IMPACT OF TRANSPORTATION ON COST, ENERGY, AND PARTICULATE EMISSIONS FOR RECYLED CONCRETE AGGREGATE

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
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To my family

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Transportation distances can have a huge impact on cost, energy, and particulate emissions for concrete recycling. This study looks at the alternative methods that could be taken for the procurement of coarse aggregate. This research looks at the feasibility of recycled concrete aggregate over virgin aggregate in terms of cost, energy, and particulate emissions. This study was also conducted to determine the extent to which transportation impacts the cost, energy, and particulate emissions. The study was undertaken using Gainesville, Florida, as the location of the jobsite and tested for varying transportation distances. The conclusions from the analysis of the results showed (1) that using a portable crusher onsite to crush the demolished concrete is the most favored option in terms of cost, energy, and particulate emission for reuse on the same site; and (2) that the transportation distance has a direct impact on cost, energy, and particulate emissions and determines the preferability of recycled concrete aggregate or virgin aggregate.

CHAPTER 1
INTRODUCTION

When a concrete structure is demolished, concrete recycling is done regularly instead of disposing it at landfills. Concrete crushers are used to crush the demolished concrete. The small pieces of crushed concrete aggregate can be used as aggregate for new construction projects, and the larger pieces are used as sub-base for road construction. This method helps minimize mining for aggregates, decreases landfill wastes and also helps to keep construction costs low. Environmental awareness groups and other governmental regulations and incentives have helped gain recognition for this method.

Background

Concrete has been one of the main building materials used widely all over the world. In recent times, increased concern has arisen about the environmental impact of concrete usage. The production of concrete requires the usage of non-renewable natural resources. One of the major components of concrete is the coarse aggregate. The coarse aggregate is usually obtained through mining a quarry or extraction from domestic riverbeds and banks. To minimize depletion of natural resources, there has been an increased effort to recycle concrete. The total impact of concrete recycling could be assessed only through analyzing its economic and environmental impact. Some of the parameters that this study takes into consideration are the cost, energy consumption, and particulate emission. The cost includes the overall cost for production and transportation of recycled concrete aggregate and virgin aggregate. To estimate the total energy consumption for the usage of concrete, all stages in the life of concrete has to be considered, which involves the energy for production, construction, life cycle and demolition. However, this study looks only at the total energy required for production and transportation of recycled concrete and virgin aggregate. The production of recycled concrete involves the crushing of demolished concrete in a concrete crusher. For virgin aggregate, the production involves mining and crushing. Transportation for recycled concrete involves the transportation from the demolition site to the recycling plant and then from the recycling plant to the construction site. The particulate emissions include the emissions for the production and transportation of the recycled concrete aggregate and the virgin aggregate. Sometimes the cost, embodied energy and particulate emissions for recycled concrete are more than for virgin aggregate. This largely depends on the transportation distances for concrete. Sometimes the transportation distance between the construction site and the source of virgin aggregate is closer than that of recycled aggregate which involves transportation between the demolition site, recycling plant, and the construction site. This study will compare the cost, embodied energy, and particulate emissions for production and transportation of virgin aggregate and recycled aggregate by giving different values for the transportation distances.

Objective

In recent times, more concrete recycling has taken place, thus helping in minimizing the use of natural resources. Other costs and environmental impacts of concrete recycling have to be considered to truly estimate its environmental benefits. The other costs and environmental impacts that have to be taken into account are the cost, embodied energy, and particulate emissions required for production and transportation of recycled concrete aggregate. The cost, embodied energy, and particulate emissions in the transportation and production of recycled concrete can sometimes be more than using virgin aggregate. Some research has been done in this area, but most of the studies have focused on economic feasibility. No specific research on cost, embodied energy, and particulate emission for production and transportation of recycled concrete has been found during the preliminary literature review. The objectives of this study are

1. To determine the cost, embodied energy, and particulate emission for the transportation and production of recycled concrete aggregate and virgin aggregate.
2. To compare the cost, embodied energy, and particulate emission for the transportation and production of recycled concrete aggregate and virgin aggregate for varying distances and to show the impact of transportation on cost, embodied energy, and particulate emission.

Scope

The environmental factor considered in this study is limited to energy and particulate emissions (i.e., embodied energy and particulate emissions required for production and transportation). This study takes into account only one scenario: a concrete structure has been demolished and a new concrete structure has to be built on that same site, and an alternative has to be found for the best use of this demolished concrete. This study is done using Gainesville, Florida as the location of the site that was created to study this problem and this may not be suitable for all situations.

CHAPTER 2
LITERATURE REVIEW

Introduction

Aggregate is an industrial commodity term for sand, gravel, and crushed rock materials in their natural or processed state (Barksdale, 2000). Aggregate is extensively used (Robinson and Kapo, 2004) in asphalt pavement, cement concrete, and structural fill in construction activities to provide bulk, support, strength, and wear resistance.

Aggregate is a high-bulk, low unit-value (Bates, 1969) mineral commodity whose cost to the end user is strongly influenced by the cost of transporting processed aggregate from the source site (quarry, pit, or processing site) to the construction site (Poulin, Pakalnis and Sinding, 1994). According to Poulin et al. (1994), aggregate production sites (including recycled aggregate) that are closer to the consumer can be more competitive than aggregate producers offering higher quality aggregate from more distant locations.

Virgin Aggregate

Natural aggregate consists of sand and gravel mined from sedimentary deposits and stone crushed from a variety of hard rock deposits (Robinson and Kapo, 2004). According to U.S Geological Survey (USGS, 2009), crushed stone valued at $12 billion was produced by 1,450 companies operating 3,620 quarries, 86 underground mines, and 193 sales/distribution yards in 50 states. Leading states, in descending order of production, were Texas, Pennsylvania, Missouri, Georgia, Illinois, Virginia, North Carolina, Florida, Indiana, and Ohio, together accounting for 51% of the total crushed stone output. Of the total crushed stone produced in 2008, about 69% was limestone and dolomite, 15% was granite, 7% was traprock, the remaining 9% was shared, in descending order of tonnage, by miscellaneous stone, sandstone and quartzite, marble, volcanic cinder and scoria, slate, shell, and calcareous marl. According to USGS (2009), it was estimated that 1.36 billion tons of crushed stone were consumed in the United States in 2008. Of the 666 million tons reported by use, 83% was used as construction aggregates, mostly for highway and road construction and maintenance; 11% for cement manufacturing; 2% for lime manufacturing; 2% for agricultural uses; and 2% for special and miscellaneous uses and products.

Environmental Impacts

According to USGS (2009), shortages in some urban and industrialized areas are expected to continue to increase owing to local zoning regulations and land development alternatives. These issues are expected to continue and to cause new crushed stone quarries to locate farther from large population centers, causing longer distances of travel for the procurement of material to the jobsite and eventually leading to higher particulate emissions. The crushed stone industry (USGS, 2009) continues to be concerned with environmental, health, and safety regulations. According to Hsiao, Huang, Yu, and Wernick (2002), until the late 1990s, more than 90% of the aggregate supply has been extracted from domestic riverbeds and banks. Years of digging have left ecological damage and a depleted reserve base as a legacy (Chen, 1998). Thus causing the depletion of non-renewable resources. Continued unauthorized extraction causes severe erosion of riverbeds and infrastructure (Hsiao et al., 2002). Virgin aggregate deposits have already been depleted in many areas (Mehta, 2001). The most obvious environmental impact of aggregate mining is the conservation of land use, most likely from undeveloped or agricultural land use, to a hole in the ground. According to Langer and Arbogast (2003), the major impact effects of aggregate mining are loss of habitat, noise, dust, vibration, chemical spills, erosion, sedimentation, changes to the visual scene, and dereliction of the mined site. Mining in some environments may cause stream erosion. Erosion may cause loss of shade along stream banks, which, in turn, may cause loss of fish habitat (Langer and Arbogast, 2003). Therefore the use of virgin aggregates has a huge environmental impact.

Recycled Concrete Aggregate

Recycled aggregate consists mainly of crushed asphalt pavement (Robinson and Kapo, 2004), reclaimed primarily from road paving and parking lot construction activities and crushed Portland cement concrete, which is reclaimed from construction and demolition debris. According to Wilburn and Goonan (1998), reclaimed asphalt pavement (RAP) and reclaimed Portland cement concrete (RPCC) are the most abundant and available of the potential substitutes for natural aggregate in urban areas.

According to Chini and Bruening (2005), building-related C&D waste was estimated to be 143.3 million metric tons (MMT) in 2000. An estimated 35% to 45% of this debris is sent to Municipal Solid Waste (MSW) landfills or unpermitted landfills, and 20% to 30% is reused or recycled. Total building-related and infrastructural C&D waste concrete, generated annually in United States, is estimated to be 182 MMT (Sandler, 2003). It is estimated that 50% (91 MMT) of waste concrete is recycled annually into usable aggregates. This is roughly 5% of the 1.8 billion metric tons total aggregates market (Chini, 2007). More than 91 MMT of worn-out asphalt pavements are recovered annually. About 80% of the recovered material is currently recycled and the remaining 20% is land filled. One-third of the recycled material is used as aggregates for new asphalt hot mixes, and the remaining two-thirds is used as road base (Kelly, 1998). An estimated 68% of aggregate recycled from concrete is used as road base, and the remainder is used for new concrete (6%), asphalt hot mixes (9%), and low value products like general fill (Deal, 1997). The low usage rate of recycled concrete aggregate (RCA) in new concrete and asphalt hot mixes (15%) compared to higher usage rates in lower valued products, is related to real and perceived quality issues.

