PAVEMENT SUSTAINABILITY OPTIMIZATION USING QUARRY BY-PRODUCTS AND GEOSYNTHETICS

BY

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THESIS

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ABSTRACT

Sustainability has become a major concern in the construction industry, especially highway construction. In the U.S, significant effort is being exerted to quantify the environmental emissions associated with construction and production of materials used in pavement construction. The increased aggregate demand by the construction industry has resulted in increased production of quarry by-products (QB) and overall energy consumption because of the production of aggregates. The use of geosynthetics and QB in unbound material pavement applications can mitigate the high demand for natural aggregates, thus reducing the depletion of natural aggregates, environmental emissions, and energy consumption caused by stockpiling of QB and aggregate production. The use of geosynthetics at the subgrade/base interface has been adopted by many states in the U.S, and design standards have shown that this particular application results in a reduction of aggregate base thickness or increase the pavement service life; however, limited studies have been conducted to assess the environmental impacts caused by the production and use of geosynthetics in pavement applications. While the use of QB in pavement applications can reduce the consumption of natural aggregates and, consequently, all associated environmental burdens, there are no developed guidelines and specifications on using QB in these applications. A pilot study intended to develop specifications and guidelines for the use of QB and assess the environmental impacts of pavement materials was conducted at the University of Illinois at Urbana-Champaign (UIUC). A detailed laboratory study was conducted to characterize the engineering properties of QB materials, produced in the primary, secondary, and tertiary aggregate production stages. The results show that the unconfined compressive strength of QB materials is very low, and chemical admixtures, such as Portland cement and Class “C” fly ash, were used to improve the strength properties of QB materials. In general, treated QB materials were 10 to 30 times stronger than the virgin QB samples. Such significant increases in the strength of stabilized QB materials may indicate suitability of QB for sustainable pavement applications. Under a similar study, the environmental impacts of using geosynthetics in pavement were assessed. The results show that that the use of geosynthetics in pavement may reduce environmental emissions by 6.5%, and total energy by 2.7% compared with conventional pavements.

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LIST OF ACRONYMS AND ABBREVIATIONS

AASHTO	American Association of State highway and Transportation Officials
ASTM	American Society for Testing and Materials
CP	Conventional Pavement
eGRID	Emissions and Generation Resource Integrated Database
EIA	(U.S.) Energy Information Administration
EPA(U.S.)	Environmental Protection Agency
E-UIAIA	Enhanced University of Illinois Aggregate Image Analyzer
GHG	Greenhouse Gases
GP	Geosynthetic-Reinforced Pavement
GWP	Global Warming Potential
HB	HMA Base
HDPE	Polyethylene
HMA	Hot-Mix Asphalt
IAAP	Illinois Association of Aggregate Producers
ICT	Illinois Center for Transportation
IDOT	Illinois Department of Transportation
ISO	International Standards Organization
LCA	Life-Cycle Assessment
LCI	Life-Cycle Inventory
LCIA	Life-Cycle Impact Assessment
MOVES	Motor Vehicle Emission Simulator
p-ILCA	Pavement LCA
PP	Polypropylene
QB	Quarry By-products
QD	Quarry Dust
QF	Quarry Fines
RAP	Recycled Asphalt Pavement
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
U.S.	United States
UCS	Unconfined Compressive Strength
US-EI 2.2	U.S. Ecoinvent Database Version 2.2
USGS	U.S. Geology Survey
WS	Wearing Surface

1 INTRODUCTION

1.1 Foreword

Current economic conditions and increased emphasis in the construction industry on sustainability and recycling require the use of environment friendly materials in civil engineering, including pavement engineering. Pavement is a multilayer system composed of various layer materials. Pavement layers may have different strengths and durability potential. Aggregates constitute 80-55% by volume of asphalt mixtures and 62 to 68% by volume of typical concrete mixtures. In the U.S. in 2012, approximately 1,324 million tons (1200 million mt) of crushed stone worth approximately $12 billion was produced by 1,550 companies operating 4,000 quarries, 91 underground mines, and 210 sales/distribution yards in all 50 states. Of the total crushed stone produced in 2012, about 69 percent was limestone and dolomite, 14 percent granite, 7 percent traprock, 5 percent miscellaneous stone, and 4 percent sandstone and quartzite (USGS 2013a). Limestone is also used in the manufacture of most hydraulic cements including Portland cement as well as being used as the aggregate in concrete and asphalt mixtures and for base and subbase layers. Granite and traprock (such as basalt) are used extensively as aggregate in both concrete and asphalt mixtures. Of the portion of total crushed stone production reported by use in 2012, 82 percent was used as a construction material, mostly for road construction and maintenance and 10 percent, for cement manufacturing (USGS 2013a).

Similarly, approximately 927 million tons (840 million mt) of construction sand and gravel worth $6.4 billion was produced in 2012 by an estimated 4,000 companies from about 6,400 operations in 50 states (USGS 2013a). It is estimated that about 43 percent of construction sand and gravel was used as concrete aggregates, 26 percent for road base and coverings and road stabilization; 12 percent as construction fill; and 12 percent as asphalt concrete aggregates and in other asphalt-aggregate products (USGS 2013a).

Crushed aggregates, being one of the most important necessities for construction of pavements, are highly demanded for satisfying the current need in the construction industry. The U.S. Geology Survey (USGS) has predicted that the amount of crushed aggregates produced will jump to 1.6 billion of metric tons in 2020, approximately 20% increase. Reducing the use of virgin materials is one of the most effective ways of saving natural resources and improving sustainability of pavements. There are numerous ways of replacing virgin materials in practice including the use of recycled, co-product (or by-products) and waste (RCWMs). The use of RCWMs do not only help conserving natural resources when used properly but also reduce the environmental burden associated with aggregate production. In addition, as more RCWMs are used and less aggregate is produced, utilization of RCWMs reduces the burden on the landfills (Hudson et al., 1997). Therefore, the proper selection of environmental friendly materials that would replace/minimize the use of natural aggregate can considerably reduce the amount of energy consumption and emissions released into the environment.

One way of improving sustainability of pavements is using aggregate by-products. Puppala et al.(2008; 2012) showed that the use of aggregate by-products or quarry by-products (QB) as base/subbase material can replace the use of crushed aggregates. While the use of aggregate by-products in pavement applications is promising, there are no developed guides and specifications for incorporating aggregate by-products in pavement applications. This thesis presents a pilot study intended to develop guidelines and specifications for incorporating aggregate by-products in pavement applications. Similarly, the use of geosynthetics at the base-subgrade interface may reduce the use of base/subbase crushed aggregates. Geosynthetics in pavements applications has not only proven to be cost effective, but also to extend the pavement life and/or reduce the amount of materials used in pavement construction (Al-Qadi et al., 1997; 2003; Norejo, 2003; Bhutta, 1998). However, there is no reliable data for environmental impacts associated with production of geosynthetics in the U.S. The results from a research program undertaken at UIUC with the objectives of developing a life-cycle inventory (LCI) for production of geosynthetics and to evaluate the environmental impacts of using geosynthetics in pavement applications are presented in this thesis.

1.2 Problem Statement

There is a need to reduce the environmental impacts associated with construction materials in order to improve sustainability of pavements. QB and geosynthetics are potential materials that can be used to reduce the environmental impacts associated with aggregate production and pavement construction. However, the impact of using QB, currently a waste material as there is no potential application and demand in the market, on the environment due to reduced stockpiling and landfilling as well as the use of crushed aggregate needs to be evaluated. In the case of geosynthetics guidelines and specifications for incorporating geosynthetics in pavements were developed (Koerner, 2012). Some studies addressing the environmental concern associated with the use of geosynthetics in pavements were conducted in Europe. However, there is a lack for similar studies in the U.S. Unlike geosynthetics, there are no guidelines and specifications for using QB in pavements.

1.3 Research Objective

In light of the growing environmental concerns and sustainability, the development of eco-friendly construction practices has become increasingly important. This study focuses on some of the sustainable practices applicable for the construction of pavements. The major objectives of this study are summarized below:

1. To assess the amount of aggregate by-products produced in the State of Illinois and to evaluate, through laboratory testing, the use of aggregate by-products for sustainable unbound pavement applications.
2. To develop LCI data in accordance with ISO 14040 (2006) guidelines, for the production of geosynthetics and to assess the environmental impacts of geosynthetics used in geosynthetics-reinforced/stabilized pavements.

3. To use the pavement life-cycle assessment (p-ILCA) tool to conduct, quantify, and compare the global warming potential (GWP) and total energy consumption associated with geosynthetic-reinforced/stabilized pavements versus conventional pavements.

1.4 Scope of Study

This thesis presents aggregate quarry survey results and laboratory assessment of QB for potential pavement applications. In addition, the engineering property improvement of aggregate by-products due to the addition of low cement and Class C fly ash was evaluated and presented. Finally, the total energy and greenhouse gas emissions due to material production and construction of geosynthetic-reinforced/stabilized pavement were assessed.

1.5 Impact of the Work

The results of this study will serve as a baseline for the development of design guidelines and specifications for incorporating aggregate by-products in pavement applications. The study provides a quantitative environmental impact due to the use of QB and geosynthetics in pavements. This will result in constructing more sustainable and cost effective pavements.

1.6 Thesis Organization

Chapter one of this thesis presents the introduction. The detailed literature review is provided in chapter 2. Chapter 3 addresses the laboratory evaluation of QB for pavement applications; while Chapter 4 evaluates the environmental impacts of producing geosynthetics (focusing on geotextile) and using geotextile in pavement applications based on the U.S. LCI inventory data. Finally, over all summary and conclusions are presented in chapter 5.

2 LITERATURE REVIEW

A literature survey was conducted to compile a summary for the use of quarry by-products and geosynthetics in pavement applications. The QB and geosynthetics, used in pavement construction, are the focus of this study and a state-of-the-knowledge is presented in this chapter.

2.1 Quarry By-products

According to an International Center for Aggregates Research report (Hudson et al., 1997), 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. The amount of aggregate by-products produced from hard rock crushing has increased in response to factors such as the adjusted design specifications for asphalt mixtures, which restricts the use low fines, resulting in changes to crushing processes during aggregate production.

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

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

2.1.1 Common Terms and Definitions

Aggregate quarry processes, such as blasting, crushing, and screening of coarser-graded aggregates resulting in mainline product, as well as by-product mineral fine materials, are commonly known as quarry waste or quarry dust. Quarry dust, quarry waste, and quarry fines are the common terms used to define the 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 accumulates over time and is subjected to no further processing. 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 do not exceed 0.25 in (6.25 mm). Baghouse fines are smaller than No. 200 sieve (0.075 mm) and can generally be mixed with plant fines.

Manning (2004) defined quarry fines as materials less than 0.157 in (4 mm) in size and intended for use as fine aggregate. The same report also defined fines as less than 0.079 in (2 mm). The variation is attributed to the fact that fines can generally be defined depending on the application. Therefore, quarry fines may cover a range of aggregates with maximum sieve sizes ranging from 0.079 to 0.25 in (2 to 6.25 mm).

2.1.2 Production

Production of 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, QB are produced during aggregate crushing stages and washing operations. For most practices, QB produced from the extraction of 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 shows a schematic representation of the different processes involved in aggregate production, as well as the approximate amount of fines produced during the various stages of aggregate production. Owing to different sizes of aggregate produced from each crusher and different crusher types, shown in Figure 1, the amount of fines produced may increase from the primary crusher to the tertiary crusher.

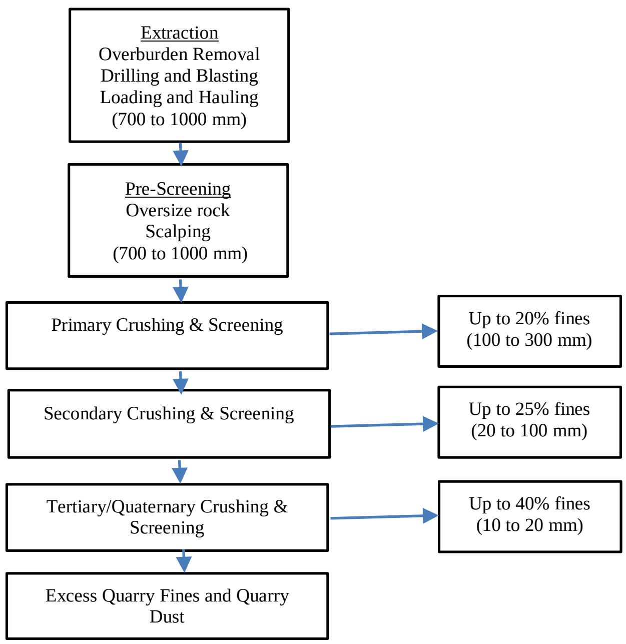


Figure 1. Flowchart for a typical quarry operation (Stroup-Gardiner and Wattenberg-Komas, 2013).

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

2.1.2.1 Screening Fines

According to the User Guidelines for Waste and By-Product Materials in Pavement Construction (FHWA, 1998), screenings are minus 4.75 mm (No. 4 sieve) material.

Crushed stone screening is a generic term used 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 (Wood and Marek, 1995). The size distribution of screenings, shape, and their physical properties differ depending on the parent rock's geological source, crushing method, ratio of reduction, and the coarse aggregate separation method (Wood, 1995; Wood and Marek, 1995; Stroup-Gardiner and Wattenberg-Komas, 2013).

2.1.2.2 Baghouse Fines

Baghouse fines are produced in dry plants and their particle size does not exceed 0.075 mm (No. 200 sieve). Dry plant operations use fine recovery units such as cyclones and baghouse, which collect fines from the secondary crusher. This operation is similar to the fine collecting system implemented in hot-mix asphalt plants to recover the unwanted dust produced in the drums. Baghouse fines are easy to handle compared with other wastes produced in quarries because they are produced in the dry condition and can be easily stored without further processing. In general, the properties of a baghouse vary based on the rock type and producer (Tepordei and Valentin, 1992).

2.1.2.3 Pond Fines

Usually 90-95 % of pond fines are finer 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 a specified use because washing involves removal of dust and clay impurities, if present. Such aggregate products are specifically used 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%. The moisture content can reduce to 20-30% when allowed for natural dewatering for several months.

