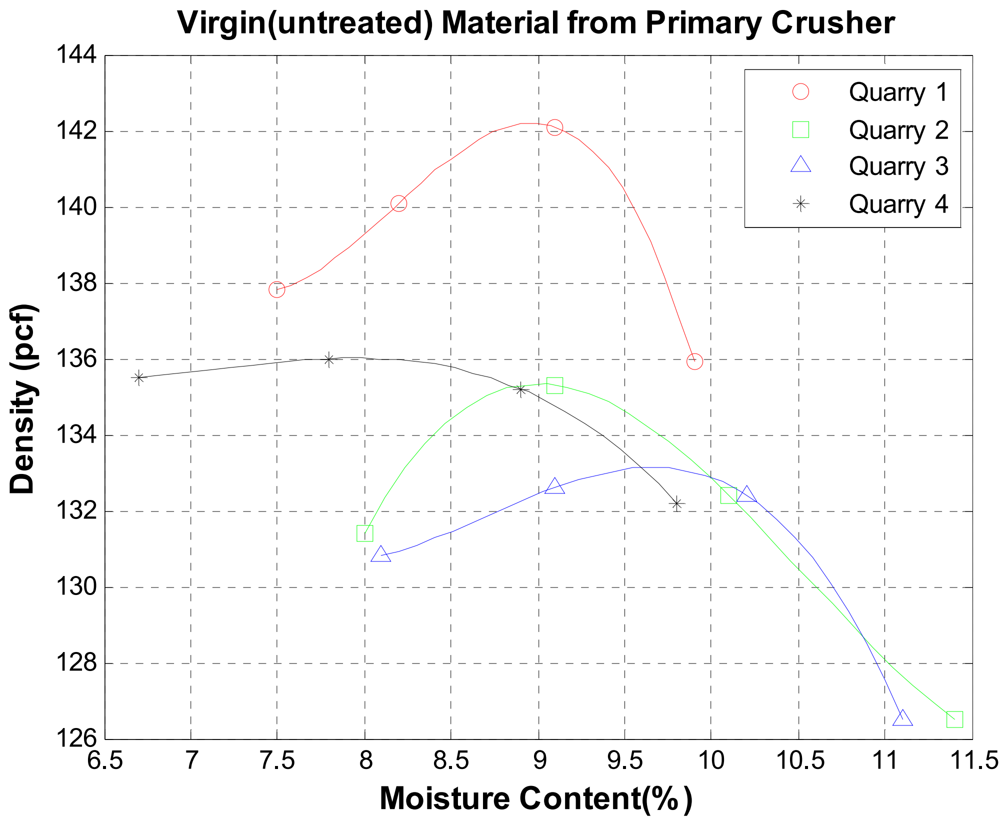
A-3-3 QB from Tertiary Crushing Stage



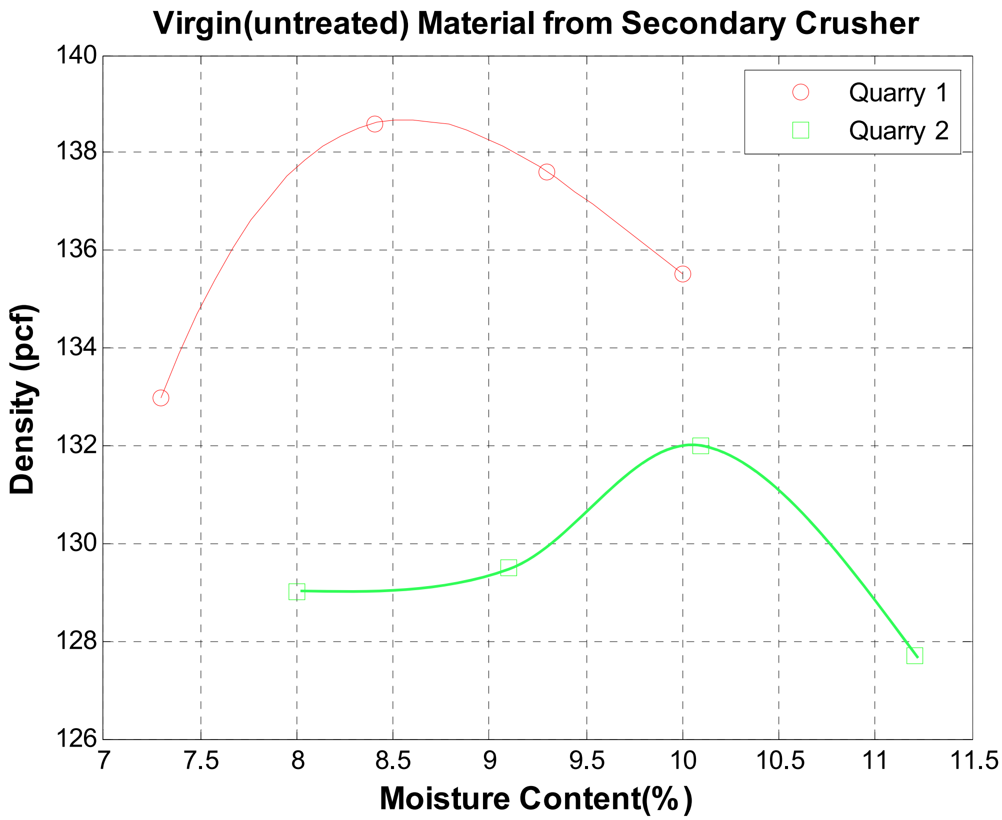
APPENDIX B