In recent years, the recycling of concrete to produce aggregates suitable for nonstructural concrete applications is emerging as a commercially viable and technically feasible operation (Sagoe-Crentsil, Brown and Taylor, 2001). Many demolition contactors are integrating recycling as a side business. According to one estimate in 2005, 3,500 C&D recycling facilities were in the United States. (Taylor, 2005).

Why Recycled Concrete Aggregate (RCA)?

According to the Construction Materials Recycling Association (CMRA, 2009), recycled concrete aggregate is a high quality material and meets or exceeds all applicable state and federal specifications. It is an accepted source of aggregate used in new concrete by ASTM and AASHTO. Recycled concrete aggregate is currently being used in concrete and asphalt products with better performance over comparable virgin aggregates. Recycled concrete aggregate provides superior compaction and constructability. Recycled aggregates are higher yield and lighter weight per unit of volume, which means less weight per cubic yard, resulting in reduced material costs, haul costs, and overall project costs. It weighs 10%-15% less than comparable virgin quarry products. Recycled concrete aggregate offers a way to reduce landfill waste streams and it minimizes the environmental impact in an urban quarry setting (CMRA, 2009).

According to Robinson and Kapo (2004), the use of recycled aggregate has increased in response to: 1) the increasing demand for aggregate; 2) the difficulty and cost of developing and permitting new sites of natural aggregate production; 3) other costs. such as increasing waste disposal fees and increasing transport distance from sites of natural aggregate production to construction sites; and 4) national and community efforts to reduce waste streams through the substitution of natural resources with reused and recycled materials. Increasing transportation costs for natural aggregate plus increasing costs and decreasing availability of landfill options to dispose of construction and other wastes creates an economic incentive to market recycled aggregate materials reclaimed from local sources of construction debris (Wilburn and Goonan, 1998). Proximity to population centers, major transportation corridors, and a lack of local availability of other aggregate sources are business conditions that favor the development of local recycling of aggregate materials (Robinson, Menzie and Hyan, 2004). This rise in demand for aggregate and the difficulty of developing and permitting new sites of natural aggregate production (Stanley, Marlon and Harris, 2000) creates a marketplace incentive to expand the recycling of aggregate and create more aggregate recycling centers throughout the region that are strategically located close to areas of construction activity and major transportation corridors. According to Wilburn and Goonan (1998), recycling of construction debris into new construction offers a way to reduce waste disposal loads sent to area landfills and to extend the life of natural resources by supplementing resource supply. According to Robinson et al. (2004), dual-haul strategies where construction debris is hauled from the construction site to the recycling site and processed aggregate or asphalt hot mix is returned to the construction site can result in significant transportation cost reductions. Recycling concrete waste for new production is a cost- effective method that also helps protecting the environment and achieves construction sustainability (Tam, 2008). According to Gao, Ariyama, Ojima and Meier (2001), the energy consumption needed to recycle most disassembled materials is less than that for a virgin product. This shows that recycled concrete can save energy.

How Is It Produced?

According to Construction Material Recycling Association (CMRA, 2009), products (aside from base course) are high quality aggregate, processed in steps with time and effort involved in crushing, pre-sizing, sorting, screening, and contaminant elimination. The major factor is to start with clean quality rubble to meet design criteria easily, and ultimately yield a quality product that will go into end use. Crushing and screening systems start with primary jaws, cones, and/or large impactors taking rubble from 30 inches to 4 feet. A secondary cone or impactor may or may not need to be run, and then primary and secondary screens may or may not be used, depending upon the project, the equipment used, and the final product desired. A scalping screen will remove dirt and foreign particles. A fine harp deck screen will remove fine material from coarse aggregate. Further cleaning is necessary to ensure that the recycled concrete product is free from dirt, clay, wood, plastic, and organic materials. This procedure is done by water floatation, hand picking, air separators, and electromagnetic separators.

Mobile recycling plants

This type of recycling plant can be moved to various locations economically. Track-mounted plants allow superior on-site mobility.

Portable recycling plant

Choosing the right crusher for a particular concrete recycling project depends on several factors to be successful and profitable (CMRA, 2009). What goes into the crusher, what is used to feed it (loader or hoe), and the specifications for the final product determine the size, type, and capacity of the units.

Most popular types of crushers

Jaw Crushers: Jaws compress the concrete between a stationary and moveable plate (CMRA, 2009). Concrete is reduced in size as it travels down the length of the wedge between the two plates. Jaws are used as primary crushers and typically produce a 4" to 8" minus product usually used as fill.

Impact Crushers: Impactors have a spinning rotor with bars or hammers that fling the concrete into a solid plate, several plates, or rods (CMRA, 2009). Impactors can be used as primary, secondary, and even tertiary crushers and produce a product typically 2" minus used as base material in some parts of the country.

Cone Crushers: Cones are also compression type machines with the concrete being compressed between two cone shaped plates (CMRA, 2009). Concrete feed to a cone is typically 6" minus as they are used mostly as secondary crushers behind a Jaw or Impact Primary. Cones typically produce products of 1-1/2" minus.

Portable crushers are mounted on rubber-tired chassis and towed to the site by truck. Onsite, they are moved by loaders or tugs. Mobile crushers are carried to the site by truck and trailer and have their own onboard drive system typically track driven. These units move easily on sites where several moves are required. Stationary crushers are just that they are permanently fixed to the ground, typically used in a recycling yard where all materials are trucked to the site. Most recycling projects require the operator to produce a sized or specified end product with gradations that need to be met.

Applications

In general, applications without any processing include: 1) many types of general bulk fills 2) bank protection 3) base or fill for drainage structures 4) road construction 5) noise barriers and embankments. Most of the unprocessed crushed concrete aggregate is sold as 37.5 mm (1-1⁄2 in.) or 50 mm (2 in.) fraction for pavement subbases (ACI, 2001).

After removal of contaminants through selective demolition, screening, and /or air separation and size reduction in a crusher to aggregate sizes, crushed concrete can be used as: 1) new concrete for pavements, shoulders, median barriers, sidewalks, curbs and gutters, and bridge foundations 2) structural grade concrete 3) soil-cement pavement bases 4) lean-concrete or econo-crete base and 5) bituminous concrete (ACI, 2001).

Issues and Concerns

According to Cosper and Stephen (2007), the presence of lead-based paint on concrete from demolition projects raises questions regarding suitable reuse or disposal. According to Environmental Council of Concrete Organizations (ECCO, 2009), concrete recovered from urban locations is more likely to contain "contaminants such as plaster, soil, wood, gypsum, asphalt, plastic, vinyl, or rubber." If the aggregate is to be used in a concrete, the contaminant level must be monitored and kept equal to or less than the virgin aggregate. When used as aggregate in concrete, some ready-mix companies voice concerns about the durability of recovered concrete. The irregular surface of recovered concrete aggregate can be less effective than sand or crushed stone because it takes more cement to fill the voids. This is potentially counterproductive, as it requires the use of more cement, and thereby increases the energy and raw materials needed for the concrete mix (ECCO, 2009). The major intrinsic material properties that limit the use of Reclaimed Portland cement concrete are (Forster, 1997): specfic gravity, absorption, soundness (resistance to environmental conditions such as chemical and physical weathering), gradation (grain-size distribution), and contaminant solubility and the potential for groundwater contamination. The major external factors that limit the use of RPCC are (Forster, 1997): cost, state specfications, and environmental regulations.

According to Robinson et al. (2004), reclaimed Portland cement concrete as an aggregate alters the new concrete in multiple ways. Its compressive strength will be lower than non-recycled concretes because of weaker aggregate particles. Some RPCC can dissolve in the water passing through the pavement system. This dissolved material will raise the pH of the groundwater and may possibly affect vegetation within the vicinity of the road. When this water containing dissolved concrete meets the outside air, the carbon dioxide in the atmosphere will precipitate out calcium carbonate, which can potentially clog up a drainage system (Forster, 1997). Soundness, solubility, and groundwater contamination still remain concerns (Forster, 1997).

Embodied Energy

Embodied energy is the quantity of energy required to manufacture and supply to the point of use of a product, material or service (Pearce, Johnsona and grant, 2007). According to Pulselli, Simoncini, Ridolfi, and Sinding (2008), Energy is embodied through a chain of transformation processes and its memory is conserved in the building frame. Embodied energy can be split into: 1) energy consumed in the production of basic building materials, 2) energy needed for transportation of the building materials, and 3) energy required for assembling the various materials to form the building (Reddy and Jagadish, 2001). According to Bonilla and Salling (2008), the energy required for the transportation of material for every 100 km is 265.5kJ/kg. And according to Lippiatt (2007), the energy used in the production of crushed aggregate is 82kJ/kg. To minimize the transportation distances, some methods such as the Weights of Evidence analyses (WofE) and weighted logistic regression (WLR) were used regionally as a reconnaissance method to quickly identify tracts that rank the relative suitability for the presence of an aggregate recycling center location in a particular area based on transportation network and population parameters (Robinson and Kapo, 2004).