2.1.3 Engineering Properties of Quarry By-products

2.1.3.1 In situ Moisture Content

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

2.1.3.2 Swelling Characteristic of Fines

According to the research conducted by Puppala et al.(2012), a one-dimensional vertical free-swelling test conducted to evaluate the swelling characteristics of quarry fines showed a swelling strain up to 6%, per ASTM D698. However, the result was based on one test and, hence, may not be generalized to all QBs.

2.1.3.3 Chemical and Mineralogical Properties

The quality of quarry fines reflects lithology of the worked material and the processes it has undergone. Different quarries, or activities, within the same quarry may generate a range of QB with different particle size and chemical composition. Quarry fines consist 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 are by nature inert or non-hazardous. Disaggregation, mixing, and moving to different locations, exposure to atmospheric conditions and to the surface or groundwater, as well as segregation and the increase of surface area as a result of particle size reduction, may cause physical and chemical transformations with detrimental effects to the environment (Petavratzi and Wilson, 2007).

The 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 the parent rock and the different crushing technologies employed. The proper way to determine the properties of QB is to conduct thorough laboratory characterization, including determination of engineering properties and chemical and compositional characteristics. Laboratory testing should be conducted even if the QB are produced from identical rock types using similar technologies (Manning, 2004).

According to Dumitru et al.(1999; 2001), mineralogical tests, such as x-ray diffraction analysis, should be used to determine the composition of secondary minerals and to quantify the amounts of harmful content that can be detrimental in some applications. Mineralogical tests can also be used to quantify the amount of harmful clays in QB. Stokowski (1992) showed that the finest sizes are enriched with $CaCO_3$, SiO_2, Al_2O_3, and Fe_2O_3 relative to $MgCO_3$. Thus, QB have lower specific gravity and are relatively soft because of calcite ($CaCO_3$) as well as the enrichment of clay minerals (SiO_2, Al_2O_3, and Fe_2O_3).

2.1.3.4 Gradation

Gradation of quarry fines varies depending on the type of the parent rock 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 distribution for different types of rocks (Table 1). The particle distribution of screenings from different types of rock follows a similar gradation trend, with particles smaller than sieve No. 200 (0.075 mm) ranging from 6% to 12%.

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

	Type of Rock						
	Flint	Trachyte	Limestone	Diabase	Granite	Blast Furnace Slag	Quartzite
Sieve Size (mm)	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

2.1.4 Overview of Applications

2.1.4.1 Base and Subbase Application

Kumar and Hudson (1992) showed that QB can generally be divided into six categories based on the percentage passing the No. 200 sieve through a series of quarry by-product sample evaluations. Based on this classification, the authors proposed the following potential paving applications for QB:

- Base course material additive
- Flowable fill
- Underslab granular fill
- Cement-stabilized subbase/base layer.

In the United Kingdom (U.K.), Petavratzi and Wilson (2007) conducted a study entitled "Sustainable Aggregates" to evaluate the current status of QB, including overburden, quarry fines, and dusts produced during extraction and processing of aggregates. In their report, the amount of QB produced in each stage of aggregate production was quantified. In addition, the viable applications and utilization potential, low volume to high volume, of aggregate by-products were also discussed. Based on their findings, the geotechnical and concrete applications were reported as applications that consume higher amount of aggregate by-products.

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

2.1.4.1.1 Kalcheff et al.(1980)

Stone screenings in combination with or without coarse aggregates have been used as cement-stabilized bases in many applications. According to Kalcheff et al.(1980), stabilization of stone screenings with cement developed relatively high rigidity with small amount of Portland cement as compared with granular soil-cement stabilization. The use of low-cement content has the advantage of decreasing shrinkage cracking. The data reported by the National Crushed Stone Association (NCSA) 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 best suited for cement stabilization.

2.1.4.1.2 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, based on 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:

- Severe shortage of regular sized construction aggregates in the area
- Low volume and low traffic road design with a very low budget attached to it
- The fines are economically transportable (100 mile radius) to the area
- No acceptable soil or gravel is found in the area for soil-lime-fly ash or Cement stabilization, or is not economical to transport.

2.1.4.1.3 Puppala et al.(2008; 2012)

Puppala and his 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 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 quarry fines, the cement-treated quarry fines 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 Stress (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 cement-treated quarry fines are similar to those of sandy material with very few fines. The untreated sample of quarry fines 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 cement-treated quarry fines was attributed to the cementing reactions of the cement and the fine sandy fraction of quarry fines 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 cement-treated quarry fines were 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. Puppala et al. (2012) concluded the study with further testing to evaluate the permanent deformation of cement-treated quarry fines.

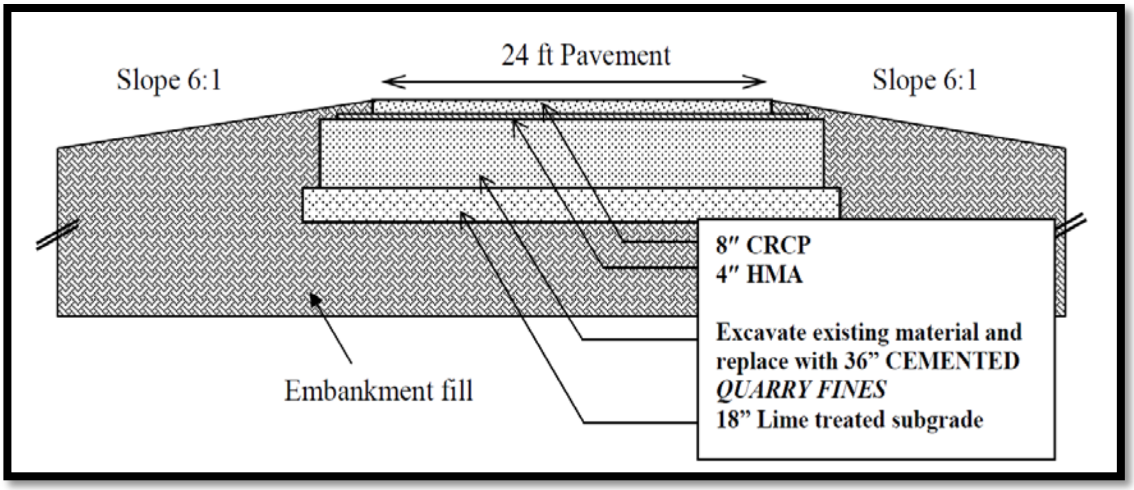


Figure 2. Typical test embankment with cement-treated quarry fines as a pavement base material in Arlington, Texas (Puppala et al., 2012).

2.1.4.2 Mechanical Stabilization of Weak Subgrade with Stone Screenings.

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 depends on the soils and the desired CBR.

2.1.4.3 Ready Mixed Flowable Fill

2.1.4.3.1 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 ¾ in and 0-10% passing No. 200 sieve), and water. Flowable fill is designed as a low strength, fluid material requiring no subsequent compaction efforts like 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 psi (137.9 kPa) to 200 psi (1379 kPa) with 40-100 psi (275.8 to 689.5 kPa), 28-day strength specified by the majority of states and 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 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. This report emphasized that the benefits of using quarry fines are highly dependent on the source of quarry fines; as a result, the mix ratio of the important parameters in flowable fill varies depending on the quarry fines properties. Some quarry fines may produce a cost effective flowable mix when replaced completely or partially with sand, while others increase water and or cement content to obtain specified consistency.

2.1.4.3.2 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. The Department of Civil Engineering at Tennessee Technological University, 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.

2.1.4.4 Partial Replacement of Sand in Concrete

2.1.4.4.1 Lohani et al. (2012)

Lohani et al.(2012) found that replacement of sand with quarry dust in concrete improved the properties of the mixture. 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 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%, respectively, 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 increased slightly with an increase in percentage of quarry dust content. The modulus of elasticity at 28 days curing for 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.

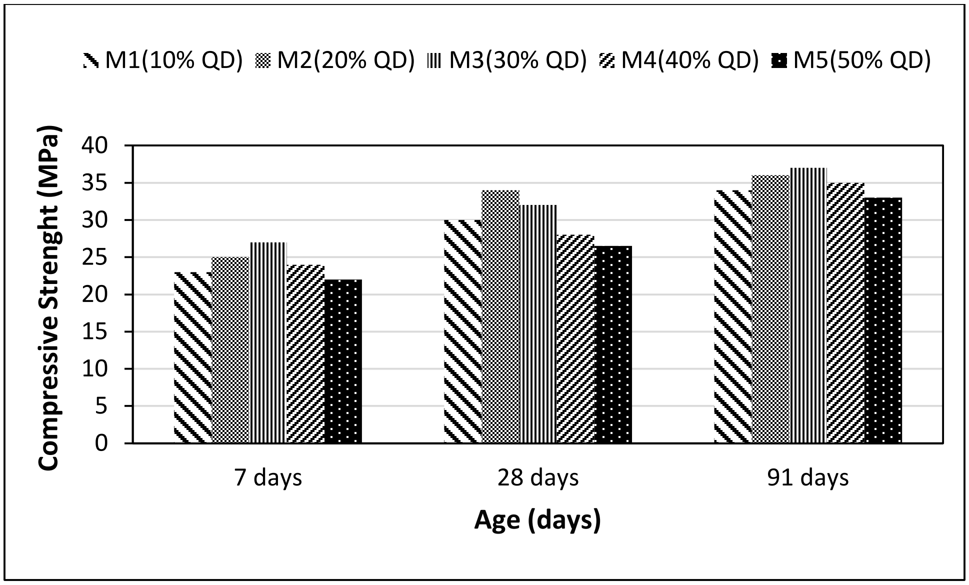


Figure 3. Compressive strength of different mixes with age (Lohani et al., 2012).

2.1.4.5 Self-Compacting Concrete

2.1.4.5.1 Naik et al.(2005)

Naik et al.(2005) examined the use of quarry fines in self-compacting concrete. They found that the addition of quarry fines minimized the addition of the admixture without reducing the strength of the self-compacting concrete. 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 the overall strength.

2.1.5 SUMMARY

Quarry dust, quarry waste, quarry fines, and QB 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, studies conducted to characterize QB showed that the strength properties of aggregate by-products are very low and can be improved by adding 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, and self-compacting concrete.

2.2 Geosynthetics

Another possible approach to increase sustainability in pavements is using geosynthetics. The use of geosynthetics in pavement applications may reduce the total thickness and/or reduce the total cost associated with construction of pavements (Al-Qadi and Yang, 2007). Significant efforts are being exerted to quantify the environmental emissions and total energy consumption associated with the construction and production of materials used in construction of pavements (Kang, 2013; Yang, 2014). However, limited work has been done to quantify the environmental impacts associated with geosynthetics used in pavement systems. Most of the tools used to quantify environmental impacts of pavements lack the life-cycle inventories data for geosynthetics. Therefore it is not easy to evaluate the environmental impacts associated with geosynthetics reinforced/stabilized pavements.

In a research conducted at UIUC, a pavement life-cycle assessment (p-ILCA) tool that uses the life-cycle analysis technique was developed to quantify the environmental impacts of different types of pavements (Yang 2014). While this tool contains most of the LCI for different materials used in construction of pavements, this tool lacks LCI for geosynthetics and, therefore, the tool is limited to the environmental impacts of pavements, without geosynthetics reinforcement. This section discusses existing LCI inventory data and the environmental impacts related to the production of geosynthetics. An overview of the variability of regional data related to production of geosynthetics is also discussed in this section.

2.2.1 Production of Geosynthetics

Werth et al.(2012) and Stucki et al.(2013) conducted studies that summarize the inventories related to production of geosynthetics. These studies also present details of the raw materials used in the production of geosynthetics, which are very essential to understand the processes for producing geosynthetics. Most of the data reviewed in the literature are based on European standards and production techniques that may be different from the one used in the U.S.

2.2.1.1 Raw Materials Used in the Manufacture of Geosynthetics

The manufacturing of geosynthetics starts with the production and acquisition of raw materials that include polymer resin. Along with polymer, various additives such as antioxidants, plasticizers, fillers, carbon black, and lubricants are added (Koerner, 2012). Depending on the intended purpose of geosynthetics, the amount and properties of these raw materials may vary from manufacturer to another. Therefore, the best source of LCI data for geosynthetics can be obtained from the manufacturers, provided that the property of the geosynthetics to be used in a specific study is known (Stucki et al., 2013). The four main polymer families most widely used as raw material for geosynthetics production are polyester, polyamide (nylon), polypropylene, and polyethylene. Table 3 shows the common polymers used in the manufacturing of various types of geosynthetics.

Table 3. Polymers Used in Manufacturing of Different Types of Geosynthetics

Geosynthetics Type	Main Polymer Used
Geomembranes	Polypropylene(PP)
Geonets	Polyethylenes(HDPE)
Geogrids	HDPE, polyesters, polypropylene (PP)
Geotextile	PP, polyesters

2.2.2 Life-Cycle Inventory for Production of Geosynthetics

Life-cycle assessment (LCA) is a potential technique used to quantify the environmental burden associated with production and use of geosynthetics in pavement. It is very crucial to understand all stages of geosynthetics processing to minimize the uncertainty associated with the use of this technique. Unlike the U.S., the European Association for Geosynthetics manufactures (EAGM) have invested a lot of efforts to study the environmental impacts associated with the use of geosynthetics and to quantify the benefits of using geosynthetics in construction of civil engineering infrastructures.

2.2.2.1 Werth et al.(2012)

Werth et al.(2012) conducted an LCA study to compare the environmental impacts associated with the use of geosynthetic drainage layer with the use of conventional materials. This study has shown that the cumulative greenhouse gas emissions associated with the geosynthetic drainage layer was 2.7kg CO_2-eq per kg. Figure 4 shows the environmental impacts of geosynthetics layer used in this study. Werth et al.(2012) concluded that the overall environmental impacts associated with production of geosynthetics are dominated by raw materials and electricty consumption (Figure 4). Moreover, the authors found that, when geosynthentics is used as drainage layer, energy consumption and environmental emissions were very low compared with the use of conventional materials.

2.2.2.2 Research Center for Energy Economics (FFE 1999)

According to Germany Research Center for Energy and business, Study FFE 1999 has reported that the production of 1kg polypropylene (PP) geogrid emits 2.28 kg of CO_2 and consumes 78.7 MJ of energy. In this study, exploration, treatment, and transport of crude oil to the refinery, distillation and steam cracking of polypropylene, polymerization and injection into PP molded part were considered. While this thesis focuses more on CO_2 emissions and total energy consumption, all emissions reported by FFE 1999 are summarized in Table 4 below.