B-1 STANDARD PROCTOR COMPACTION CURVES – VIRGIN (UNTREATED) QB MATERIALS

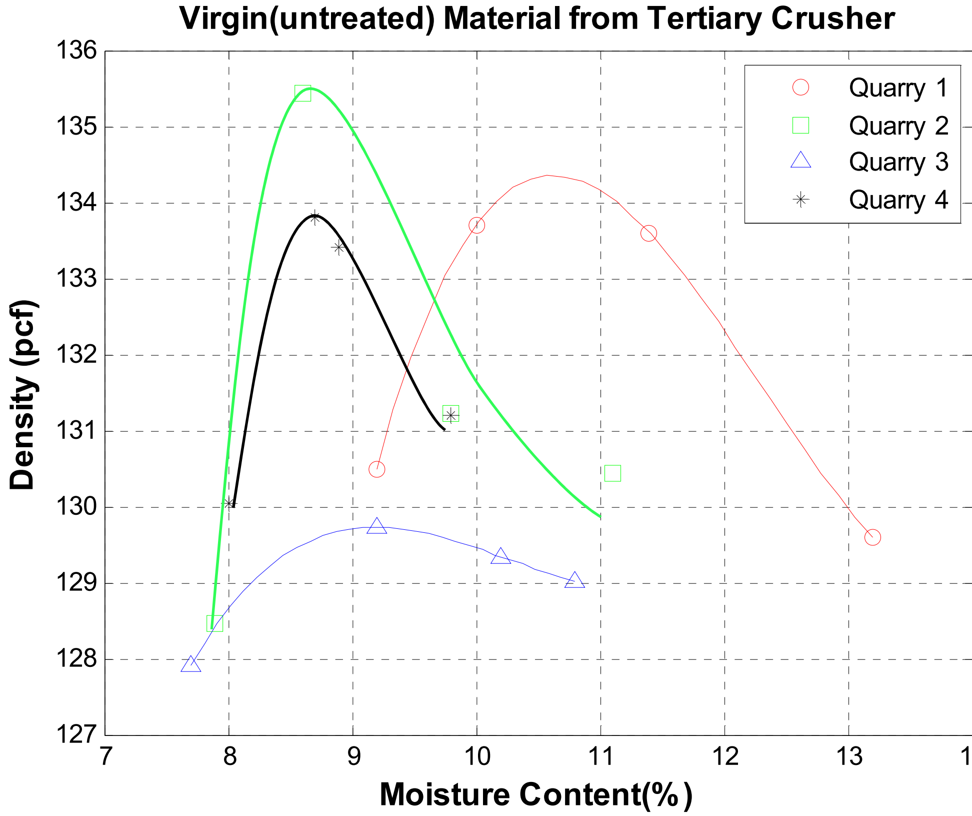
B-1-1 QB from Primary Crusher