Particulate Emissions

An emissions factor is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant (EPA, 2009). Some of the activities that cause particulate emissions in our study are loading and unloading of material, crushing and screening operations and transportation of material from one point to the other. Transportation of material through the paved road is one of the major factors that cause particulate emissions. The paved road emissions model in AP 42 Compilation of Air Pollutant Emission Factors is based on the intuitively appealing idea that PM 10 emissions from paved roads are primarily caused by resuspension of material deposited on the road (Venkatram, 2000). The AP-42 model for estimating particulate matter of size 10μm (PM 10) emissions from paved roads was developed by Midwest Research Institute under contract with the US EPA (Cowherd and Englehart, 1984). Gaffney, Bode and Murchison (1995) estimated that about 30% of PM 10 emissions in California are associated with traffic activity on paved roads. Zimmer, Reeser, and Cummins (1992) estimated that PM 10 emissions from paved roads accounted for about 40–70% of the total PM 10 impacts at modeled receptors in the Denver metropolitan area.

For many years, the atmospheric particulate standards of many countries were based on the mass concentration measurement of the total suspended particles (TSP). Since an important mass fraction of TSP is made of non-inhalable particles with a lower impact on respiratory and cardiovascular diseases, the relationship between health effects and TSP levels was found to be much lower than the levels of atmospheric particulates finer than 10, 2.5 or 1 μm (PM10, PM2.5 and PM1, respectively), on comparison. This was the reason for the application of PM10 and

PM2.5 measurements to the U.S ambient air quality standards (US EPA, 2009). Future trends for particulate monitoring strategies tend to monitor PM2.5 rather than PM10 because of its more direct relationship with health effects and to avoid natural particulate interference. However, industrial activities with high primary particulate emissions, such as cement, concrete, ceramics, or the mining sectors, may have a great impact on the ambient air quality due to their intensive particulate emissions in the 2.5–10μm range (Querol et al., 2001).

CHAPTER 3
METHODOLOGY

General

The primary objective of this research was to compare the cost, energy consumption and particulate emissions for the three alternative methods used in handling concrete demolition waste and also to determine the best alternative for the disposition of this demolished concrete. A case was therefore created in which a four-story concrete structure is demolished. This theoretical building is located in Gainesville, Florida, at the intersection of University Avenue and 13th Street. Three different demolition and disposal alternatives were examined. All three cases were studied using actual locations in Gainesville, Florida. The first case considered was to recycle the demolished concrete using a portable crusher and hence to use the same recycled concrete aggregate as a base material at the same site. The second case considered was to dispose the demolished concrete at the nearest landfill and then buy new virgin aggregate from a concrete plant for the same site. The third case considered was to dispose the demolished concrete at a concrete recycling plant and then to buy the recycled concrete aggregate from the same recycling plant.

All the three cases were studied and analyzed and their cost, energy consumption and particulate emissions were determined. Data were collected by personally visiting the different concrete related companies in and around Gainesville, Florida.

The Model

A model was created to calculate the cost, energy consumption, and particulate emission for all three cases. The model structure and development is explained in the following sections.

Cost

The overall quantity of concrete that has to be processed or new aggregate purchased is 6,169 metric tons. The cost was based on price quotes from local aggregate suppliers. The cost for case 1 involves the cost for using a portable crusher onsite to crush the demolished concrete and to use the same as base material in the same site. The portable crusher, rented from Florida Concrete Recycling Inc is located at a distance of 2.41 km from the jobsite. The cost for using a portable crusher was $5.44 for every metric ton of concrete crushed. An additional cost of $5,000 was charged for mobilization and installation.

The cost for case 2 involves the cost for disposing the demolished concrete waste at the landfill and buying new virgin aggregate from the quarry. The landfill that was considered in the study was the Watson C & D landfill located at Archer, Florida, at a distance of 26.5 km from the jobsite. The cost for landfilling was $5.98 for every metric ton of concrete waste. This overall cost for landfilling includes the cost for loading/unloading and transportation. The virgin aggregate was bought from Limerock industries Inc, which is located in Newberry, Florida at a distance of 24.7 km from the jobsite. The cost for buying virgin aggregate was $10.84 for every metric ton, and this cost includes the cost of material and the cost for delivery. The virgin aggregate required for this site is 6,169 metric tons.

The cost for case 3 involves the cost of disposing the concrete waste at the recycling plant, which is slightly less than the cost of disposing at the landfill, and the cost for buying recycled concrete aggregate from the same recycling plant. The recycling plant chosen for case 3 is the same recycling plant considered in case 1, which is the Florida Concrete Recycling Inc located at a distance of 2.41 km from the jobsite. The overall cost for disposing the waste concrete at the recycling plant was $4.35 per metric ton. The overall cost of buying recycled concrete aggregate from the same plant was $10.34 for every metric ton. Quantity of 6,169 metric tons of RCA was required for the site. A tax of $6.75 was charged for the overall cost for the activities in all the cases.

Energy

The two major areas in which energy consumption was calculated were for crushing and transportation in all three cases. The energy consumption was calculated based on Building for Environmental and Economic Sustainability Technical Manual and User Guide (Lippiatt, 2007). According to BEES 4.0 (Lippiatt, 2007), the energy used in the production of crushed aggregate is 82 kJ/kg, and according to Bonilla and Salling (2008), the energy required for the transportation of material for every 100 km is 265.5 kJ/kg.

The energy consumption in the first case involves the energy consumed for transporting the portable crusher to the jobsite and the energy consumed in crushing the demolished concrete using the portable crusher. The total round trip distance from the recycling plant to the jobsite and back to the recycling plant was 4.81 km. The total quantity of waste concrete required to be crushed by the portable crusher was 6,169 metric tons. Using these values, the total energy consumption in the first case was calculated.

The energy consumption in the second case involves the energy consumed in transporting the waste concrete from the jobsite to the landfill, energy consumed in transporting the virgin aggregate from the recycling plant to the landfill, and the energy consumed in crushing for the production of virgin aggregate. The distance between the jobsite and the quarry pit was 24.7 km and the distance between the jobsite and the landfill was 26.5 km. Using these values, the total energy consumption in the case 2 was calculated.

The energy consumption in the case 3 involves the energy consumed in transporting the waste concrete from the jobsite to the recycling, energy consumed in transporting the recycled concrete aggregate from the recycling plant to the jobsite, and energy consumed in crushing the demolished concrete at the recycling plant. The distance between the jobsite and the recycling plant is 2.41 km. By using these values, the total energy consumption in the third was calculated.

Particulate Emission

The particulate emissions were calculated based on the Environmental protection agency's (EPA) emission factor and AP 42. The activities that cause the particulate emissions in all three cases are loading, unloading and material transfer operation, crushing and screening operation, and transportation.

PM for Loading and Unloading Operation

The particulate emissions from the loading and unloading operations were calculated from section 13.2.4 of EPA's AP 42 using the formula:

$$EF = \frac{K(0.0016)\left(\frac{U}{2.2}\right)^{1.3}}{\left(\frac{M}{2}\right)^{1.4}} \tag{3-1}$$

Where EF is the emission factor, K is particle size multiplier, U is mean wind speed (m/s), and M is material moisture content (%). From section 13.2.4 of EPA AP 42, the value for K is 0.35, U is 3 m/s, and M is 0.7. Using these values, the value of emission factor (EF) was found to be 0.0036 kg/mt. Since the value for loading and unloading is the same for all three cases, the total emissions from loading and unloading operations can be calculated from EPA AP 42 using the formula:

$$E = A \times EF \times \left(\frac{1-ER}{100}\right) \tag{3-2}$$

Where, E is the total emission, A is the activity rate, EF is the emission factor, and ER is the emission reduction efficiency. From section 13.2.4 of EPA AP 42, the value of ER was found to be 0.03 and the value of A is 6,169 metric tons from this study. Therefore, by using these values in the Equation 3-2, the value of emission (E) was found to be 0.21806 kg. This value is the same for all loading and unloading operations in all three cases.

PM for Crushing Operation

The emission factors from crushing operations can be calculated for PM 10 and PM 2.5 from table 11.19.2.1 of EPA AP 42. From table 11.19.2.1, the value of ER was found to be 0.77. Using these values in Equation 3-2, the value for emission (E) for crushing operations can be calculated.

PM for Screening Operation

The emission factors from screening operations can be calculated for PM 10 and PM 2.5 from table 11.19.2.1 of EPA AP 42. From table 11.19.2.1, the value of ER was found to be 0.77. Using these values in Equation 3-2, the value for emission (E) for screening operations can be calculated.