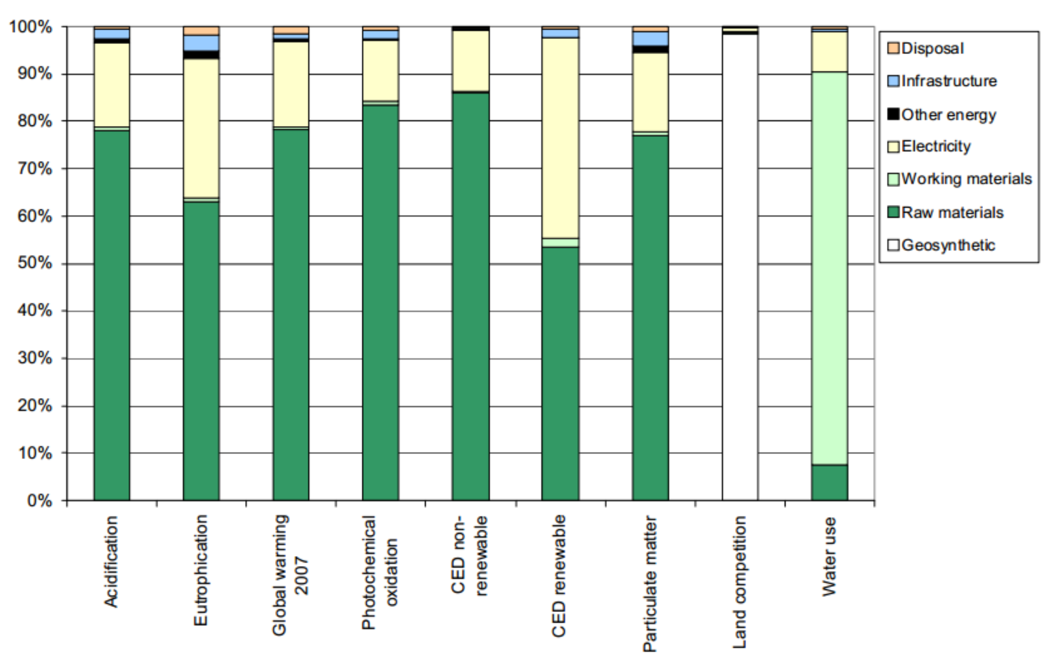


Figure 4. Environmental impacts caused by the geosynthetic drainage layer (Werth et al., 2012).

Table 4. Emissions and Total Energy Consumption for Production of 1 Kg of PP Injection Moulded Part

Product	**CED [MJ]**	**CO_2 [kg]**	**CO [g]**	**NO_x [g]**	**SO_2 [g]**	**CH_4 [g]**	**MNVOC [g]**	**N_2O [g]**	**dust [g]**
Production 1kg PP-geogrid	78.7	2.28	1.7	6.8	4.3	8.7	9.8	0.1	0.7

2.2.2.3 University of Bath

The Department of Mechanical Engineering at the University of Bath, U.K. developed the Inventory of Carbon and Energy (ICE) database for different materials including geosynthetics (Table 5). Even though these inventories were developed based on U.K. standards, they are reported in EPA 2005 report and are currently being used to reflect the production of geosynthetics in the U.S.

Table 5. CO_2 Inventory for Production of Different Raw Materials Used In Production of Geosynthetics

Material	Material (kg-CO_2/kg)
HDPE Geosynthetic	1.6
Geomembrane (PE)	1.75
Geotextile-polypropylene	2.7

2.2.2.4 Stucki et al.(2013)

Stucki et al.(2013) studied the LCA assessment of gravel and geosynthetics-based filter layers. The pavement filter layer of 30 cm and functional equivalent of the geosynthetics filter were compared through LCA for a period of 30 years. The processes considered in this study are raw material supply, manufacture of the geotextiles, and extraction of mineral resources. In addition, the construction phase, use phase, and end of life phase were considered in this study. The authors found out that geosynthetics-based filter layer resulted in lower environmental impacts per unit area (square meter). Cumulative greenhouse gas emissions were 0.81 kg CO_2-eq for geosynthetics-based filter compared with 7.8 kg CO_2-eq for gravel-based filter. In fact, the environmental impacts of the geosynthetics-based filler were dominated by material provision (plastic granulate) and electric consumption during manufacturing of the geosynthetics. In the same report, Stucki et al.(2013) compared the environmental impacts associated with pavement foundation stabilization. The environmental impacts of using cement, lime, hydraulic binder and geosynthetics were assessed and compared. The use of geosynthetics resulted in 28% reduction in gravel compared with conventional stabilization (where no stabilizer was used). According to Stucki et al.(2013), the production of geosynthetics used for roadway stabilization emits 3.4 kg CO_2-eq; these emissions are dominated by raw material provision and electric consumption. For all alternatives compared, the emissions resulting from stabilization of 1 km stabilized road were 730 t CO_2-eq for conventional, 650 t CO_2-eq for geosynthetics-reinforced, and 950 t CO_2-eq for cement/quicklime stabilized pavement foundation. These results show that the geosynthetics-reinforced pavements resulted in lower CO_2 emissions and that geosynthetics not only improve the engineering properties of the pavements but are also environmentally friendly for this particular application.

2.2.3 Summary

The studies conducted in Europe show that the pavement stabilized/reinforced with geosynthetics can reduce CO_2 emissions and energy consumption compared with unstabilized/unreinforced pavements (conventional pavements). Reduction in emissions and energy consumption is primarily governed by reduction in thickness and the volume of the base or subbase materials used. The impacts associated with the production of geosynthetics depend on the type and production region due to differences in production process and upstream energy impacts (i.e. regional difference in electricity production). The literature shows that polypropylene (PP), polyethylene (HDPE), and polyesters are the most common raw materials used for producing different types of geosynthetics. The production of geosynthetics consumes energy and releases CO_2 into the atmosphere; this process is dominated by raw materials production and electricity consumption during production of these raw materials. Therefore, the amount of energy consumed and CO_2 released depends on the type of geosynthetics produced and the region where the inventory data related to the production of electricity was collected. There is limited carbon footprint and energy consumption data associated with the production of geosynthetics in the U.S. Most of the data reported by the U.S Environmental Protection Agency (EPA) are based on European geosynthetics production standards, or were retrieved from findings of studies conducted in Europe. Because of the differences in electricity production and distribution, and material production between the U.S. and Europe/other parts of the world, the data obtained from studies conducted in Europe and other parts of the world may not necessarily represent the emissions and energy consumption caused by production of geosynthetics in the U.S. Therefore, there is a need to evaluate emissions and energy consumption related to production of geosynthetics in the U.S.

3 CHARACTERIZATION AND STABILIZATION OF QB FOR PAVEMENT APPLICATIONS

3.1 Introduction

Nearly two billion tons of aggregate are produced every year in the U.S. with a value of approximately $17.2 billion, contributing an average of $40 billion to the American gross domestic product (National Stone, Sand and Gravel Report, 2014). Although the production of aggregate contributes significantly to the economy, the by-products associated with production of aggregates are often considered as waste. According to the International Center for Aggregates, stockpiling and disposal of aggregate by-products is a major problem facing the aggregate industry (Hudson et al., 1997).

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 QB as referred to herein, are typically less than ¼ in (6 mm) in size and consist of coarse, medium, and fine sand particles, and a clay/silt fraction, which is less than No. 200 sieve (0.075 mm) in size. Current economic conditions and the increased emphasis in the construction industry on sustainability and recycling encourage the production of aggregate gradations with lower dust and smaller maximum sizes. These new production limitations resulted in "unbalanced" aggregates production stream, in part because of the demand for cleaner aggregates with smaller top sizes in light of the increased use of finer asphalt concrete mixes, thus resulting in excessive energy use and increased waste fines. Because of these increased energy and disposal costs for aggregate production, reusing and recycling of waste products (e.g., reclaimed asphalt pavement [RAP], recycled asphalt shingles [RAS], and recycled concrete aggregate [RCA]) may sometimes exceed the potential economic and environmental benefits.

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 recent NCHRP Synthesis 435 (volume 4), depending on the type of rock quarried, QB can be up to 25% of the total aggregate produced (Stroup-Gardiner and Wattenberg-Komas, 2013). This reflects a high production rate of QB, and the need exists for more green applications in which higher amounts of QB can be used.

Several studies report successful use of QB in road base/embankment and flowable fill applications (Kumar and Hudson, 1992; McClellan et al., 2002). Like other materials used in construction, the engineering properties of QB greatly determine their suitability for pavement applications. For example, the unbound application of QB has been a focus of several research studies (Stroup-Gardiner and Wattenberg-Komas, 2013; Kumar and Hudson, 1992; Kalcheff and Machemehl, 1980; Puppala et al., 2008); however, there are no complete specifications or guidelines for incorporating QB in these applications. Several factors affect the quality of QB, which should be evaluated before using them for a particular application. McClellan et al., 2002 reported engineering backfill as a potential area of 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 to quantify the amounts of minerals that are harmful to any of the anticipated applications. The best way to determine the properties of QB 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 QB are produced from identical rock types using similar technologies (Pitre, 2012).

Through a series of QB sample evaluations, Kumar and Hudson (1992) showed that quarry fines can generally be divided into six categories based on the percentage passing the No.

200 sieve. In the same research, Kumar and Hudson also proposed base course material additive, flowable fill, underslab 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 as compared with granular soil-cement stabilization. This also has an advantage of decreasing shrinkage cracking because of 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 the 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. Based on field and laboratory studies, Puppala et al.(2008) concluded that the strength and resilient modulus of cement-treated quarry fines are similar to those of sandy material with very few fines. The authors also suggested that further experimental research be conducted to understand the permanent deformation behavior of cement-treated quarry fines.

3.2 Overview of QB Production in Illinois

To understand the current QB production in the State of Illinois, a survey questionnaire was prepared and distributed to Illinois aggregate producers. The survey questionnaire included questions such as annual production amounts of QB, crushing procedures and equipment used, current applications of excess QB, and post-production tests. Survey responses were intended to help producers, transportation agencies, and researchers gain knowledge about the general production volumes and procedures of aggregate by-products and better understand potential application areas for local QB utilization. In July 2013, a survey questionnaire was sent out to stone quarries operating throughout Illinois with the help and oversight of the Specifications Committee of the Illinois Association of Aggregate

Producers (IAAP). 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 Illinois; therefore, the responses received represent 42 quarries. Also among the respondents are three of the top five crushed stone producers (ranked according to number of quarries operating in Illinois) that are more likely to experience excess QB problems.

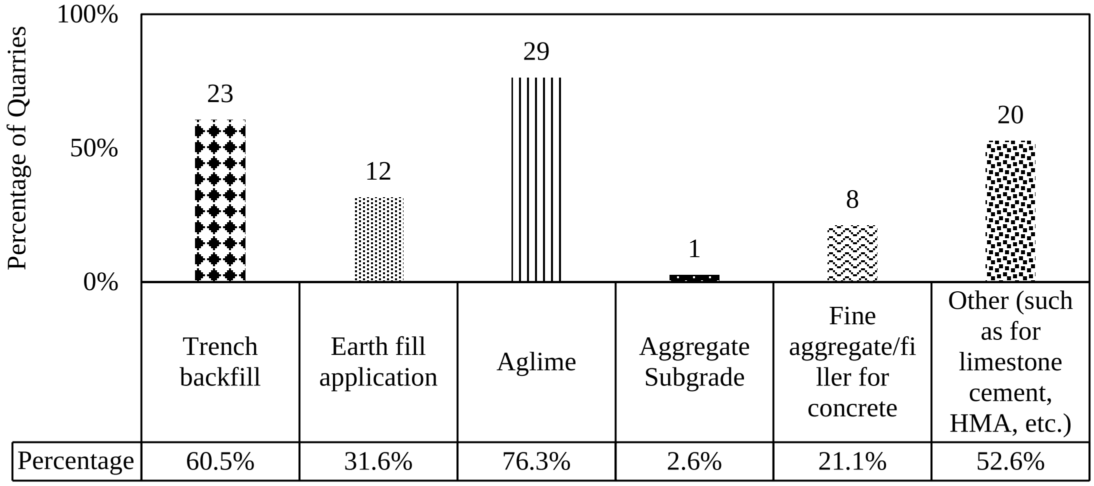
According to survey results, 90% of respondents are producing QB (defined in the questionnaire as “typically less than ¼ in in size”). Table 6 lists the typical annual tonnage information collected. Among the quarries that produce quarry fines, 55% have a typical annual amount of QB greater than 100,000 tons; 26% between 25,000 and 100,000 tons, and 19% less than 25,000 tons. Thirty three of the quarries surveyed (78% of respondents) have excess fines that are not currently used in a calendar year. The approximate amounts of excess fines produced in a year are listed in Table 6. Six respondents indicated that over 100,000 tons of QB were not fully used each year. Fourteen respondents indicated over 25,000 tons of QB were in excess category. The excessive QB produced each year are as high as, or even greater than, 950,000 tons in the 20 quarries that responded 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 aglime or other products for agricultural applications.

Table 6. Survey Results: Quarry By-product Production

	Annual Tonnage of QB	**Annual Tonnage of Quarry By-product in Excess Category (e.g. not used/sold)**
Quantity Category	[Percent of Respondents]	[Percent of Respondents]
Less than 25,000 tons	18.4	39.4
Between 25,000 & 100,000 tons	26.3	42.4
Greater than 100,000 tons	55.3	18.2
No. of respondents	38	33

Approximately, 9%, 38%, and 38% of the respondents indicated that primary, secondary, and tertiary crushing/screening stages produced the most amount of fines, respectively. 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%.

Regarding the current use of QB, several application areas were reported in the survey. The results collected from 38 survey respondents are presented in Figure 5, indicating the usage percentages for each application. The most common application is agricultural lime, also called 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 (HMA) production. Based on the survey results, large amounts of quarry fines are generated through the crushing/screening stages, and a substantial portion of these quarry fines are not currently used. Excess fines produced every year are stored in nearby stockpiles. Hence, it would be of value to find potential application areas in pavements for these by-product materials. Such applications would help use the excess fines accumulating in the stockpiles while improving sustainability of pavements and reducing the cost of pavement construction by replacing virgin materials by QB.