B-1-2 QB from Secondary Crusher

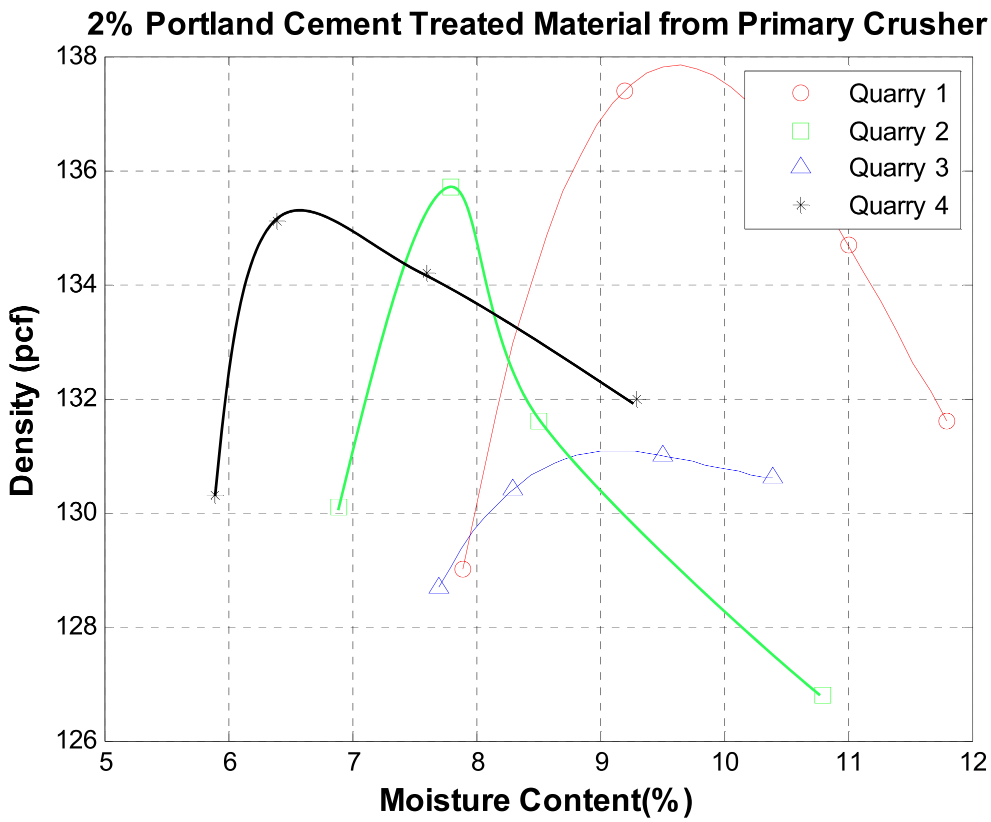


B-1-3 QB from Tertiary Crusher

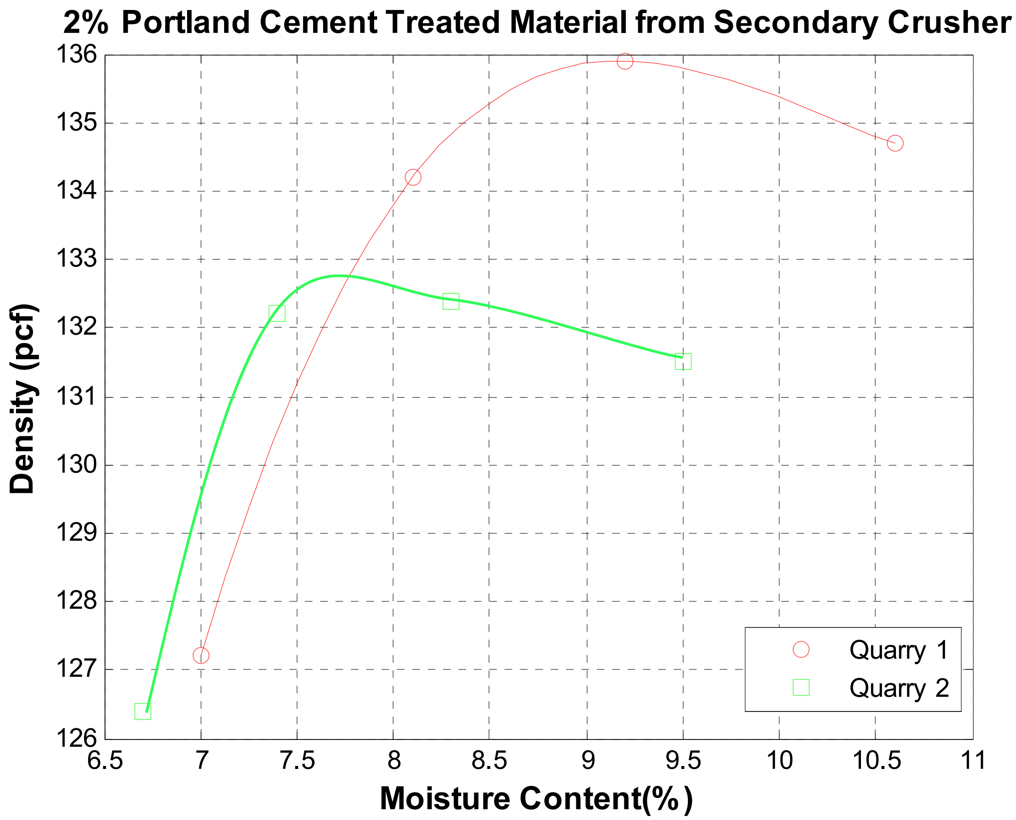