PM for Transportation

The particulate emission for PM 10 from the transportation operations were calculated from section 13.2.2.1 of EPA's AP 42 using the formula:

$$EF = \frac{K\left(\frac{s}{12}\right)^{a}\left(\frac{S}{30}\right)^{d}}{\left(\frac{M}{0.5}\right)^{C}} - C \tag{3-3}$$

Where, EF is the size specific emission factor (lb/VMT), “s” is surface material silt content (%), W is mean vehicle weight (tons), M is surface material moisture content (%), S is mean vehicle speed (mph), and *C* is emission factor for 1980s vehicle fleet exhaust, brake wear, and tire wear. k, a, c and d are empirical constants. From section 13.2.2.1 of EPA’s AP 42, the value of K is 1.8, s is 0.048, S is 50, M is 0.05, a is 1, d is 0.5, c is 0.2, and C is 0.00047. Using these values, the emission factor (EF) was calculated to be 0.01473 lb/VMT. This can be converted to lb/VKT using the formula:

$$1 lb/VMT = 281.9 g/VKT \tag{3-4}$$

Using this formula, the value of EF was found to be 4.0204 g/VKT. From table 13.2.2-5, the value of ER was found to be 0.95. The activity rate A is 6,169 metric tons and the capacity of each truck was assumed to be 36.74 metric tons to transport the concrete. Therefore, it takes approximately 168 trips to transport 6,169 metric tons of concrete. Using these values in Equation 3-2, the value of emission (E) was found to be 0.3377 g/km.

Similarly, the emission factor (EF) for PM 2.5 was calculated the same way as for PM 10, except the value of C was changed to 0.00036, found in table 13.2.2-4. Therefore, the value of EF was found to be 0.3138 g/VKT. From table 13.2.2-5, the value of ER was found to be 0.95. The activity rate A is 6,169 metric tons, and the capacity of each truck was assumed to be 36.74 metric tons to transport the concrete. Therefore, it takes approximately 168 trips to transport 6,169 metric tons of concrete. Using these values in Equation 3-2, the value of emission (E) was found to be 0.0263 g/km.

PM Calculation for Case 1

The activities that produce particulate emissions in case 1, given in sequential order, are as follows:

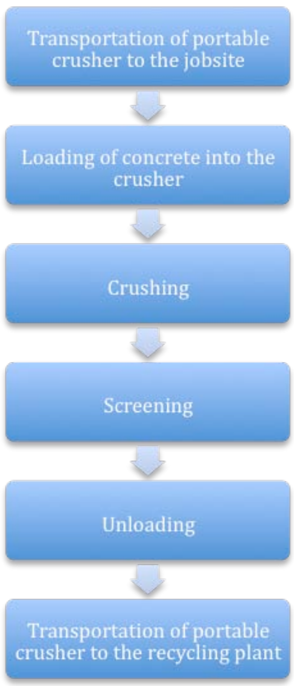

Figure 3-1. Flowchart for case 1

The first and last activity in case 1 is the transportation of the portable crusher. The emission (EF) for transportation, as calculated above, was 4.02 g/VKT and 0.3138 g/VKT for PM 10 and PM 2.5, respectively. The value of ER is 0.95 and the round trip distance between the recycling plant and the jobsite is 4.81. Therefore, from these values, the emission (E) for transportation in case 1 was calculated to be 0.0000096 kg and 0.00000075 kg for PM 10 and PM 2.5 respectively. The loading and unloading operations, as previously calculated are the same for all three cases, and it is 0.21806 kg. The crushing operation for PM 10 and PM 2.5, as calculated before is the same for all cases and it is equal to 0.00383kg and 0.00070 kg for PM 10 and PM 2.5, respectively. The screening operation for PM 10 and PM 2.5, as calculated before is the same for all three cases and it is equal to 0.00205 kg and 0.00013 kg for PM 10 and PM 2.5, respectively.

PM Calculation for Case 2

The activities that produce particulate emissions in case 2, given in sequential order, are as follows:

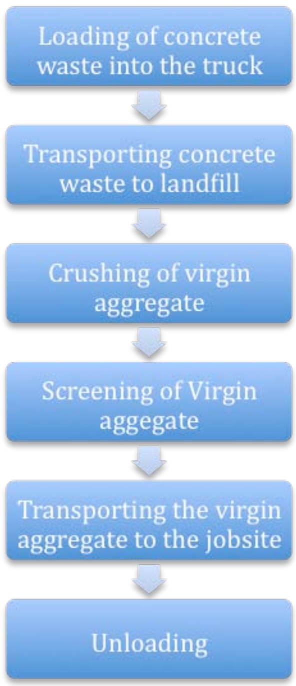

Figure 3-2. Flowchart for case 2

The emission (E) for transportation, as calculated before was 0.3377 g/km and 0.0263 g/km for PM 10 and PM 2.5, respectively. The round trip distance between the landfill and the jobsite is 52.6 km. Therefore from these values the emission (E) for transportation to landfill was calculated to be 0.0177 kg and 0.00138 kg for PM 10 and PM 2.5 respectively. Similarly, the round trip distance between the quarry pit and the jobsite is 49.56 km. The emission (E) for transportation from the quarry pit was calculated to be 0.0167 kg and 0.0013 kg for PM 10 and

PM 2.5, respectively. The loading and unloading operations, as calculated before, are the same for all three cases, and it is 0.21806 kg. The crushing operation for PM 10 and PM 2.5, as calculated before, is the same for all three cases, and it is equal to 0.00383kg and 0.00070 kg for PM 10 and PM 2.5, respectively. The screening operation for PM 10 and PM 2.5, as calculated before is the same for all three cases, and it is equal to 0.00205 kg and 0.00013 kg for PM 10 and PM 2.5, respectively.

PM Calculation for Case 3

The activities that produce particulate emissions in case 3 given in sequential order are as follows:

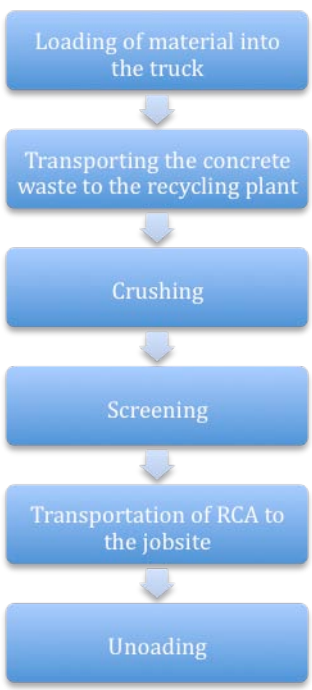

Figure 3-3. Flowchart for case 3

The emission (E) for transportation, as previously calculated, was 0.3377 g/km and 0.0263 g/km for PM 10 and PM 2.5, respectively. The round trip distance between the recycling plant and the jobsite is 4.81 km. Therefore, from these values, the emission (E) for transportation from the jobsite to the recycling plant was calculated to be 0.0016 kg and 0.00012 kg for PM 10 and PM 2.5 respectively. Similarly, the emission (E) for transportation from the recycling plant to the jobsite was the same and found to be 0.0016 kg and 0.00012 kg for PM 10 and PM 2.5, respectively. The loading and unloading operations, as calculated before is the same for all three cases, and it is 0.21806 kg. The crushing operation for PM 10 and PM 2.5, as calculated before, is the same for all cases and it is equal to 0.00383kg and 0.00070 kg for PM 10 and PM 2.5, respectively. The screening operation for PM 10 and PM 2.5, as calculated before, is the same for all cases and it is equal to 0.00205 kg and 0.00013 kg for PM 10 and PM 2.5, respectively.

Impact of Transportation on Cost, Energy and Particulate Emission

To test the impact of transportation distance on cost, energy consumption, and particulate emissions, the distance between the jobsite and the recycling plant was changed at an increment of every 5 km from 5 km to 35 km. The other distances were kept constant. The case 1 and case 3 were calculated again the same way, as calculated before, except the distance between the jobsite and the recycling plant was changed at an increment of 5 km each time up to 35 km.

List of Assumptions

The assumptions made in this study are

- The study begins after the building is demolished and the concrete debris is separated from steel and stockpiled.
- The portable crusher in the first case comes from the same recycling plant as considered in the third case.
- The energy consumption for producing crushed virgin aggregate and recycled concrete aggregate is assumed to be the same for all three cases.
- The energy consumption for transportation of virgin aggregate or recycled concrete aggregate per kilometer is assumed to be the same for all vehicles in all the cases considered in this study.

- The particulate emissions from loading and unloading operations were assumed to be the same for all cases and at all locations.

- The particulate emissions from crushing and screening operations were assumed to be the same for all three cases.

- The particulate emissions from transportation operations per kilometer were assumed to be the same for all the vehicles in all three cases.

Limitations of the study

Limitations of this study are

- Crushing concrete debris and using the recycled concrete aggregate onsite may take longer than buying virgin aggregate from the quarry. This factor was not considered in the study.

- The use of EPA AP 42 may not be a comprehensive approach to calculate particulate emissions.

- The effect of pollution from the particulate matter between crushing and screening operations onsite (urban) and at the aggregate plant (rural) was not considered in this study.

- The use of a portable crusher onsite requires a minimum threshold limit of at least 1,000 metric tons of concrete for it to be economically feasible.

- The use of a portable crusher onsite requires enough space for crushing the concrete and stockpiling.

- The use of a portable crusher onsite requires at least two weeks prior notice for getting the necessary paperwork from the respective county in order to get the permit for the use of portable crusher at the specific location.

CHAPTER 4
RESULTS

Data was collected for three parameters namely energy, cost, and particulate emissions for three different cases separately. The data from all three cases were then analyzed thoroughly by comparing them with each other.

Cost

The cost incurred in the first case was the cost for renting the portable crusher for recycling the demolished concrete that was $5.44 per metric ton.