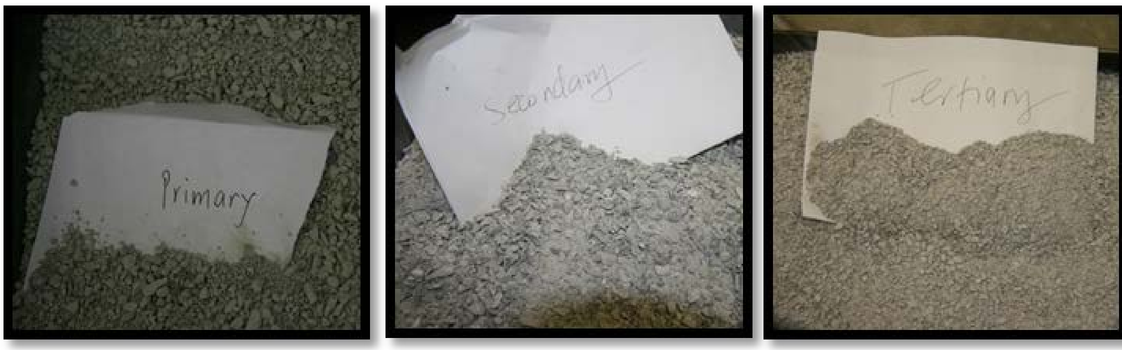
No. of respondents was 38. No. above the chart bars indicate the No. of quarries utilizing QB for that application.
Note: Respondents own at least one quarry

Figure 5. Percent use of different quarry by-product applications.

3.3 Laboratory Assessment of Properties of QB-(Prior to Stabilization)

Both literature review and the survey have shown that QB can be used in pavement applications; however; there are no developed specifications on how to incorporate QB in pavement. To establish and understand the characteristics of QB, a detailed laboratory test matrix was developed to determine basic properties of the collected QB samples so that a framework could be established to evaluate engineering characteristics for the most suitable pavement applications.

The scope of the experimental program focused on assessing the suitability of QB for unbound pavement applications; and the scope for this testing includes gradation, particle shape properties, and strength characteristics of QB produced in each crushing stage. Aggregate by-product samples were obtained from a quarry that generates large quantities of QB annually near Chicago, IL. Two batches of QB samples were collected within a 5-month period, first in December 2013 (batch #1) and then in April 2014 (batch #2). In each case, the materials were sampled from three main crushing/screening stages—primary, secondary, and tertiary as shown in the Figure 6. Collecting two batches of materials also allowed the evaluation of variability in the engineering properties of QB materials sampled at different times.



(a) (b) (c)

Figure 6. Samples collected from different crushing stages: (a) Primary, (b) secondary, (c) tertiary stage.

In addition to sieve analysis and the imaging-based aggregate shape testing, modified methylene blue, moisture density, atterberg limits, unconfined compressive strength (UCS), and direct shear tests were conducted on the QB samples. The quarry staff provided X-ray diffraction test results. Chemical oxide compositions of QB samples obtained from X-ray diffraction were used to determine their adequacy for admixture treatment. Both Portland cement and Class C fly ash type chemical admixtures were considered to treat and evaluate strength gain of QB samples.

3.3.1 X-Ray Diffraction and MMB Test

Table 7 presents the X-ray diffraction results of the aggregate by-product compositions for the QB samples used in this study. As shown in the Table 7, calcium and magnesium carbonates are the major components of 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 in the three crushing stages. The secondary and tertiary crusher by-products were quite similar in mineralogy. Compared with the secondary and tertiary crusher by-products, the primary crusher samples exhibited only a slight difference in the chemical composition.

The clay contents of the aggregate by-products were determined from a modified methylene blue test, which helps to quickly assess the amount of harmful clay in the fines portion of the aggregates (Pitre, 2012*)*. The average harmful clay contents for both samples were very low (1.24% for primary QB, 0.57% for secondary, and 0.28 % for tertiary), indicating that the materials contained only a slight amount of clay because the samples were newly crushed and were not allowed to mix with deleterious materials. In general, there was no difference in the harmful clay contents of the samples from the two batches and, therefore, an average value was taken to represent the harmful clay content of the QB. A slightly higher amount of clay was found in the primary aggregate by-product samples when compared with the samples obtained from the secondary and tertiary crushing stages. In general, the harmful clay content of the aggregate by-products decreased from the primary to the tertiary crushers. This is possibly caused by the weathered rock from quarries or the overburden material, more likely to be found in the quarried rocks in the primary crusher.

Table 7. Summary of Mineralogical Composition of QB*

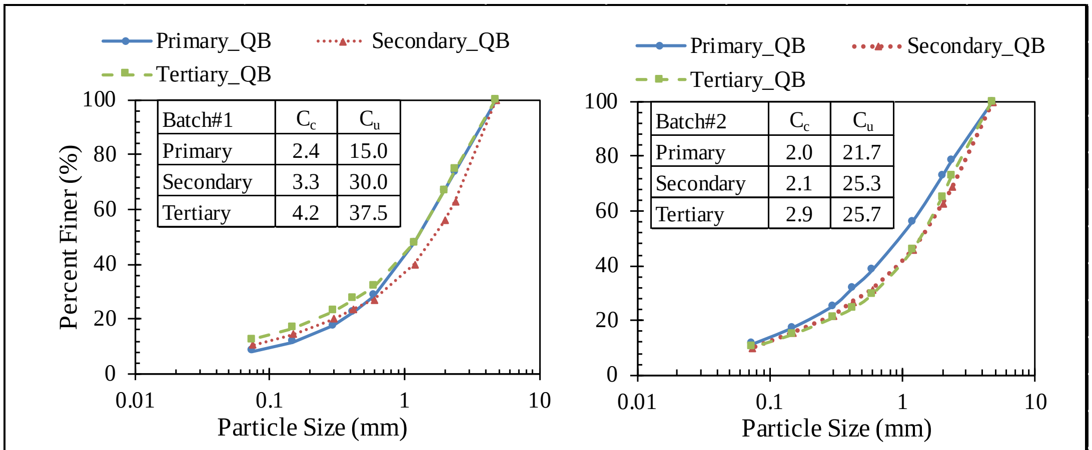
Crushing Stage	$Caco_3$	$Mgco_3$	Sio_2	Al_2o_3	Fe_2o_3	Mn_2o_3	So_3	K_2o	P_2o_5	Total
Primary	49.65	38.47	8.56	1.46	0.80	0.04	0.33	0.64	0.04	99.99
Secondary	50.27	40.52	6.62	1.05	0.66	0.04	0.20	0.53	0.04	99.93
Tertiary	50.38	40.47	6.63	1.03	0.65	0.04	0.20	0.52	0.04	99.97

*Obtained from quarry staff; values represent averages for two batches of samples.

3.3.2 Grain Size Distribution

Figure 7 shows the particle size distribution of aggregate by-products determined according to standard test method for particle size analysis of soils (ASTM D422). For two batches of QB produced and 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 samples were compared based on production stages and batch numbers. Accordingly, differences in percent passing amounts were tabulated for the different sieve sizes. A higher absolute difference in percent passing sieve sizes was found for the primary stage QB samples. The largest absolute percent passing difference was up to 50.8%, which was observed for the No. 100 sieve size, while 16.4% and 14.7% were observed for the No. 30 and No. 200 sieves for secondary and tertiary stage samples, respectively. The average values of percent passing No. 200 sieve (75 µm) were 9.9%, 10.2%, 11.4% for the primary, secondary, and tertiary stage samples, respectively. The maximum aggregate by-product size was 4.75 mm (approximately 1/5 in) amongst all the six samples collected in the two batches.

According to Figure 7, the first batch of QB samples from the primary, secondary, and tertiary crushing stages have 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 had c_c of 2.0, 2.1, and 2.9 and c_u of 22, 25, and 26, respectively. Atterberg limit tests were performed in accordance with the standard test methods for liquid limit, plastic limit, and plasticity index of soils (ASTM D4318-10). Samples from the three crushing stages were nonplastic and the liquid limits were 14.0, 13.1, and 13.3% for the primary, secondary, and tertiary crusher materials, respectively. Based on the Unified Soil Classification System (USCS), the samples from the first batch 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; whereas, samples of the second batch were all classified as SW-SM-SM, poorly graded silty sand (SP-SM), and silty sand (SM), for the primary, secondary, and tertiary crushing stages, respectively; whereas, samples of the second batch were all classified as SW-SM.



	Primary QB			Secondary QB			Tertiary QB		
Sieve size	%Passing [1]	%Passing [2]	[1]-[2]	%Passing [1]	%Passing [2]	[1]-[2]	%Passing [1]	%Passing [2]	[1]-[2]
3/8"	100.0	100.0	0.0	100.0	100.0	0.0	100.0	100.0	0.0
#4	99.6	99.9	-0.3	99.8	99.8	0.0	100.0	100.0	0.0
#8	73.6	78.8	-7.0	63.0	68.9	-9.4	74.4	73.0	1.8
#16	47.7	56.2	-17.8	40.0	45.8	-14.5	47.9	45.7	4.4
#30	28.5	38.6	-35.7	27.1	31.6	-16.4	31.8	29.8	6.2
#40	22.7	31.8	-40.5	23.8	26.9	-13.1	27.4	24.6	10.3
#100	11.6	17.5	-50.8	14.4	15.5	-7.4	16.7	15.2	9.2
#200	8.3	11.5	-38.0	10.5	9.8	6.7	12.3	10.5	14.7
Pan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

[1] and [2] imply to first and second batches, respectively.

Figure 7. Grain size distribution curves for QB.

3.3.3 Moisture Density Properties

In accordance with the ASTM D698, the moisture density compaction characteristics of the virgin QB samples were evaluated for the three crushing stages. The optimum moisture content for the tertiary crusher samples was slightly higher at 10.4%, followed by the primary crusher samples at 9% and, finally, secondary crusher samples at 8.6%. Conversely, a higher maximum dry density of 142.1 pcf was observed for the primary crusher samples, followed by 138.6 pcf for the secondary and 135.4 pcf for the tertiary samples.

3.3.4 Direct Shear Test Results

Direct shear tests were conducted using an automated pneumatic direct shear testing device following the ASTM D3080 method (Figure 8). The tests were performed on square prismatic specimens 4 in in size with a thickness of 1 in, at rate of 0.005 in/min. All the QB specimens were conditioned for a minimum of 3 hrs at the optimum moisture contents and compacted to 95% of their maximum dry densities. The direct shear tests were conducted only on QB samples from the second batch under three normal stress conditions, 10 psi, 15 psi, and 20 psi. Two test repetitions were considered at each normal stress.

Figure 8. A sample prepared for the direct shear test.

Figure 9 shows the results obtained from the direct shear test. Figure 9 (a) shows the relationships obtained between the normal stress and maximum shear stress; R^2 values are over 0.8. The friction angles obtained for primary, secondary, and tertiary crusher 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 9 (b) shows typical test results obtained under 10 psi normal stress. Note that the three QB materials have similar responses to shearing. The shear stress increases with shear displacement until the maximum peak failure condition, and then gradually decreases. Dilative characteristics of the samples from the three crushing stage is similar, with a slight reduction in the tertiary QB.

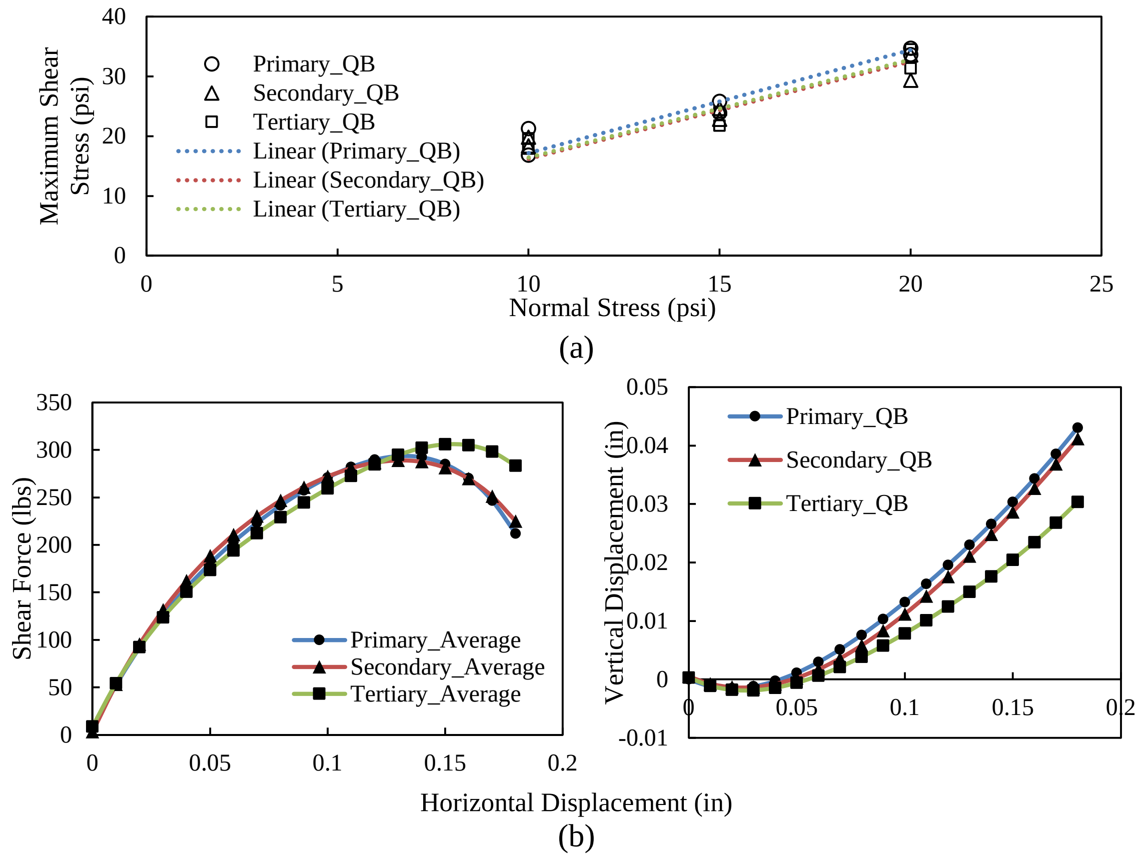


Figure 9. Direct shear test results: (a) maximum shear stress under different normal stresses; (b) shear force and vertical displacement varying with horizontal displacement at 10 psi normal stress.