B-2 COMPACTION CURVES FOR 2% CEMENT-TREATED MATERIALS

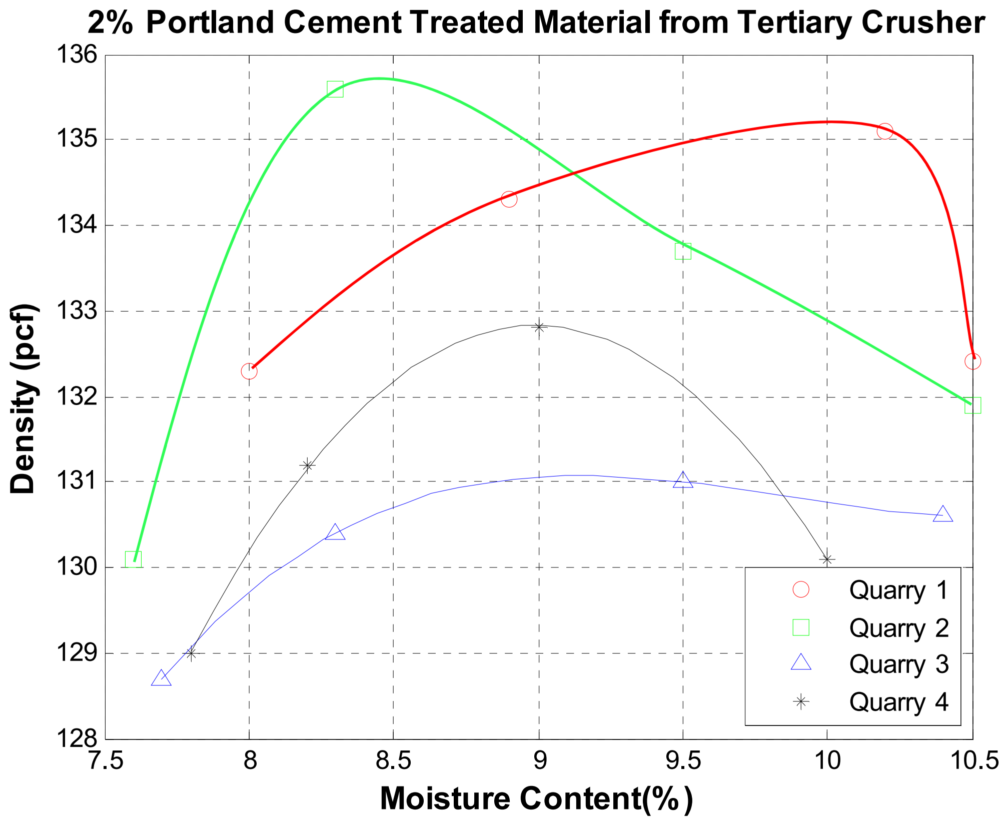
B-2-1 2% Cement-Treated QB from Primary Crusher