Table 4-1. Cost calculations for case 1

Cost for using portable crusher to recycle concrete onsite per ton	$5.44	/mt
Quantity of concrete to be recycled	6,169.00	mt
Cost	$33,559.00	
Cost for mobilization and installation	$5,000.00	
Tax 6.75%	$2,265.00	
Total Cost	$40,824.00	

Hence, the total cost for recycling 6,169 metric tons of concrete using the portable crusher was $33,559. An additional cost of $5,000 was charged for mobilization and installation of the portable crusher. Therefore, the total cost, including taxes amounted to $40,825 for the first case.

The second case involves the disposing of the demolished concrete and buying new virgin aggregate. The cost incurred for the second case was the cost for landfill and the cost for buying new virgin aggregate.

Table 4-2. Cost calculations for case 2

Cost to landfill demolished concrete per ton	$5.98	/mt
Quantity of demolished Concrete	6,169.00	mt
Cost to landfill demolished concrete	$36,891.00	
Cost for buying Virgin aggregate per ton	$10.84.00	/mt
Quantity of virgin aggregate needed	6,169.00	mt
Cost for buying Virgin aggregate	$66,853.00	
Total cost	$103,744.00	
Tax 6.75%	$7,003.00	
Total cost	$110,747.00	

The cost for landfill was $5.98 per metric ton, which amounted to $36,891 for 6,169 metric tons. The cost for buying virgin aggregate was $10.84 per metric ton, which amounted to $66,853 for 6,169 metric tons. Therefore, the total cost incurred in the second case including the taxes, amounted to $110,747.

The cost incurred in the third case involved cost for disposing the demolished concrete at the recycling plant and buying recycled concrete aggregate (RCA) from the same recycling plant.

Table 4-3. Cost calculations for case 3

Cost for disposing concrete at the recycling plant	$4.35	/mt
Quantity of concrete to be recycled	6,169.00	mt
Cost for disposing concrete at the recycling plant	$26,860.00	
Cost for buying RCA per ton	$10.34	/mt
Quantity of RCA needed	6,169.00	mt
Cost for buying RCA	$63,787.00	
Total Cost	$90,647.00	
Tax 6.75%	$6,119.00	
Total Cost	$96,766.00	

The cost for disposing the demolished concrete at the recycling plant was $4.35 per metric ton, which amounted to $26,860 for 6,169 metric tons, and the cost for buying RCA was $10.34 per metric ton, which amounted to $63,787 for 6,169 metric tons. Therefore, the total cost incurred in the third case including taxes, amounted to $96,766.

Table 4-4. Results of cost

CASES	COST ($)
Portable crusher	$40,825
Virgin aggregate	$110,747
Recycling plant	$96,766

Comparing the costs for all three cases shows that using the portable crusher from the first case is the most cost-effective and buying virgin aggregate from the second case is the least cost-effective.

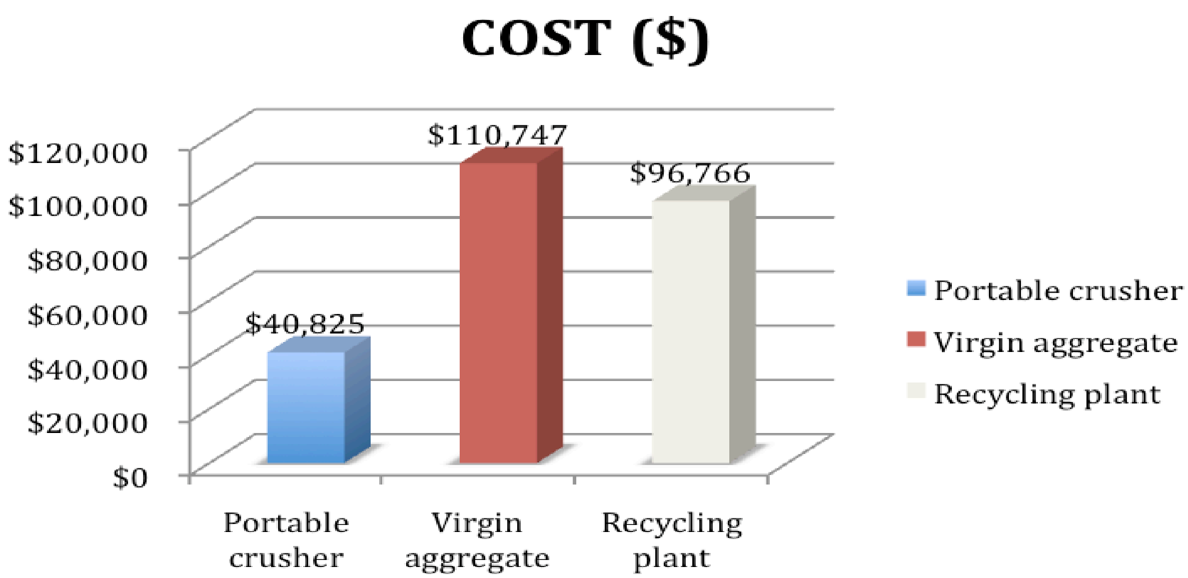

Figure 4-1. Results of cost

Energy

The energy required to recycle the concrete is 82 kJ/kg (Lippiatt, 2007), and the energy required to transport material for every 100 km is 265.5 kJ/kg (Bonilla and Salling, 2008). The energy consumption in the first case involves the energy required to crush the demolished concrete and the energy consumption in the transportation of the portable crusher.

Table 4-5. Energy calculations for case 1

Energy required to recycle 6,169mt of concrete	505,858,000.00	KJ
Distance from the recycling plant	2.41	Km
Approximate Weight of the portable crusher	5000.00	Kg
Energy required for transportation	63,985.50	KJ
Total energy consumption	505,921,985.50	KJ
Or	505.92	GJ

The energy required in recycling 6,169,000 kg of demolished concrete using a portable crusher equals 505,858 MJ, and the energy required in the transportation of the portable crusher is 63,985.50 KJ. Therefore, the total energy consumption in the first case is 505.92 GJ.

The energy consumption in the second case involves the energy required to transport the demolished aggregate from the jobsite to the landfill, the energy required to produce the virgin aggregate and the energy required to transport the virgin aggregate from the quarry pit to the jobsite.

Table 4-6. Energy calculations for case 2

Energy required to produce virgin aggregate	505,858,000.00	KJ
Distance from the jobsite to the landfill	26.50	Km
Energy required to transport demolished concrete to landfill	434,035,418.00	KJ
Distance from the quarry pit to the jobsite	24.70	Km
Energy required to transport VA from quarry pit to the jobsite	404,553,767.00	KJ
Total Energy	1,344,447,184.00	KJ
Or	1,344.44	GJ

The energy required to transport the demolished concrete from the jobsite to the landfill equals 434,035 MJ. The energy required to produce 6169,000 kg of virgin aggregate equals 505,858 MJ, and the energy required to transport virgin aggregate from the quarry pit to the jobsite is 404,553 MJ. Therefore, the overall energy consumption in the second case is 1,344.44 GJ.

The energy consumption in the third case involves the energy required to transport the demolished concrete from the jobsite to the recycling, the energy required to recycle the concrete at the recycling plant and the energy required to transport the recycled concrete aggregate from the recycling plant to the jobsite.

Table 4-7. Energy calculations for case 3

Energy required to recycle the demolished concrete	505,858,000.00	KJ
Distance from the jobsite to the recycling pant	2.41	Km
Energy to transport demolished concrete to the recycling plant	39,472,655.00	KJ
Distance from the recycling plant to the jobsite	2.41	Km
Energy to transport RCA to the jobsite	39,472,655.00	KJ
Total Energy	584,803,310.00	KJ
Or	584.80	GJ

The energy required to transport 6169,000 kg of demolished concrete to the recycling plant is 39,473 MJ. The energy required to recycle the concrete is 505,858 MJ, and the energy required to transport the recycled concrete to the jobsite is 39,473 MJ. Therefore, the overall energy consumption in the third case equals 584.803 GJ.

Table 4-8. Results of energy

CASES	ENERGY (GJ)
Portable crusher	505.92
Virgin aggregate	1,344.44
Recycling plant	584.80

Comparing energy consumption for all three cases shows that the first case in which portable a crusher is used onsite to recycle the concrete is the most energy efficient and the second case, which involves the disposal of demolished concrete and the buying of virgin aggregate, is the least energy efficient.