3.3.5 Unconfined Compressive Strength Test Results

To evaluate the strength properties of QB, four samples (one from each production stage in the first batch and the other three from each production stage of the second batch), 2.8 in in diameter by 5.6 in in height, were prepared for conducting the UCS tests for each QB material according to ASTM D-2166 standards. While all strength properties were very low for all production stages, it was observed that UCS values decreased from the primary crusher QB, with an average value of 10.5 psi, to the secondary crusher samples at 8.8 psi; the tertiary crusher samples exhibited the lowest UCS value of 3.3 psi. On the other hand, the results obtained from the direct shear tests showed high friction angle values because of the higher confinement. Despite the high friction angle of QB, the compressive strength values of the materials were low, indicating the need for improvement through stabilization. Therefore, Portland cement and Class C fly ash were used to improve the strength characteristics of the QB.

3.3.6 Image Analysis for Particle Shape and Angularity

Aggregate particle shape, texture, and angularity have been recognized to influence the engineering behavior of unbound aggregates. The 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 (CCD) progressive scan color cameras to capture three orthogonal views (front, top, and side) of individual particles for establishing the morphological indices of aggregate particle shape, texture, and angularity. More details on the features of the E-UIAIA can be found elsewhere (Moaveni at al., 2013). Figure 10 shows the E-UIAIA and the three side views captured by it.

The flat and elongated (F&E) ratio and angularity index (AI) were the key indices—measured with E-UIAIA—to determine physical properties of QB. As introduced in test scheme section, particle shape properties were conducted on all collected samples. Approximately 100 particles retained on the No.8 sieve were scanned for each material from the second batch so that trends in particle shape could be identified and compared. Average AI values for QB materials from primary, secondary, and tertiary crusher are 497, 550, and 542, respectively. QB samples from the primary crusher had the lowest AI value. The samples from the secondary crusher had slightly higher value than the samples from the tertiary crusher. Average AI values for QB materials from primary, secondary, and tertiary crusher are 497, 550, and 542, respectively. QB samples from the primary crusher had the lowest AI value.

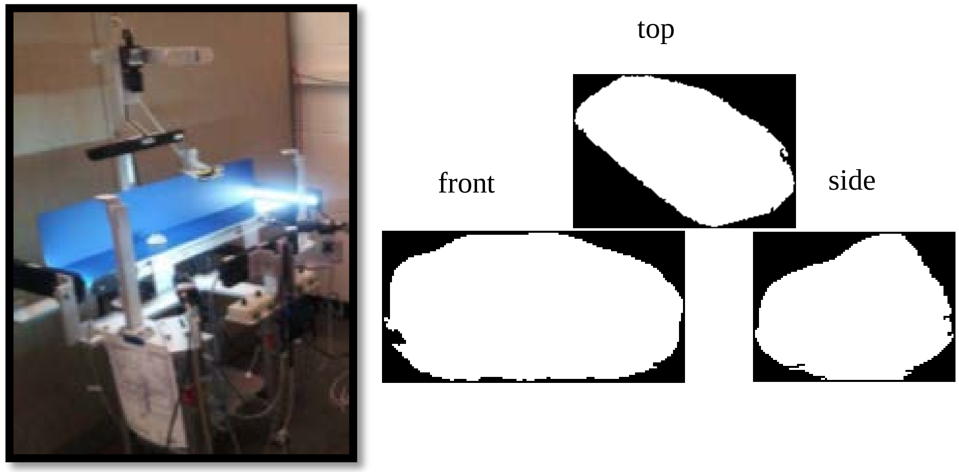


Figure 10. E-UIAIA and captured side views.

Average AI values for QB materials from primary, secondary, and tertiary crusher are 497, 550, and 542, respectively. QB samples from the primary crusher had the lowest AI value. 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; QB from the secondary crusher were more angular. Average F&E ratios for QB materials from primary, secondary, and tertiary crusher were 2.3, 3.2, and 3.3, respectively. Another trend observed is that QB from primary crusher had the lowest F&E ratio and QB from the secondary tertiary crushers had very close F&E ratios. These findings indicate that particles from primary crusher were more cubical and, therefore, may have better resistance to breakage.

3.4 Laboratory Assessment of Properties of QB (Treated)

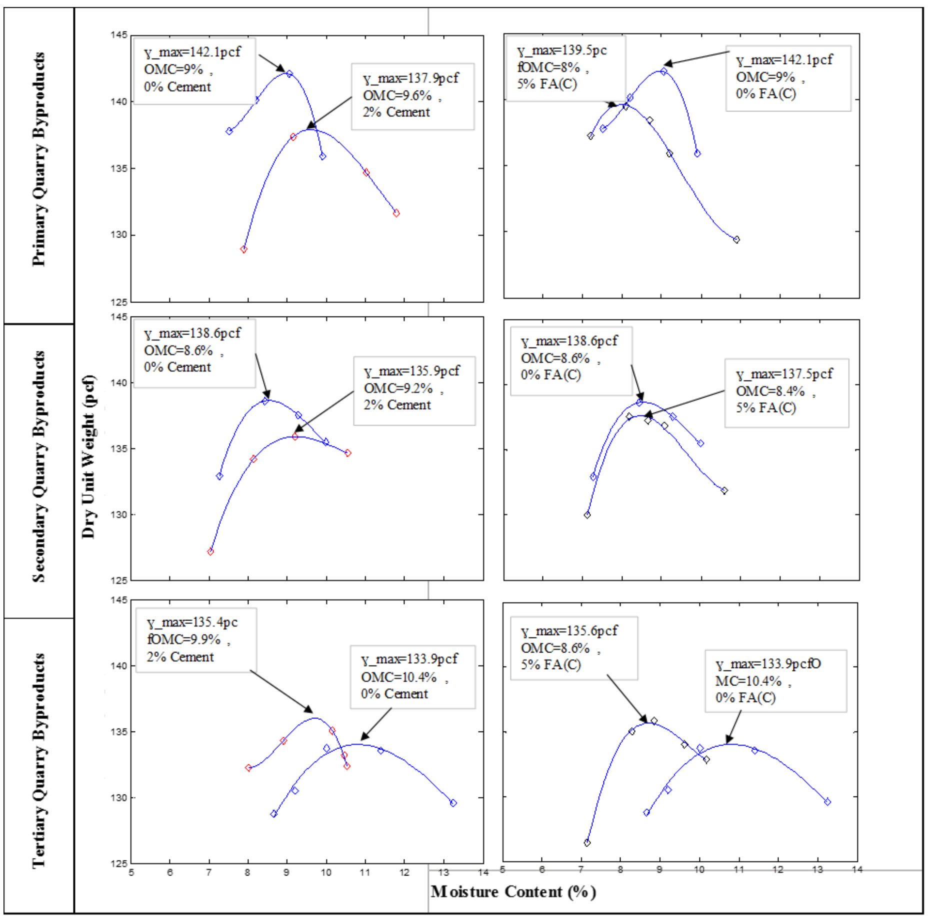
To increase the strength properties of the QB samples, chemical stabilizers were chosen for this study. While chemical stabilization of soil and aggregates improves their physical and engineering properties, this process heavily depends on the chemical reaction between soil/aggregates and the stabilizers. It is very important to choose the right stabilizers to effectively improve the strength. Economical stabilizers with maximum strength gain and low environmental impacts were preferred in this study. Studies have shown that lower cement content is economical and was successfully used to stabilize QB. Moreover, lower cement content has benefits of reducing shrinkage potential of cemented materials. 2% Type I Portland cement by weight of oven dry aggregate by-products was used in this study. Like cement, Class C fly ash possesses cementitious and pozzolanic properties that do not depend on the reaction with clay particles to develop strength. Based on trial and error method, 5% and 10% Class C fly ash were also used to improve the strength properties of aggregate by-products.

3.4.1 Moisture Density Properties

To increase the strength properties of the QB samples, 2% Portland cement, 5% Class C fly ash, and 10% Class C fly ash were used as stabilizers. The Class C fly ash material conformed to ASTM C-618 and AASHTO-M295 standards. The compaction curves were determined per the ASTM D558 method for the QB samples treated with both stabilizers.

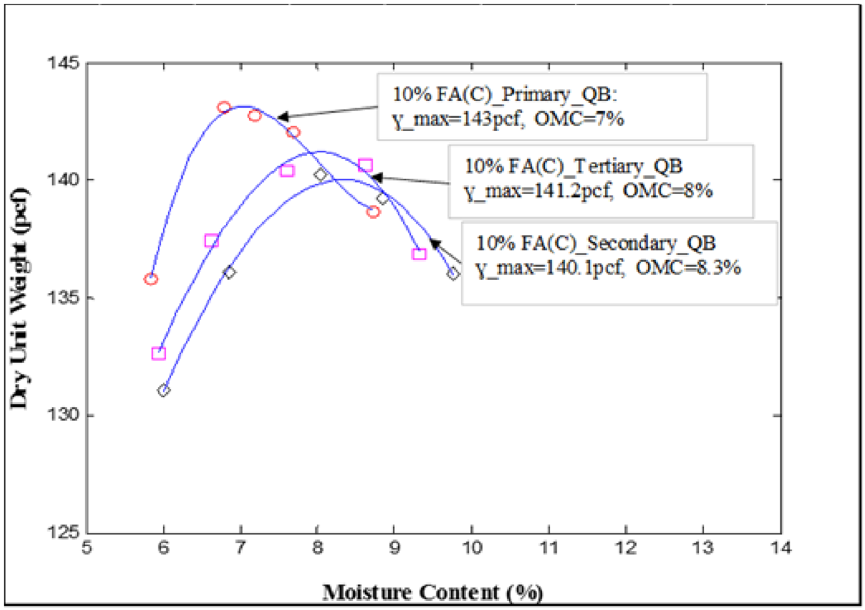
Figure 11 (a) compares the moisture density characteristics of the virgin and stabilized aggregate by-products. The addition of the 2% cement resulted in a reduced maximum dry density and increased optimum moisture content trend for the primary and secondary crusher QB samples. Conversely, the addition of Class C fly ash resulted in a reduced maximum dry density and increased optimum moisture content trend with these QB samples. Such a difference in the characteristics of aggregate by-products stabilized with Portland cement and Class C fly ash is attributed to the various amounts of free lime each stabilizer contributes during the flocculation and agglomeration of the treated QB samples. Unlike the primary and secondary crusher aggregate by-products, the maximum densities for the tertiary crusher QB samples slightly increased when cement and Class C fly ash were added.

Figure 11 (b) shows a comparison of moisture density characteristics of the three categories of QB samples when 10% Class C fly ash was added. The results show that the primary crusher QB samples exhibit higher maximum dry densities and lower optimum moisture contents, followed by the tertiary crusher QB samples. The secondary crusher stage by-products had the lowest maximum dry densities and the highest optimum moisture contents. These findings confirm that the moisture density behavior of the three categories of aggregate by-products is different and highly dependent on the type of stabilizers used. The results also show that maximum dry densities achieved for all QB samples were in the range of 130 pcf to 140 pcf, and the optimum moisture contents for all QB samples were in the range of 7% to 10.5%, regardless of the type of stabilizer.



(a)

Figure 11 . Moisture density characteristics of QB (a) treated with 2% Portland cement and 5% Class C fly ash.



(b)

Figure 11 (cont.). Moisture density characteristics of QB treated with 10% Class C fly ash (b).

3.4.2 Unconfined Compressive Strength Test Results

Unconfined compressive strength (UCS) tests were also conducted on the QB materials to investigate their shear strength properties both in the unstabilized and admixture-treated conditions. UCS tests are commonly performed for evaluating benefits of chemical admixture treatment and for showing 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 both virgin and treated aggregate by-products were used to prepare the samples for the UCS tests. Samples 2.8 in in diameter by 5.6 in in height were prepared for conducting the UCS tests for virgin materials as per ASTM D-2166 method.

Because of the shortage of materials from the first batch QB samples, only one specimen from each type of crushing stage was prepared and tested. Two test repetitions were carried out per ASTM D-1632 and ASTM D-1633 for each of the 2% cement–treated materials. All samples treated with admixtures were cured for seven days at room temperature under

100% humidity. Before UCS testing, all stabilized samples were soaked for 4 hrs to evaluate the effect of harsh moist environment on the strength properties. Significant strength increases were observed after treating QB specimens with 2% cement. However, more repetitions were needed to validate the findings, which led to the collection and testing of the second batch of QB samples. Both 5% and 10% Class C fly ash stabilization were considered with the second batch QB materials.

Using the second batch of QB samples, three UCS tests were first performed on virgin unstabilized specimens. Two more tests repetitions were conducted for the 2% cement-treatment and the three more repetitions of the 5% and 10% Class C fly ash stabilized samples. Details of test replicates and UCS properties measured are shown in Table 8.

Table 8. Unconfined Compressive Strength Test Results (psi)

QB Sample	Batch No.	Test No.	Virgin (untreated)	2% Cement	5% Class C Fly Ash	10% Class C Fly Ash
Primary Crusher	1	1	17.0	189	-	-
		2	-	215	-	-
	2	1	8.7	196	103	335
		2	9.5	206	106	315
		3	6.8	-	105	347
Secondary Crusher	1	1	13.0	157	-	-
		2	-	164	-	-
	2	1	6.8	257	154	324
		2	7.1	273	145	360
		3	8.2	-	167	318
Tertiary Crusher	1	1	7.0	181	-	-
		2	-	196	-	-
	2	1	2.7	212	119	356
		2	3.4	231	132	337
		3	2.6	-	90	337

"-": test not conducted.

Table 8 shows virgin (untreated) aggregate by-products with very low UCS values, with an average of 10.5 psi for the primary, 8.8 psi for the secondary, and 3.9 psi for the tertiary crushing stages. Despite the fact that the two QB samples of the primary crusher showed considerable variation in angularity and particle size distribution, the average UCS values obtained from the two samples treated with 2% cement were quite similar. Unlike the primary crusher QB samples, the secondary and tertiary crusher materials from the first and second batches showed differences in UCS values, yet their angularity and gradation properties showed minimal variation. On average, the four 2% cement-treated specimens prepared for each of the QB crushing categories had UCS values slightly above 200 psi, which is approximately 19 times the initial strength for the primary crusher, 24 times for the secondary crusher, and slightly more than 52 times for the tertiary crusher QB samples. These results clearly indicate that the addition of 2% cement enhances the UCS properties of the aggregate by-products.