B-2-2 2% Cement-Treated QB from Secondary Crusher

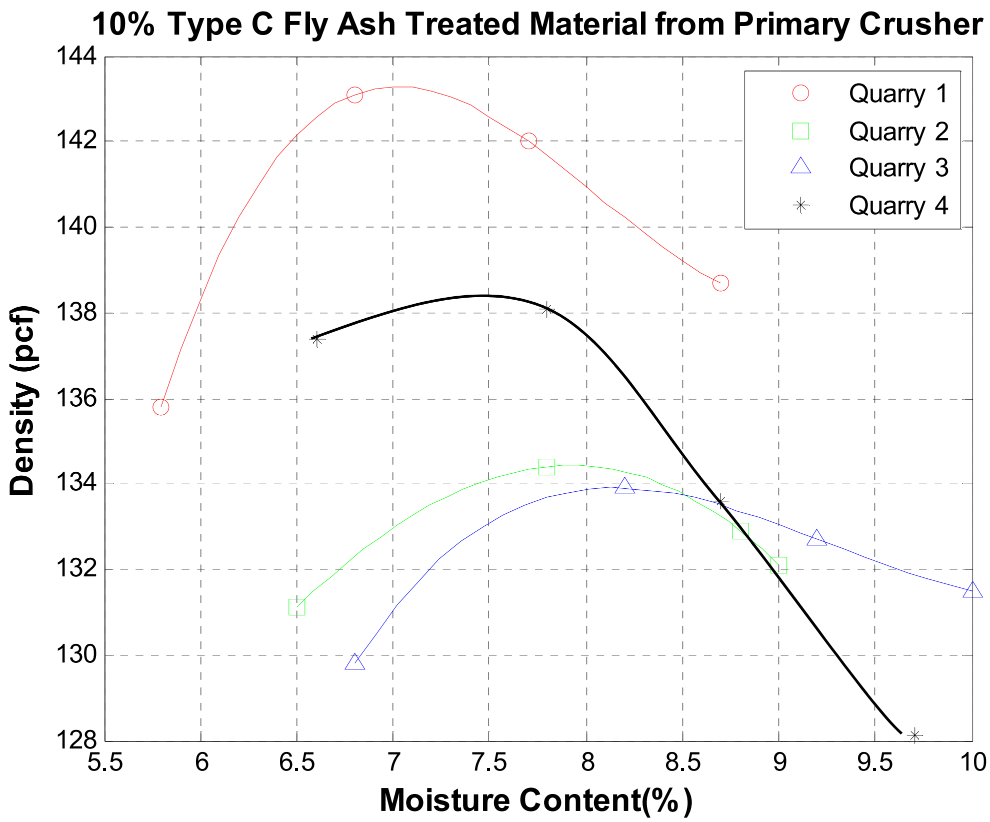


B-2-3 2% Cement-Treated QB from Tertiary Crusher

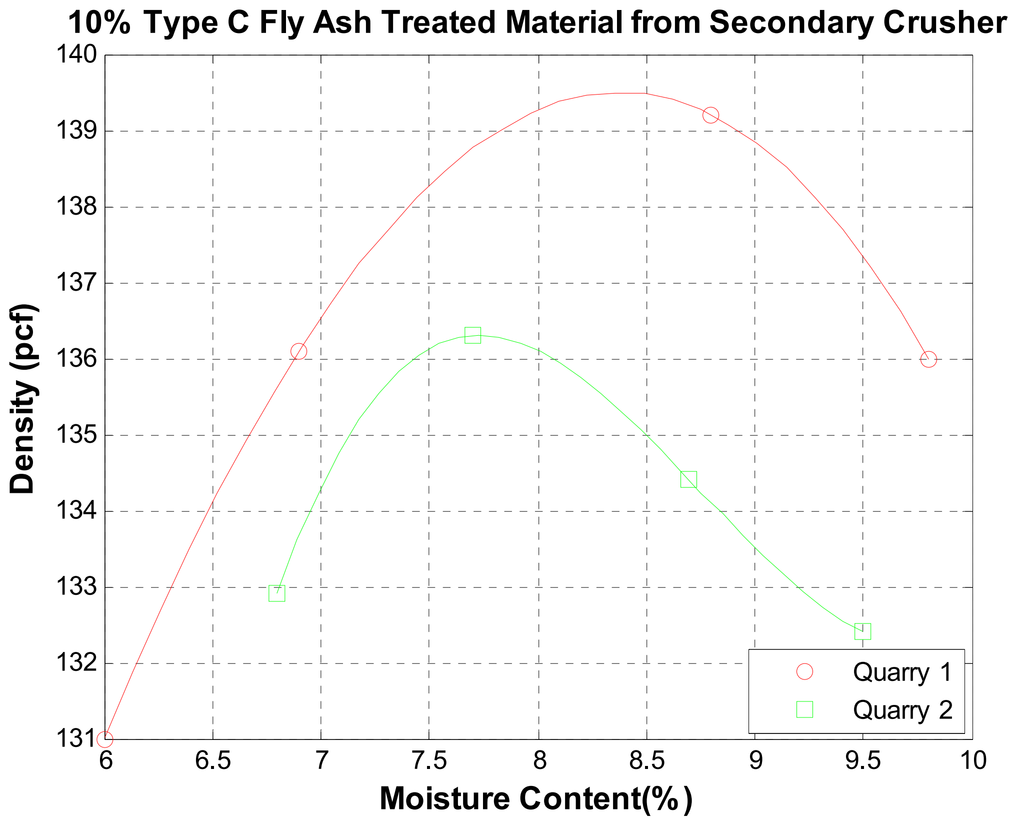