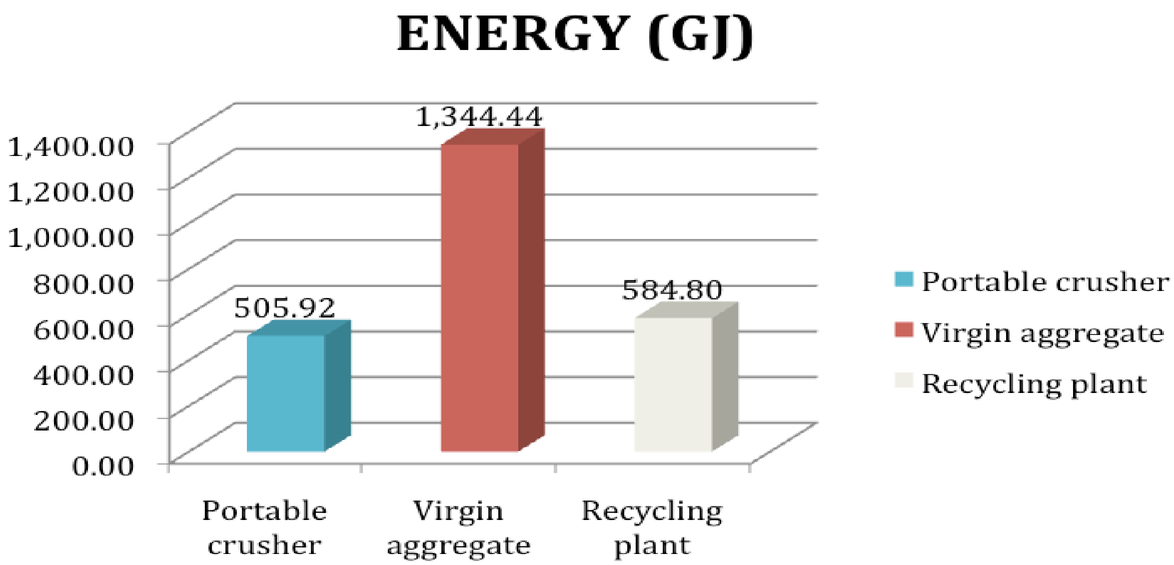

Figure 4-2. Results of energy

Particulate Emissions

Emission factors from the EPA AP 42 are representative numbers that attempts to relate the amount of emissions released to the atmosphere with the activity that released the pollutant. The particulate emissions were calculated, based on emission factors section from the EPA AP 42. The activities that cause the release of particulate emissions in the first case are the loading of material into the portable crusher, crushing and screening, unloading of material from the portable crusher, and the transportation of the portable crusher to the jobsite from the recycling plant.

The total emissions for the loading and unloading operations in the first case amounted to 0.43613 kg. The crushing operation for PM 10 in the first case amounted to 0.0038 kg and 0.000709 kg for PM 2.5. The screening operation in the first case amounted to 0.00205 kg for PM 10 and 0.0001388 kg for PM 2.5. The particulate emission from transportation for PM 10 and PM 2.5 is negligible.

Table 4-9. PM results for case 1

CASE 1	PM (kg)	PM 10 (kg)	PM 2.5 (kg)
Loading/Unloading	0.43613		
Tertiary Crushing		0.00383	0.00071
Screening		0.00205	0.00014
Transportation		0.00001	0.00000075

In the second case, the activities that cause the release of particulates in the second case are loading of material into the truck from the demolition site, transportation of material from the jobsite to the landfill, unloading of material into the landfill, crushing and screening of virgin aggregate, loading of virgin aggregate, and unloading virgin aggregate into the jobsite.

Particulate emissions from all the loading and unloading operations in the first case amounted to 0.87226 kg. The particulate emission for the crushing operation in the second case amounted to 0.0038 kg and 0.000709 kg for PM 2.5. The screening operations in the second case amounted to 0.00205 kg for PM 10 and .0001388 kg for PM 2.5. The particulate emission from transportation for PM 10 was 0.0345 kg and 0.00269 kg for PM 2.5.

Table 4-10. PM results for case 2

CASE 2	PM (kg)	PM 10 (kg)	PM 2.5 (kg)
Loading/Unloading	0.87226		
Tertiary Crushing		0.00383	0.00071
Screening		0.00205	0.00014
Transportation		0.03450	0.00269

The activities that cause the emission of particulates in the third case are loading of material into the truck, transportation of material from the jobsite to the recycling plant, unloading of material into the recycling plant, crushing and screening operations, loading of material into the truck, transportation of material from the recycling plant to the jobsite, and the unloading material at the jobsite.

The particulate emissions for all the loading and unloading operations in the third case amounted to 0.87226 kg. All the transportation operations amounted to 0.003255 kg for PM 10 and 0.000254 kg for PM 2.5. The particulate emission from the crushing operations in the third case amounted to 0.0038 kg and 0.000709 kg for PM 2.5. The screening operations in the third case amounted to 0.00205 kg for PM 10 and .0001388 kg for PM 2.5.

Table 4-11. PM results for case 3

CASE 3	PM (kg)	PM 10 (kg)	PM 2.5 (kg)
Loading/Unloading	0.87226		
Tertiary Crushing		0.00383	0.00071
Screening		0.00205	0.00014
Transportation		0.00326	0.00025

Comparing the particulate emissions in all three cases shows that the first case where a portable crusher is used, emits the least particulate emissions and the second case in which demolished concrete is landfilled and virgin aggregate is bought, emits the most particulate emissions.

PM Results for Loading and Unloading Operations

The results of loading and unloading for particulate emissions shows that case 1 where the portable crusher is used emits the least particulate emissions compared to case 2 and case 3.

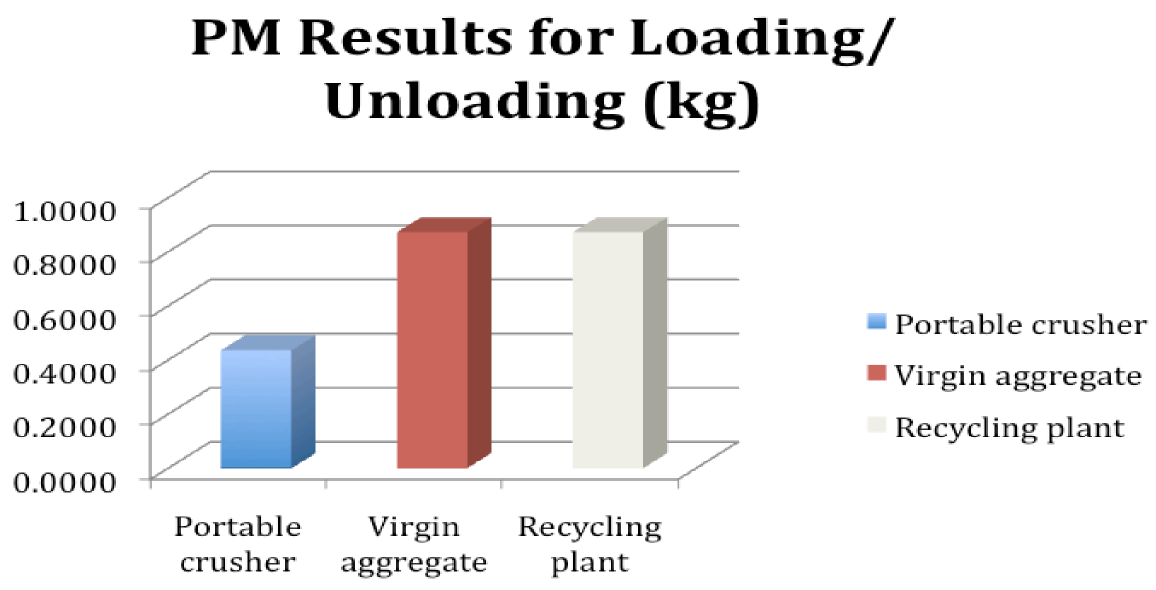

Figure 4-3. PM results for loading and unloading operations

PM results for Crushing Operation

The results of crushing operation for particulate emissions show that case 1, case 2 and case 3 emit the same amount of particulate emission for PM 10 and PM 2.5.

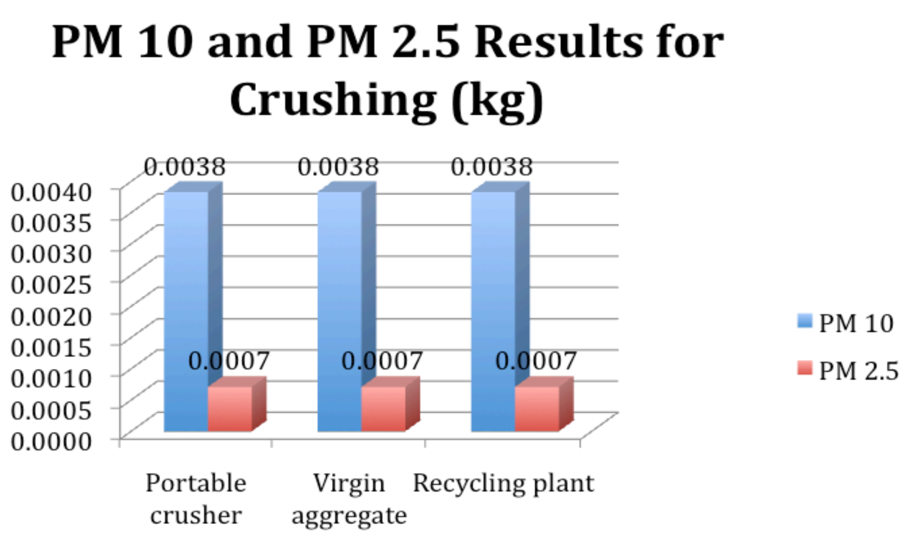

Figure 4-4. PM results for crushing

PM Results for Screening

The results of the screening operation for particulate emissions shows that case 1, case 2 and case 3 emit the same amount of particulate emission for PM 10 and PM 2.5.