Figure 12 shows that 10% Class C fly ash treatment resulted in the highest strength gains for all QB sample categories. However, when only 5% Class C fly ash was used for treatment, the stabilized QB samples resulted in the least strength gains. Unlike the cases of the 2% cement and 5% Class C fly ash treatments, for which the strength gains varied considerably among the crushing by-product categories, the 10% Class C fly ash–stabilized aggregate by-products showed very small variation in strength. This implies that as the percentage of Class C fly ash increased, the strength of the three aggregate by-products reached a certain significantly high value.

Based on the UCS measurements, 2% cement, 5% Class C fly ash, and 10% Class C fly ash are all potential stabilizers which can be used with the aggregate by-products for improvement. However, Class C fly ash is certainly more economical when considering that fly ash itself is also a waste by-product of coal burning plants. Therefore, 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 given that strength requirements are met.

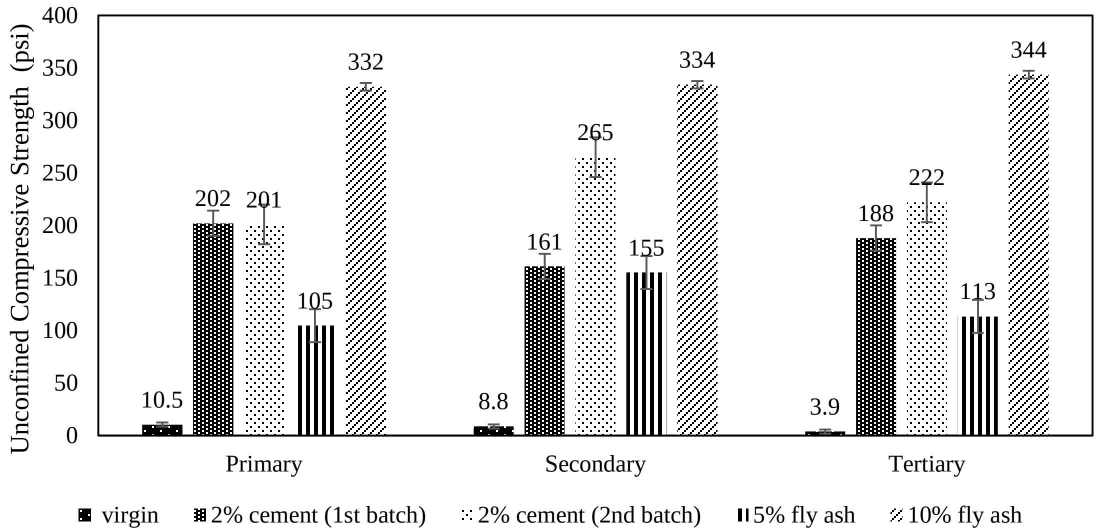


Figure 12. Unconfined compressive strength test results for virgin QB samples and samples stabilized with 2% Portland cement, 5% Class C fly ash, and 10% Class C fly ash.

3.5 Sustainability Assessment of Aggregates and QB-Current Status in U.S

According to the Environmental Protection Agency (EPA 2013), total emissions in the United States in 2011 were 6,526 million metric tons CO_2-equivalent. The mineral industry contributed 107 million metric tons CO_2-equivalent of that total (1.64%). Crushed aggregate production contributed 2.3 million metric tons CO_2-equivalent, at 2.15% of the mineral industry. This implies that the mineral industry contributes considerably to the total emissions in the United States. A preliminary closer look at the crushed aggregate production in the United States was taken to quantify energy and emissions release from the production of crushed aggregate.

Findings show that the production of 1 ton of aggregates consumes an average value of 57.21 MJ in non-renewable energy and results into 1.94 kg CO_2-equivalent for GWP. This implies that the production of 682 tons of crushed aggregate would consume 10,837 kWh, which is equivalent to the average annual electricity consumption per household in the United States (Ozer et al., 2015). Note that these numbers include the environmental impacts from upstream processes and downstream process for electric energy and diesel fuel production. The environmental impacts from the use of explosives in blasting of rock were not considered in this analysis. Due to limited inventories and data allocation related to the production of quarry by-products, it is difficult to quantify the environmental impacts due to production of QB. A detailed data collection by researchers and aggregate producers is needed in order to collect and allocate LCI data for QB production.

3.6 Summary

An industry survey conducted among crushed stone producers operating throughout Illinois indicated that the current usage of QB is limited to applications that use low amounts of QB; therefore, excessive amounts of QB may remain in the stockpiles. Several laboratory tests were performed to explore feasibility of using QB in pavement applications as an area that can consume higher amount of QB. Two batches of QB materials, primarily from a carbonate quarry, were collected in sequence, then tested and compared during the laboratory study.

- QB samples obtained from a carbonate quarry source were essentially nonplastic and had low harmful clay contents. According to grain size distributions, the QB samples were silt and sand sized particles. In two batches collected from the same quarry, differences were observed in the UCS (untreated) and gradation 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.
- Significant increases in UCS values were achieved for all potential stabilizers tested (2% Portland cement, 5% Class C fly ash, and 10% Class C fly ash). Cement-treated materials were more than 20 times stronger than the virgin QB materials, 5% fly ash–treated samples were more than 10 times stronger, and 10% fly ash–treated ones produced samples more than 30 times the strength of virgin QB samples.

4 LIFE-CYCLE ASSESSMENT OF GEOSYNTHETICALLY STABILIZED PAVEMENTS

4.1 Introduction

Geosynthetics is one of the potential materials currently used in different fields of civil engineering; however, the environmental impacts resulting from of use of geosynthetics in civil engineering applications are rarely accounted for. The increased traffic pattern reduces the expected life of pavements and, therefore, the use of geosynthetics in pavements replaces and/or enhances the use of conventional materials, thus increasing the life of pavements. Various types of geosynthetics with different performance mechanisms are available on the market; hence, their pavement engineering applications differ (Koerner, 2012). Common pavement applications of geosynthetics in pavement include separation and filtration, reinforcement, drainage layer, and moisture barrier. (Al-Qadi et al., 2003; Koerner, 2012). The use of geotextile at the subgrade-granular interface can be used for stabilization of weak subgrade, thus preventing the intrusion of the aggregate base into the subgrade. This operation mechanism of geotextile improves pavement life and/or reduces the thickness of crushed aggregates used as aggregate base (Al-Qadi et al., 1997; 2003; Norejo, 2003; Bhutta, 1998).

With the growing environmental concern, the development of eco-friendly construction practices has become increasingly important. A research study conducted at UIUC clearly shows that pavement construction and material production practices consume vast amounts of energy, which, in return, release a large amount of emissions into our environment (Kang, 2013). Proper selection of environmental friendly materials, appropriate material production techniques, and construction practices can considerably reduce the amount of energy consumption and emissions released into the environment.

Production of geosynthetics including the raw materials used in these processes is an energy intensive process. This implies that quantification of the environmental impacts related to geosynthetics production and construction is critical for LCA applications that include geosynthetics. This will help in accurate quantification of the environmental impacts associated with the construction of geosynthetics-reinforced pavements.

In Switzerland, Elsing et al.(2012) compared the use of geosynthetics in road construction with conventional construction material using life-cycle analysis (LCA) technique. LCA is a technique used to quantify environmental impacts of a product, in this case, pavement, through its different life-cycle stages (Santero, 2009). In his study, a series of questionnaires were sent to geosynthetics producers to obtain LCI data for the production of geosynthetics used in soil stabilization. Through a series of studies, the authors compared the environmental impacts of conventional materials with other materials used for soil stabilization, such as geosynthetics, cement, and lime; it was concluded that using geosynthetics results in lower environmental impacts compared with the conventional materials.

Additional studies were conducted in Switzerland to assess the environmental impacts of geosynthetics in different civil engineering applications. The use of geosynthetics in landfill construction drainage layer, slope retention, and filter layer results in lower environmental emissions compared with the corresponding conventional materials (Werth et al., 2012; Fraser et al., 2012; Ehrenberg et al., 2009). These findings reflect the material production and construction processes applied in Switzerland; it is inappropriate to assume that these findings are true in other parts of the world because of variability in material production and construction practices.

Quantification of environmental impacts using LCA varies depending on the location. Material production and the nature of equipment used in construction may vary from one region to another. This chapter presents the global warming potential (GWP) and total energy caused by production of geosynthetics (geotextile) in the U.S. The environmental impacts associated with production of geosynthetics will be used to quantify and compare

CO_2 emissions and total energy consumption caused by construction of geotextile-reinforced pavement and conventional pavement (pavement without geotextile). In this study, the pavement life-cycle assessment (p-ILCA) tool developed at UIUC is used to quantify the environmental impacts. The p-ILCA tool contains LCI data that closely reflects the material production and construction practices in the U.S-Midwest region. The development of p-ILCA database can be found elsewhere (Kang, 2013; Yang, 2014).

4.2 Life-Cycle Assessment for Production of Geotextile

4.2.1 Methodology

Despite the fact that geosynthetics are used in pavement applications in the U.S, there is limited LCI data that can be used to quantify the environmental impacts caused by production of geosynthetics. In this study, life-cycle inventory has been developed using the principles, rules, and regulations outlined in the life-cycle assessment methodology. As per ISO 14040-2006 (Figure 13) guidelines, goal and scope, inventory analysis, impact assessment for production of geotextile and interpretation of the results will be discussed in this section.

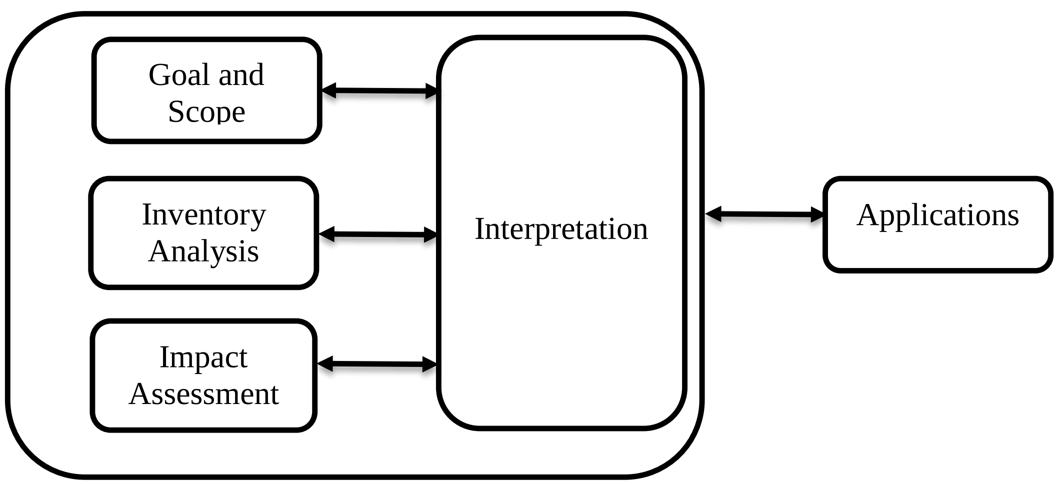


Figure 13. Procedure flow for conducting LCA (ISO 14040).

4.2.2 Goal and Scope Definition

The goal of this study is to quantify the global warming potential and total energy consumption caused by production of geotextile used in subgrade stabilization. The impact assessment chosen for geosynthetics is based on the U.S Environmental Protection Agency's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts Version 2 (EPA TRACI). For the purpose of this study, all TRACI impacts categories for the production of geosynthetics were modeled; only GWP and energy consumption were used in the case study.

This study is intended to fill the gap in material production for the p-ILCA tool. While p-ILCA includes the LCI database for most of the materials used in pavement construction, the tool lacks the LCI data for production and construction of geosynthetics. To fill this gap, this study addresses the environmental impacts of producing the geotextile used in stabilization of pavement subgrade.

4.2.2.1 System Boundaries

The use of geotextile for stabilization of subgrade soil improves the bearing capacity of subgrade and prevents the intrusion of aggregate base into the subgrade (Al-Qadi et al., 2003; Koerner, 2012). This study focuses on the environmental impacts caused by the production of geotextile used for soil stabilization. Raw material transportation and processing until the product is ready to be shipped to the end users is considered in this study. Upstream emissions from fuel and electricity consumption as a result of raw material transportation and processing are part of the analysis. Because of the limitation of data and the low environmental impacts associated with the equipment infrastructure system used in the production of geotextile, these two items are not included in the analysis.

4.2.2.2 Functional Unit

The functional unit defines a reference to which the results of the LCA study can be normalized (ISO, 2006). In this section, the functional unit is production of 1 kg of geotextile.

4.2.3 Data Collection

The amount of water, fuel, raw materials, electricity, and other inventories used in the production of 1 kg geotextile used for subgrade stabilization was obtained from the literature (Elsing et al., 2012) as shown in Table 9. The data represents average LCI data collected from different geosynthetics manufacturers in Europe. Production of geosynthetics in the U.S. and Europe may differ slightly, but the environmental impacts caused by these small differences were considered negligible because of the fact that the U.S- regional LCI data was used in modeling of total energy and CO_2 emissions.

Table 9. LCI Data for Production of 1kg of Geosynthetics Used in Foundation Stabilization (Elsing et al., 2012)

	Unit	Value
Raw materials	kg/kg	1.02
Water	kg/kg	0.5
Lubricating oil	kg/kg	3.62E-04
Electricity	kWh/kg	1.76
Thermal energy	MJ/kg	1.75
Fuel for forklifts	MJ/kg	0.15

4.2.4 Life-Cycle Impact Assessment for Production of Geotextile

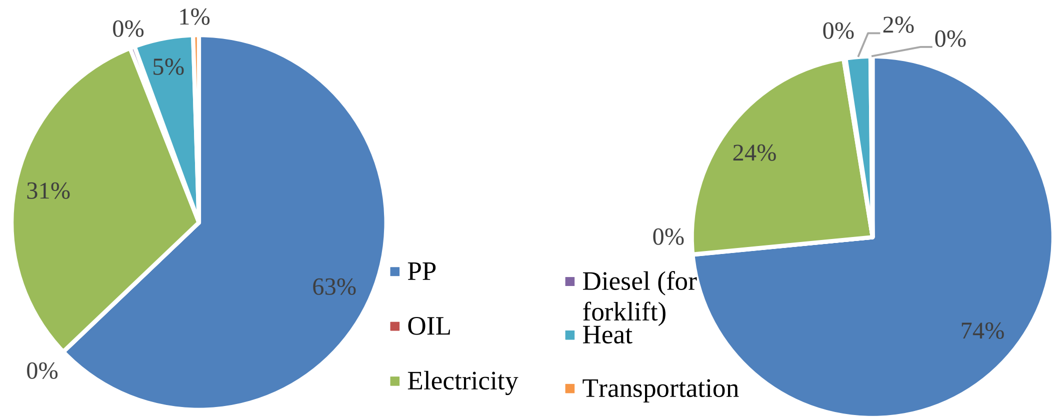
Life-cycle impact assessment (LCIA) for the production of 1 kg of geotextile was modeled as a unit process using commercial LCA software, SimaPro 8.0.4.26. The commercial U.S-Ecoinvent 2.2 library database (U.S_EI 2.2) was used as it contains U.S. electricity processes, along with few other processes. The U.S. LCI database developed by the National Renewable Energy Laboratory (NREL) was less used, as it has not been thoroughly reviewed (Yang, 2014). The LCIA for production of 1 kg geotextiles incorporates electricity and fuel usage, raw material production and transportation, water usage, and other energy sources. Infrastructure maintenance, storage of raw materials, and packaging of geosynthetics were not considered because they have very minimum environmental impacts (Ehrenberg, 2012).