B-3 COMPACTION CURVES FOR 10% TYPE C FLY ASH–TREATED MATERIALS

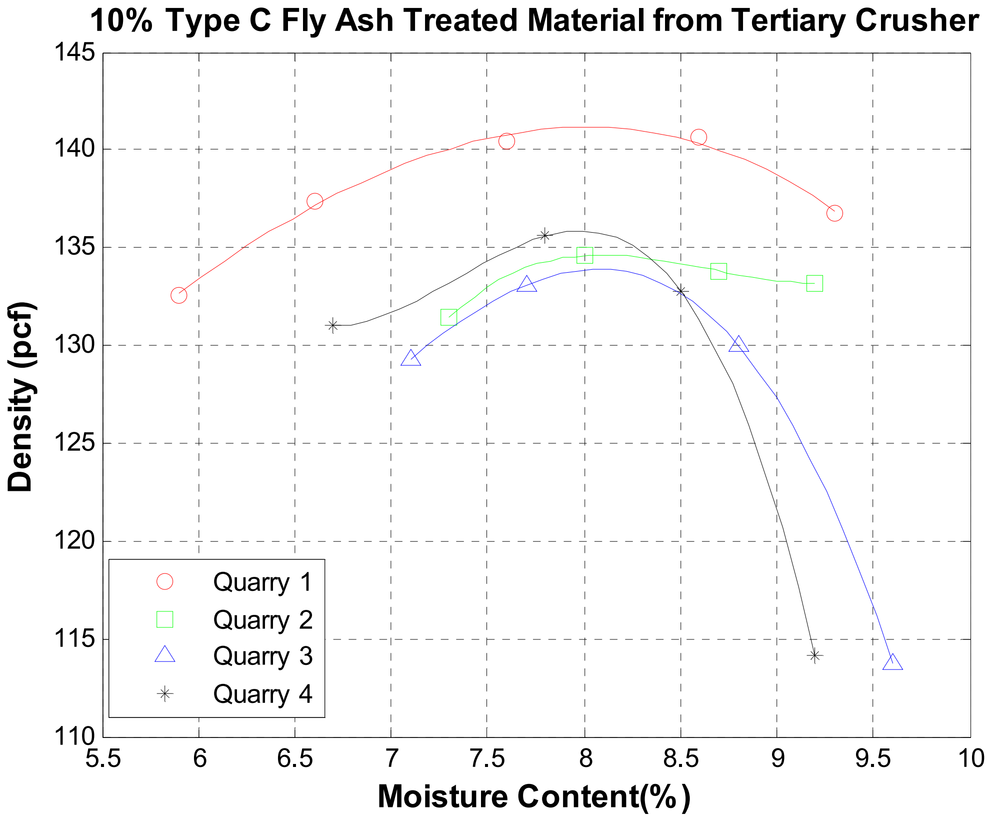
B-3-1 10% Type C Fly Ash–Treated QB from Primary Crusher