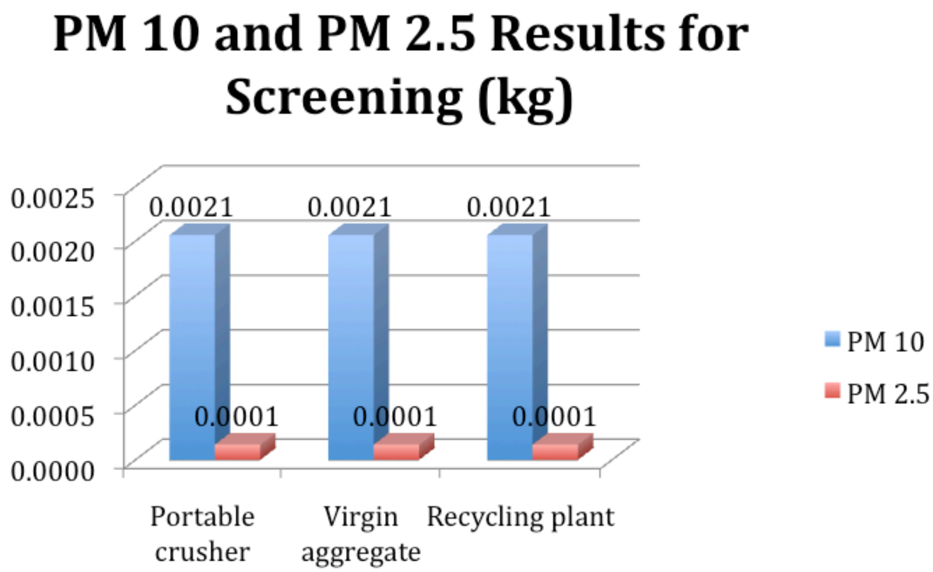

Figure 4-5. PM results for screening

PM Results for Transportation

The PM results for transportation for PM 10 and PM 2.5 show that case 2 in which virgin aggregate is used emits the most amount of particulate matter into the atmosphere, and case 1 where a portable crusher is used onsite emits the least amount of particulates.

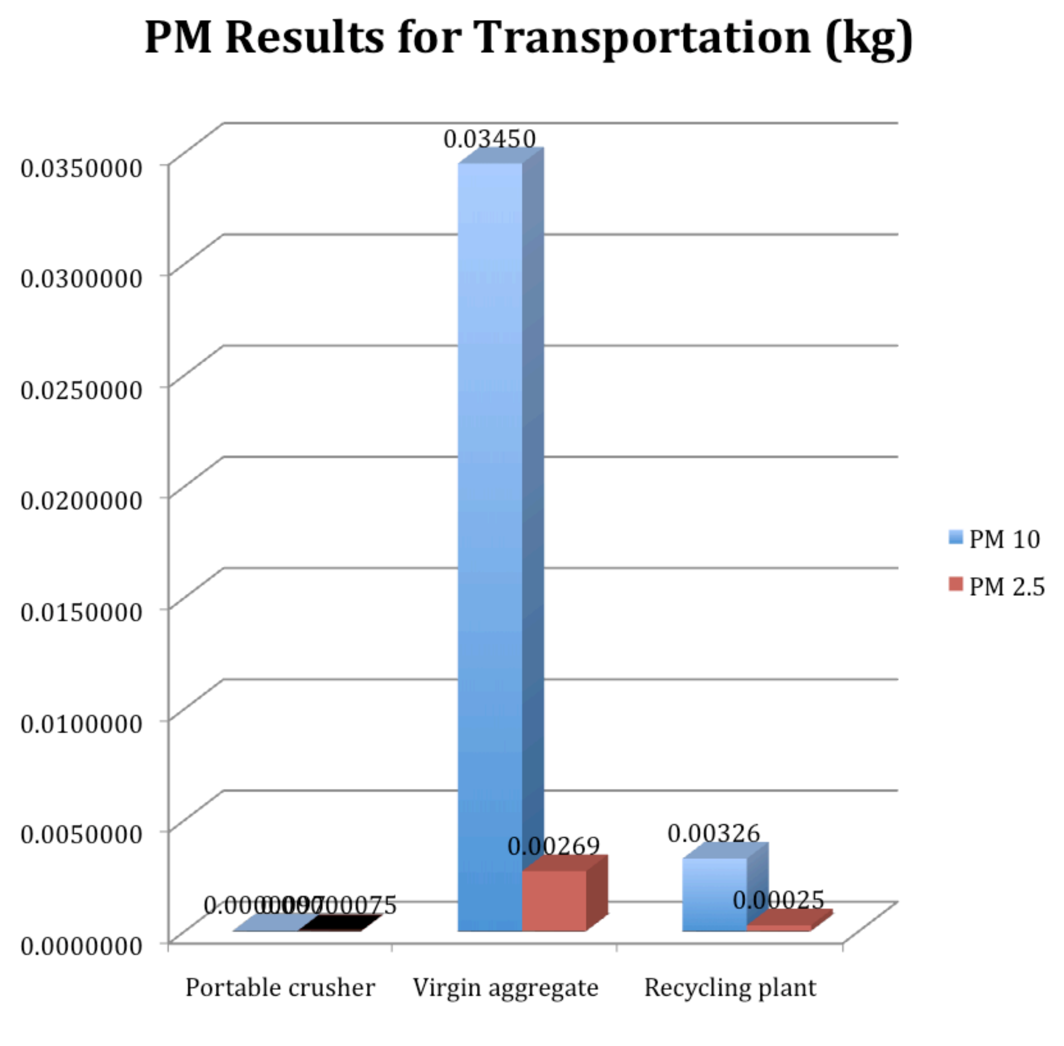

Figure 4-6. PM results for transportation

Summary of results from Cost, Energy and Particulate Emissions

The results for cost, energy, and particulate emissions in all three cases show that using a portable crusher (case 1) is the most favorable option followed by the buying of recycled concrete aggregate (case 2). Case 3 in which virgin aggregate is bought is the least favorable option in all three cases for cost, energy, and particulate emission.

Table 4-12. Summary of results

CASES	COST ($)	ENERGY (MJ)	PM (kg)	PM 10(kg)	PM 2.5(kg)
Portable crusher	$40,825	505,858	0.4361	0.0058	0.00088
Virgin aggregate	$110,747	1,344,447	0.8722	0.0403	0.00354
Recycling plant	$96,766	584,803	0.8722	0.0091	0.00110

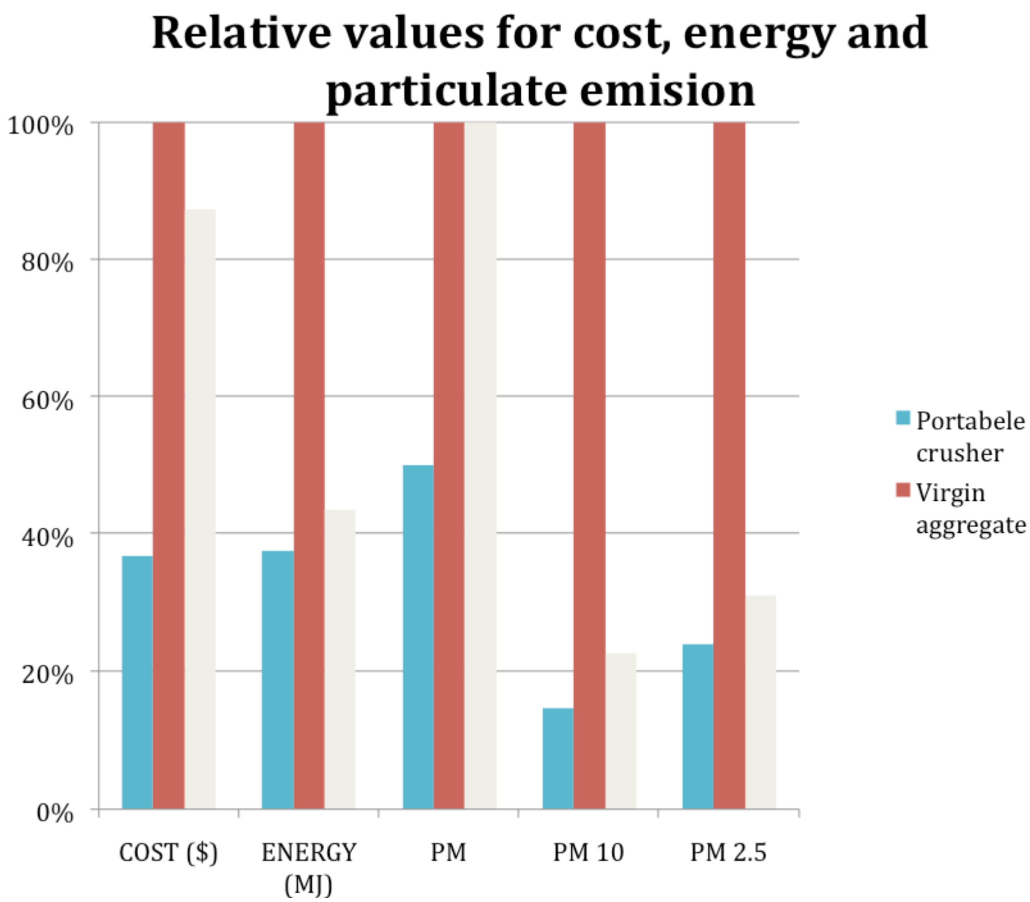

Figure 4-7. Summary of results

Impact of transportation on Cost, Energy and Particulate Emissions

The results from all the three cases show that the first case in which portable crusher is used, is the most preferred option. The cost, energy consumption, and particulate emissions are much lower and more favorable compared to the third case, where the demolished concrete is sent to the recycling plant, and the recycled concrete aggregate is bought and used at the same site. Case 1 is also more favorable than the second case, where the demolished concrete is disposed and new virgin aggregate is bought. The distance between the recycling plant and the jobsite is only 2.41 km, which is much less than the distance between the jobsite and the quarry pit, which is 24.7 km. Therefore, to test the impact of transportation distance on cost, energy consumption, and particulate emissions, the distance between the jobsite and the recycling plant was changed at the increment of every 5 km from 5 km to 35 km. The distances between the jobsite and landfill and the jobsite and quarry pit remained the same.