4.2.4.1 Major Assumption

Based on the literature review, the main raw material considered in production of geotextile is polypropylene (PP), which is a common polymer used in production of geotextiles (Koerner, 2012). Transportation of raw materials can have a major impact on emissions and energy consumption. According to Frischknecht et al.(2004), 62 miles (100km) by lorry or 373 miles (600 km) by train is assumed for transportation of raw materials. The size and type of truck used was obtained from the EPA's MOVES database (Kang, 2013). The electricity used in this model was obtained based on EPA's 2012 Emissions and Generation Resource Integration Database (eGrid) sub region for Illinois. Another assumption adopted in this study is the use of diesel as fuel for forklifts. Other assumptions for lubricating oil and thermal energy can be found in appendix-A

4.2.4.2 Summary of Results

Figure 14 shows that production of geotextile is dominated by raw material production and electricity usage for both GWP and total energy consumption. There is higher impacts of raw materials on energy consumption (74%) compared with CO_2 emissions (63%). Moreover, electricity consumption contributes 31% of the CO_2 emissions and 24% to total energy consumption. Only 5% of the emissions and about 2% of energy consumed are from thermal energy as a result of heating processes. Transportation of raw materials does not cause any considerable impact on total energy. Only 1% of CO_2 emissions results from transportation of raw materials. There is no considerable effect of lubricating oil and diesel for forklift on both CO_2 emissions and total energy consumption. GWP and total energy related to production of 1 kg of geotextile is 3.22 kg CO_2-eq and 101.53 MJ, respectively. Details of other impact categories can be found in Appendix A.



(a) (b)

Figure 14. Energy consumed (b) and GWP (a) for production of geotextile.

4.3 Case Study

The use of geotextile for stabilization of subgrade soil improves the bearing capacity of subgrade and prevents the intrusion of aggregate base into the subgrade, thereby reducing the thickness of the required aggregate base course or increasing the life of the pavement (Al-Qadi et al., 1997; Al-Qadi et al., 2003, Norejo, 2003; Bhutta, 1998). The case study undertaken in this section compares the environmental performance of geosynthetic-reinforced/stabilized flexible pavement and conventional flexible pavements with the same functional and structural performance. The emissions related to operation of construction equipment, hauling, and material production are discussed in detail.

4.3.1 Background

The regional p-ILCA tool developed at UIUC is used to quantify the environmental impacts from the material production and construction phases. While the p-ILCA tool can effectively evaluate environmental impacts caused by the construction of conventional pavements, this tool lacks the LCI database for production and placement of geotextile. For this study, the impacts associated with production of geotextile (developed in section 4.2) will be integrated in the p-ILCA tool to effectively evaluate the environmental emissions and total energy consumption associated with construction of geosynthetics reinforced/stabilized reinforced pavement.

The p-ILCA tool considers the road geometry, processes involved in material production, and construction as inputs and outputs the environmental impacts of these processes based on the TRACI impact factors (Yang, 2014). A case study was considered to compare total energy and emissions resulting from the material production and construction of a two-lane (12-ft each) geosynthetic-reinforced/stabilized pavement with conventional flexible pavement. Specific design details and traffic information were formulated for the purpose of this study. Details about the system boundary considered in this case study can be found in Appendix B.

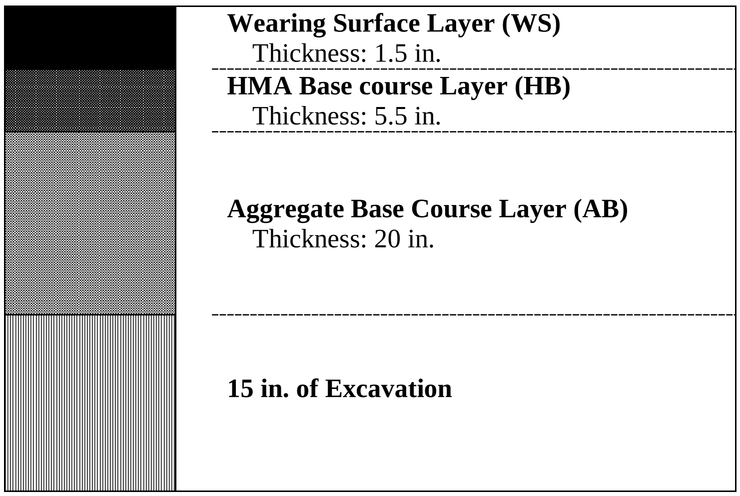
4.3.2 Design of Two Pavement Sections

GeoPave software was used for proper design of the thickness for different layers of the two pavement types to be compared. GeoPave design software is based on AASHTO pavement design standards and it helps in designing geotextile reinforced pavements (GP). The traffic characteristics, serviceability index, reliability, and material properties are the major inputs in GeoPave software; these inputs were formulated for this study and are summarized in Table 10.

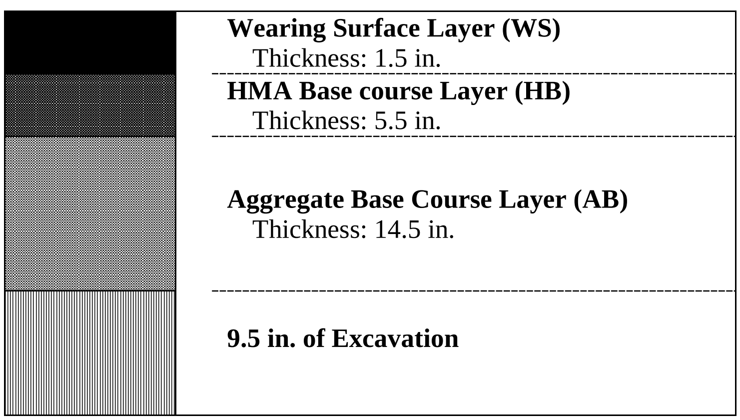
Table 10. Traffic Characteristics and Other Parameters Used to Design the Two Pavement Sections

Design Parameter	Value
ESALs	2000000
Reliability (%)	89
Initial serviceability	4.2
Change in serviceability	1.7
Subgrade resilient modulus (psi)	3054
Design period (years)	20

The existing subgrade for all pavement sections was considered poor with a CBR of 2%. To ensure similar performance and easy comparison of the environmental impacts, the design of geotextile reinforced pavement (GP) and conventional pavements (CP) was based on an equivalent service life. As shown in Figure 15, the major difference between the geotextile reinforced pavement and conventional pavement is the reduction in the aggregate base (AB) thickness and excavation (EXC) during subgrade preparation. The use of geotextile (GT) did not show any thickness in the wearing surface and HMA base.



(a)



(b)

Figure 15. Road profile for conventional pavement (a) and geotextile reinforced pavement (b).

4.3.3 Material Production Phase

As shown in the Figure 15, the main materials considered in this study are conventional material used in pavement construction and geotextile. For this study, only the material used in the mainline (excluding seal, tack, and prime coats) were considered as system boundaries for material production. The materials used in paved shoulders were not considered. It must be noted that the material production phase includes emissions caused by raw material acquisition and material production.

4.3.3.1 Estimating Quantities of Material for Each Design Scenario

Most of the environmental impacts caused by the production of materials are reported as per-unit quantity and per-distance travelled. Therefore, it is very important to accurately calculate the amount of material. The conventional materials used in this study include HMA for both wearing surface and HMA base, and aggregate base course. The mix designs of HMA used in this study were also modeled using the p-ILCA tool. Transportation of conventional materials to the HMA plant and to construction site was obtained using the p-ILCA tool (Appendix B).

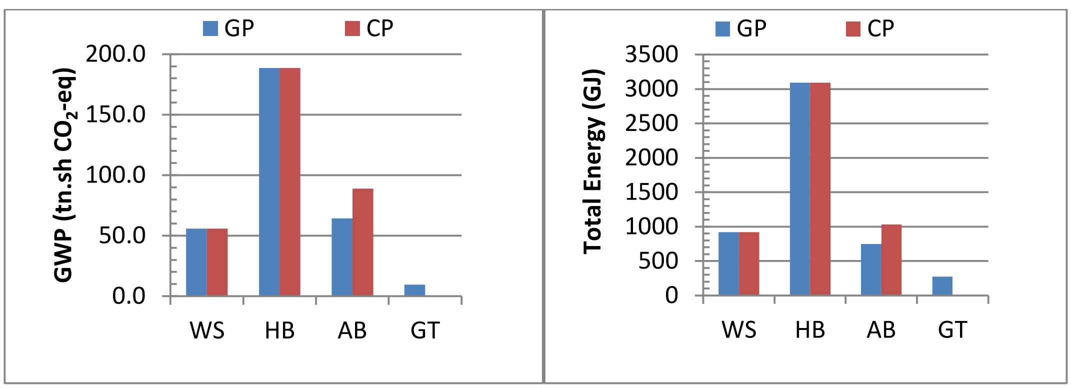
Following IDOT specification for the geotextile used in stabilization of soil, a 15 ft x 300 ft roll size of geotextile weighing 220lbs was used in this study to estimate the amount of geotextile used for the two lane-mile roadway. An additional two-ft geotextile overlap was also considered to match field practices used during construction. Based on the thickness and compaction density specification for each layer, the amount of material required were calculated and summarized in Table 11. For each material type, additional 1% of the material was considered to account for the material lost during material processing and construction.

Table 11. Material Used in Construction of Each Layer of Two Lane-mile Roadway

Material Type	Amount of Material		Units
	CP	GP	
Wearing surface (WS)	1160	1160	tn-sh
HMA base (HB)	4251	4251	tn-sh
Aggregate base (AB)	12265	8892	tn-sh
Geotextile (GT)	-	15344	SY
Excavation (EXC)	70400	44587	CY

4.3.3.2 Emissions and Energy Consumption during Material Production Phase

The p-ILCA was used to quantify the GWP and total energy caused by material production, transportation, and construction. For both CP and GP, the total energy and GWP are similar for materials used in the wearing surface and HMA base (Figure 16) because geotextile did not change their thickness. Unlike the wearing surface and HMA base, the GWP and total energy consumed in the production of material for aggregate base course (AB) differs for GP and CP. The total energy and GWP for GP is lower compared with CP. This reduction is attributed to the reduction of AB thickness when geotextile is used. In general, the production of the material for HB consumes more energy and releases higher carbondioxide for both CP and GP compared with other materials. The GWP and total energy consumed caused by the production of geotextile is the least compared with other material production.



(a) (b)

Figure 16. Comparing GWP (a) and total energy (b) for material production of different pavement layers.

4.3.4 Construction Phase

The construction phase considers the production and fuel combustion by the equipment used during material acquisition and construction. The transportation of materials to the job site was considered in this study. The transportation distances resulting from conventional material acquisition were retrieved from completed Tollway project database

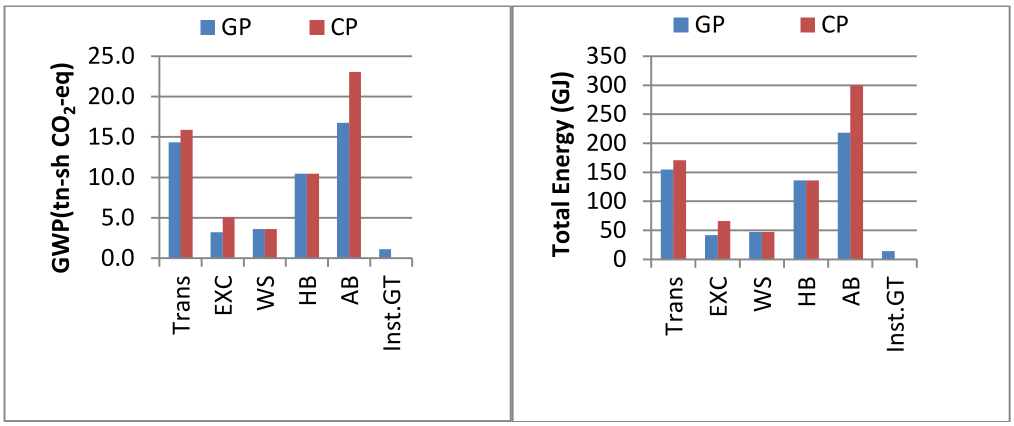
(Appendix-C). The equipment productivity rate for each construction equipment along with the fuel consumption rate were used to model the emissions related to the construction phase. This information was retrieved from the p-ILCA tool (Kang, 2013; Yang, 2014).

The transportation of geotextile from the manufacturer to the construction site was considered to be 600 km (372 miles) where 125 miles were considered to be transportation by truck and 247 miles were considered to be transportation by rail (Stucki et al., 2011). To estimate the emissions resulting from placement of geotextile, a CAT 329 excavator with productivity rate of 478.4 SY/hr at diesel consumption rate of 6.6 gal/hr was used (Athanassopoulos and Vamos, 2012). This study does not include equipment manufacturing, acquisition of construction equipment, or emissions-related construction. More information about the development of database for the p-ILCA tool can be found elsewhere (Kang, 2013; Yang, 2014).

4.3.4.1 CO_2 Emissions and Energy Caused by Material Transportation and Construction

Pavement construction involves material acquisition and the use of different construction equipment during excavation (EXC), and construction of different pavement layers along the roadway. The construction process differs from one layer to another because of the different tasks involved in construction of different layers. Figure 17 shows the GWP and energy consumption caused by construction and material transportation for each construction task. Material transportation accounts for transportation of processed materials to the construction site. All construction and transportation were modeled using the p-ILCA tool described in the previous sections. The information about geotextile installation was obtained from the literature and added to the p-ILCA tool to effectively model the GWP and total energy caused by installation of geotextile.