B-3-2 10% Type C Fly Ash–Treated QB from Secondary Crusher

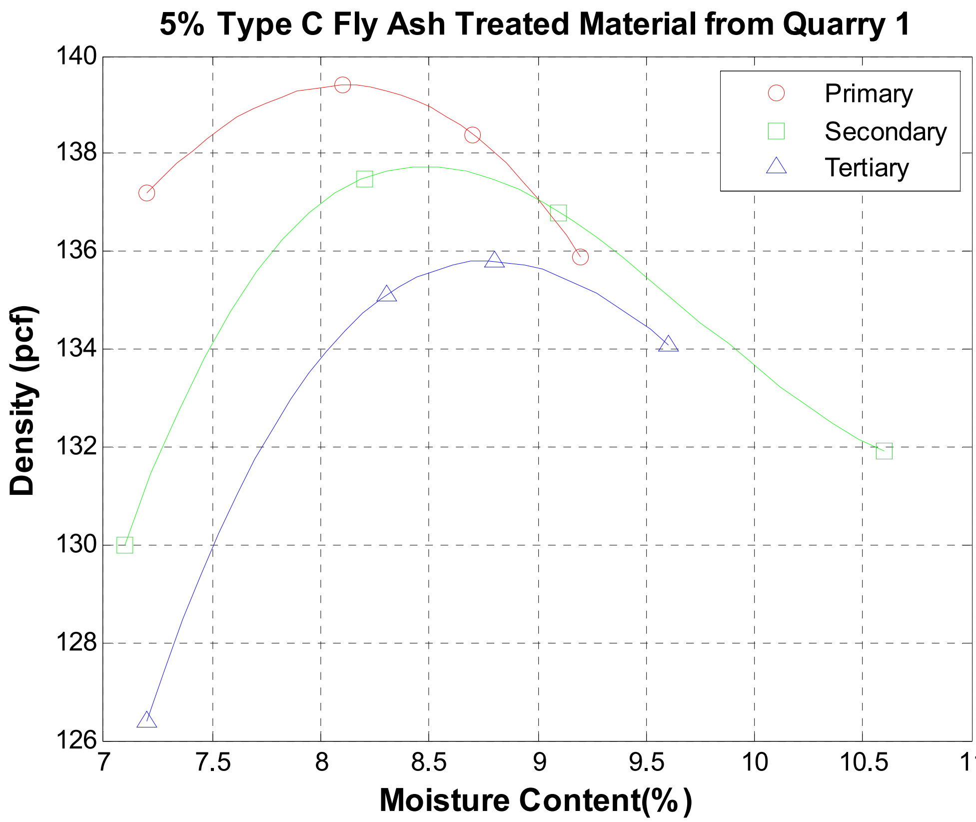


B-3-3 10% Type C Fly Ash–Treated QB from Tertiary Crusher



B-4 COMPACTION CURVES FOR 5% TYPE C FLY ASH–TREATED MATERIALS

B-4-1 5% Type C Fly Ash–Treated QB from Quarry 1



APPENDIX C

C-1 UNCONFINED COMPRESSIVE STRENGTH (UCS) TEST RESULTS

Quarry	Crusher	Batch No.	Test No.	Virgin (Untreated)	2% Cement	5% Class C Fly Ash	10% Class C Fly Ash
1	Primary	1	1	17	189	—	—
			2	—	215	—	—
		2	1	8.7	196	103	335
			2	9.5	206	106	315
			3	6.8	—	105	347
	Secondary	1	1	13	157	—	—
			2	—	164	—	—
		2	1	6.8	257	154	324
			2	7.1	273	145	360
			3	8.2	—	167	318
	Tertiary	1	1	7	181	—	—
			2	—	196	—	—
		2	1	2.7	212	119	356
			2	3.4	231	132	337
			3	2.6	—	90	337
2	Primary	1	1	8.8	234	—	177
			2	9.1	273	—	228
	Secondary	1	1	4.9	267	—	183
			2	3.9	273	—	202
	Tertiary	1	1	6.3	177	—	132
			2	6.5	260	—	173
3	Primary	1	1	5.7	186	—	109
			2	4.4	180	—	94
	Tertiary	1	1	3.4	213	—	198
			2	2.4	217	—	212
4	Primary	1	1	9.7	401	—	289
			2	6.5	376	—	305
	Tertiary	1	1	7.3	289	—	247
			2	8.9	286	—	220