Figure 17 shows that the construction of aggregate releases more carbondioxide and consumes a lot of energy compared with construction of other pavement layers. Construction of the aggregate base consumed more energy than other layers. Material transportation comes second in terms of energy consumption. The higher energy consumed for aggregate base is caused by the thicker layer. There is considerable reduction in GWP and total energy for material transportation, excavation, and aggregate base construction for GP compared with CP. The installation of the geotextile process consumes the least energy and releases a fewer amount of carbondioxide compared with other construction processes.



(a) (b)

Figure 17. Comparing GWP (a) and total energy (b) in construction of different pavement layers per 2 lane-mile.

4.3.5 Summary of Findings

In this study, emissions and energy per two lane-mile were calculated for the material production, transportation, and construction of geotextile-stabilized and conventional pavements. The average of GWP and total energy were calculated for both pavements.

In general, GWP and energy consumption are less for geotextile-stabilized pavement than conventional pavement for all project phases. The material production phase consumes more energy and releases more emissions than construction. For both GP and CP, the material production phase is responsible for more than 84% of the emissions and energy consumption (Figure 18).

In general, geotextile-stabilized pavement shows slightly higher CO_2 emissions and total energy than conventional pavement during material production phase. On the other hand, conventional pavements consume slightly higher energy than geotextile-stabilized pavement during construction phase.

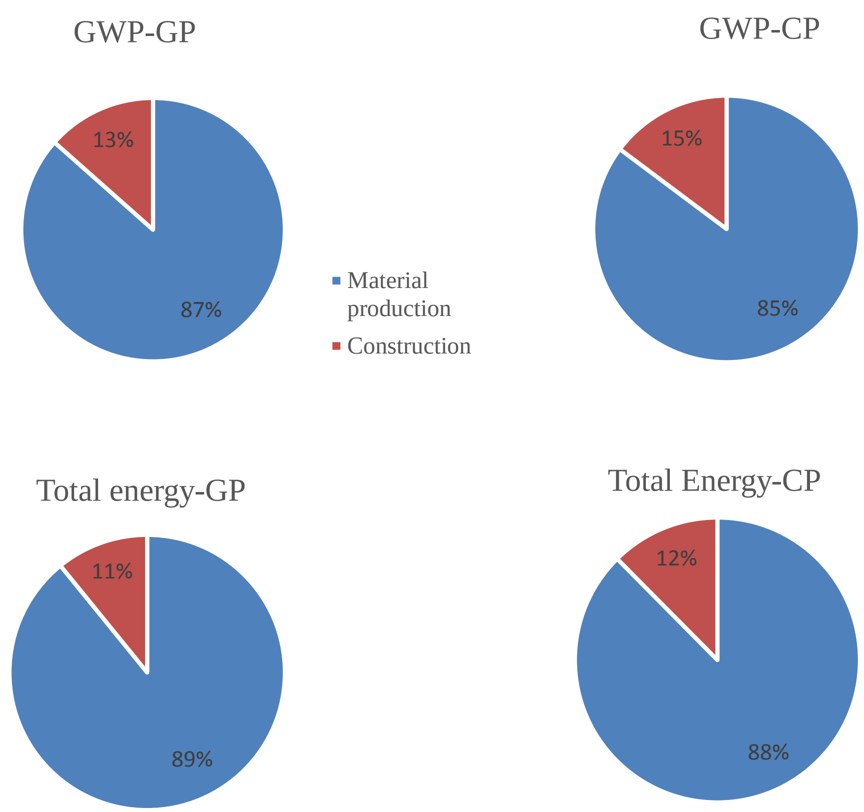


Figure 18. Comparison of GWP and total energy consumed during material production and construction phase for both CP and GP.

Table 12 shows a summary of the GWP and total energy consumption for both material production and construction. Geotextile-stabilized pavements show lower CO_2 emissions and total energy consumption compared with conventional pavements. The percentage reduction in energy consumption and CO_2 emissions resulting from the incorporation of geotextile in pavement is 2.7% and 6.5%, respectively.

Table 12. Total CO_2 Emissions and Total Energy for Material Production and Construction Phase

	GWP		TE	
	GP	CP	GP	CP
Material production	318.4	335.2	5033.1	5080.0
Construction	49.5	58.1	612.6	720.4
Total	367.9	393.3	5645.7	5800.4
CO_2 emission reduction (%)	6.5		-	
Energy reduction (%)	-		2.7	

4.4 Summary

In this chapter, the environmental impacts resulting from the production of geotextile were assessed. The findings show that the GWP and total energy related to production of 1 kg of geotextile is 3.22 kg CO_2-eq and 101.53 MJ, respectively. The production of geotextile is dominated by raw materials (PP) and electricity consumption.

A case study was conducted to evaluate the environmental benefits of using geotextile in pavements. The environmental impacts caused by the material production and construction of the two different pavement design scenarios, one with geotextile-stabilized and the other without geosynthetics (conventional pavement), were compared. For both pavement types, the highest environmental impacts were observed during the material production phase. For this case study, the overall results show that the geotextile stabilized pavements reduce environmental emissions by 6.5% and total energy by 2.7%.

5 SUMMARY, CONCLUSION, AND RECOMMENDATIONS

In this study, aggregate by-products and geosynthetics were assessed as potential environmental friendly materials contributing to the reduction in the amount and environmental hazards caused by the production and consumption of crushed aggregates. An industry survey conducted among crushed stone producers operating throughout Illinois indicated that the current usage of QB is limited to applications that use low amounts of QB; therefore, excessive amounts of QB may remain in the stockpiles. Several laboratory tests were performed to explore the feasibility of using QB in pavement applications. QB samples treated with Portland cement and Class C fly ash were evaluated based on density and unconfined compressive tests to evaluate their strength gain compared with virgin QB materials.

In addition, a sustainability assessment of geosynthetics (geotextile) in pavement applications were investigated. The life-cycle inventory for production of geosynthetics was collected from the literature, and SimaPro software was used to model its environmental impacts. Finally, a detailed case study that focused on energy consumption and greenhouse gas emissions for material production and construction of both geotextile-stabilized pavement and conventional pavement was conducted using the p-ILCA tool. For this case study, greenhouse emissions and total energy were quantified for the material production phase and construction phase for both pavements.

5.1 Findings

The findings regarding QB are summarized below:

- The QB samples obtained from a carbonate quarry source were essentially nonplastic and had low harmful clay contents.
- According to grain size distributions, the QB samples were silt and sand sized particles. In the two batches collected from the same quarry, there are notable differences in the UCS (untreated) and the gradation of the QB samples obtained

from the primary, secondary, and tertiary crushing stages. Changes in gradation characteristics could make QB samples either well-graded or poorly graded silty sand soil classifications.

- An enhanced aggregate image analyzer was used to quantify QB particle shape characteristics for particle sizes retained on No. 8 sieve. QB particles collected from the primary crusher were more rounded and cubical in shape compared with the quarry fines collected from the other crushers.
- The results from the moisture density tests showed that, for all virgin (unstabilized) and admixture-treated QB materials, maximum dry densities were in the range of 130 pcf to 140 pcf, and the optimum moisture contents were in the range of 7% to 10.5%. For virgin materials, primary crusher QB samples had the highest maximum dry density, followed by the secondary and tertiary QB materials. However, the moisture density behavior of the three crushing categories of aggregate by-products showed different trends with stabilization, which were highly dependent on the type of stabilizer used.
- Materials from the three crushing stages showed similar trends in shear strength characteristics. A rather high friction angle of approximately 59 degrees was obtained for all QB samples tested in a direct shear apparatus under adequate confinement.
- Significant increases in UCS values were achieved for all potential stabilizers tested (2% Portland cement, 5% Class C fly ash, and 10% Class C fly ash). Cement-treated materials were more than 20 times stronger than the virgin QB materials, 5% fly ash–treated samples were more than 10 times stronger, and 10% fly ash–treated ones produced samples in excess of 30 times the strength of virgin QB samples.
- Based on the strength gains observed, the use of 10% Class C fly ash could be an effective approach considering both environmental and economic aspects of aggregate by-product stabilization and given that strength requirements are met.

The 10% Class C fly ash–treated materials could achieve a UCS value as high as 340 psi.

The findings regarding geosynthetics are summarized below:

- The GWP and total energy related to production of 1 kg of geotextile is 3.22 kg CO_2-eq and 101.53 MJ, respectively, were quantified. Greenhouse gas emissions and total energy consumption for production of geotextile are dominated by raw materials (PP) and electricity consumption.
- For both geosynthetic-reinforced/stabilized pavements and stabilized pavements undertaken in the case study, more than 84% of GWP and total energy resulted from the material production phase. Less than 16% emissions and energy were generated by the construction phase.
- For this case study, the overall results show that using geosynthetics in pavement reduces the environmental emissions by 6.5%, and reduces total energy by 2.7%.

5.2 Conclusions

The major conclusions of this study are summarized below:

- The UCS of stabilized aggregate by-products is adequate for unbound pavement applications.
- Reliable greenhouse gas emissions and total energy consumption caused by the production of geosynthetics that best represent the U.S. Midwest region material production practices was developed using LCA technique.
- According to the preliminary sustainability assessment of geosynthetics applications for pavements, the results show that geosynthetic-reinforced/stabilized pavement may have a potential to reduce environmental impacts of pavements. The assessment should be extended to other life-cycle phases for complete sustainability assessment.

5.3 Recommendations for Future Work

Based on the findings of this thesis, the following are recommendations for future work:

- Conduct a full suite of strength, modulus, and deformation characteristics of treated QB to fully characterize the engineering behavior of treated QB materials in future sustainable pavement applications.
- Construct full-scale pavement test sections using the most promising applications of QB materials, including aggregate base on soft subgrades using QB in the gaps/voids between large stones, embankment and/or subgrade/subbase replacement, cement/fly ash–treated subbase (e.g., in inverted pavements), and fine aggregate replacement in 4.75 mm leveling binder asphalt mixes for overlay applications.
- Test and monitor pavements using QB applications to check against current mechanistic pavement design requirements and adequacy for field testing.
- Conduct life-cycle cost analysis to evaluate the benefits associated with QB use.
- The values obtained for total energy and GWP as a result of producing geosynthetics best represents the geosynthetics production practices of the USA Midwest region. Therefore, the same study should be conducted in other parts of the U.S.
- It is recommended that other pavement case studies, including various geosynthetics types, be performed considering all phases of LCA from cradle to grave.

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APPENDIX-A: TRACI IMPACT CATEGORIES FOR PRODUCTION OF 1KG OF GEOTEXTILE USED IN PAVEMENT SOIL STABILIZATION

Impact category	Unit	Total	Geotextile, at plant	Polypropylene, granulate, at plant/US- US-EI U	Lubricating oil, at plant/US- US-EI U	Proxy electricity, Illinois	Diesel, burned in building machine/GLO US-EI U	Heat, light fuel oil, at boiler 100kW, non-modulating/US* US-EI U	Transport, hauling truck, Illinois
Ozone depletion	kg CFC-11 eq	1E-07	0E+00	6E-10	3E-10	9E-08	2E-09	3E-08	2E-09
Global warming	kg CO_2 eq	3E+00	0E+00	2E+00	4E-04	1E+00	1E-02	2E-01	2E-02
Smog	kg O3 eq	1E-01	0E+00	8E-02	2E-05	3E-02	4E-03	3E-03	2E-03
Acidification	kg SO2 eq	1E-02	0E+00	6E-03	4E-06	4E-03	1E-04	3E-04	6E-05
Eutrophication	kg N eq	1E-03	0E+00	5E-04	8E-07	5E-04	1E-05	6E-05	9E-06
Carcinogenics	CTUh	2E-08	0E+00	1E-08	9E-13	3E-09	4E-12	6E-11	1E-11
Non-carcinogenics	CTUh	6E-08	0E+00	9E-09	2E-11	5E-08	2E-10	2E-09	4E-10
Respiratory effects	kg PM2.5 eq	7E-04	0E+00	5E-04	3E-07	2E-04	2E-05	2E-05	4E-06
Ecotoxicity	CTUe	9E-01	0E+00	7E-01	2E-04	1E-01	1E-03	1E-02	5E-03
Fossil fuel depletion	MJ surplus	1E+01	0E+00	1E+01	4E-03	2E-01	3E-02	3E-01	3E-02
Energy, renewable primary, fuel	MJ	4E-01	0E+00	3E-01	6E-05	1E-01	1E-04	3E-03	1E-04
Energy, renewable primary, non-fuel	MJ	2E-01	0E+00	2E-01	2E-05	2E-03	4E-05	8E-04	4E-05
Energy, renewable primary, total	MJ	6E-01	0E+00	5E-01	7E-05	1E-01	2E-04	3E-03	2E-04
Energy, non-renewable primary, fuel	MJ	1E+02	0E+00	7E+01	3E-02	2E+01	2E-01	2E+00	2E-01
Energy, non-renewable, non-fuel	MJ	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00
Energy, non-renewable primary, total	MJ	1E+02	0E+00	7E+01	3E-02	2E+01	2E-01	2E+00	2E-01
Use of secondary materials	kg	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00
Energy, renewable secondary, fuel	MJ	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00
Energy, non-renewable secondary, fuel	MJ	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00
Water resource depletion total [ILCD]	m^3 water eq	4E-02	5E-04	8E-03	7E-05	3E-02	2E-04	3E-03	2E-04
Waste, hazardous	kg	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00
Waste, non-hazardous	kg	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00
Waste, radio active	kg	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00	0E+00

APPENDIX-B: DISTANCE USED FOR MODELING OF TRANSPORTATION RELATED EMISSIONS AND ENERGY

Pavement Layer	Material Type	Acquisition to Plant Distance (mi)	Plant to Site Distance (mi)	Source
HMA mix	Aggregate	28	18	IL-Tollway completed projects
	Binder	100		
	Mineral filler	0		
Base	Aggregate (High quality)	-	31	IL-Tollway completed projects
Geotextile	Geotextile	-	372	Stucki et al.(2013)

APPENDIX-C: SYSTEM BOUNDARY CONSIDERED IN THE CASE STUDY