The new results show that when the distance between the jobsite and recycling plant becomes more than 20km, then the use of virgin aggregate becomes a more cost effective option than using RCA in case 3.

Table 4-13. Impact on cost

DISTANCE BETWEEN THE JOBSITE AND RECYCLING PLANT							
Distance	5km	10km	15km	20km	25km	30km	35km
Cost	$99,822	$103,351	$106,644	$109,937	$113,229	$116,522	$119,815

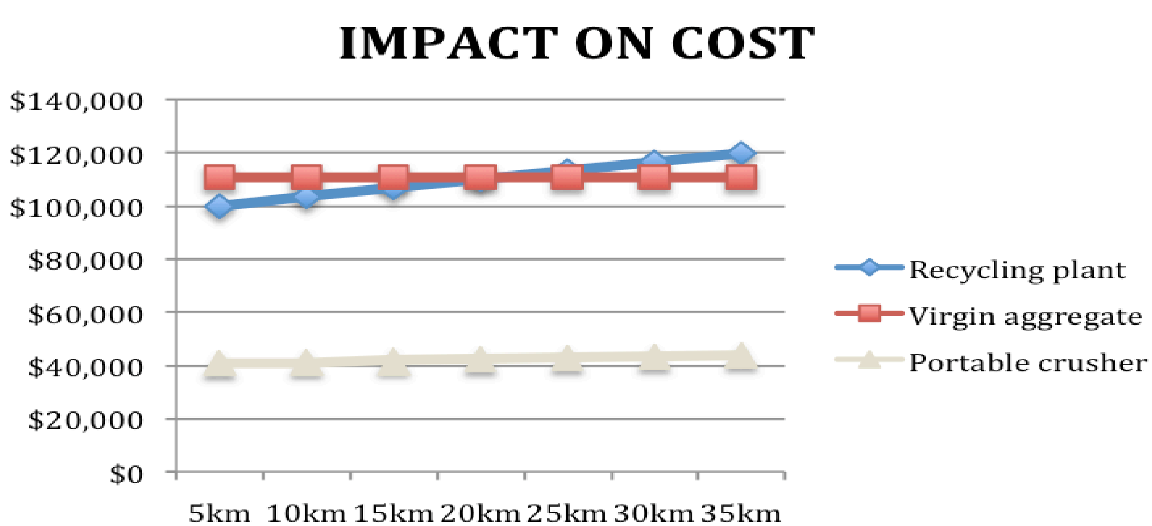

Figure 4-8. Impact of cost

The results show that when the distance between the jobsite and the recycling plant become more than 25km, then the total energy consumed for using a recycled concrete aggregate in case 3 becomes more than using a virgin aggregate in case 2.

Table 4-14. Impact on energy

DISTANCE BETWEEN THE JOBSITE AND RECYCLING PLANT							
Distance	5km	10km	15km	20km	25km	30km	35km
Energy (GJ)	669.64	833.43	997.21	1,161.00	1,324.79	1,488.58	1,652.36

At this point, the use of virgin aggregate is a more energy efficient option than RCA.

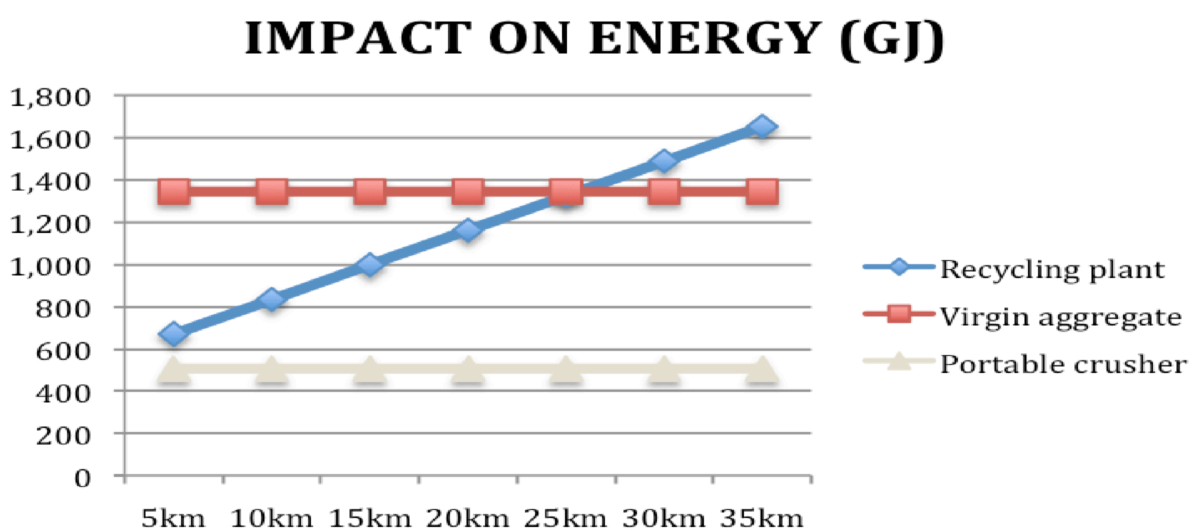

Figure 4-9. Impact on energy

Similarly, when distance the distance between the jobsite and the recycling plant becomes more than 25km, the total PM 10 emitted becomes more for using a recycled concrete aggregate in case 3 than using a virgin aggregate in case 2.

Table 4-15. Impact on PM10

DISTANCE BETWEEN THE JOBSITE AND RECYCLING PLANT							
Distance	5km	10km	15km	20km	25km	30km	35km
PM 10 (kg)	0.0126	0.0193	0.0261	0.0329	0.0396	0.0464	0.0531

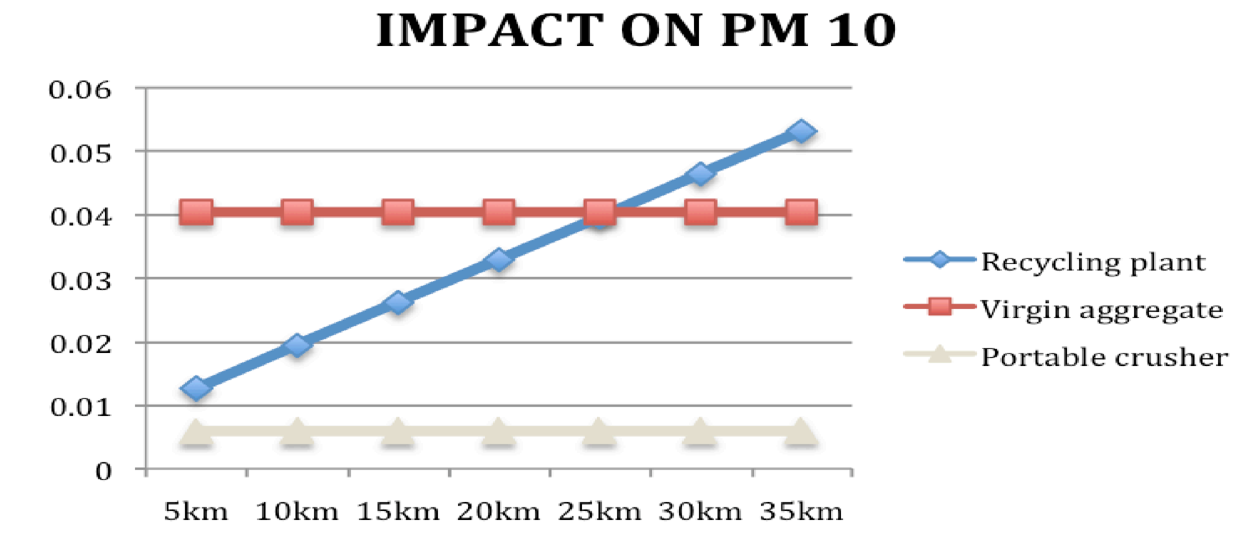

Figure 4-10. Impact on PM 10

After the distance between the jobsite and the recycling plant becomes more than 25km, PM 2.5 emitted becomes more for using a recycled concrete aggregate in case 3 than a using a virgin aggregate in case 2.

Table 4-16. Impact on PM 2.5

DISTANCE BETWEEN THE JOBSITE AND RECYCLING PLANT							
Distance	5km	10km	15km	20km	25km	30km	35km
PM 2.5 (kg)	0.0013	0.0019	0.0024	0.0029	0.0034	0.0040	0.0045

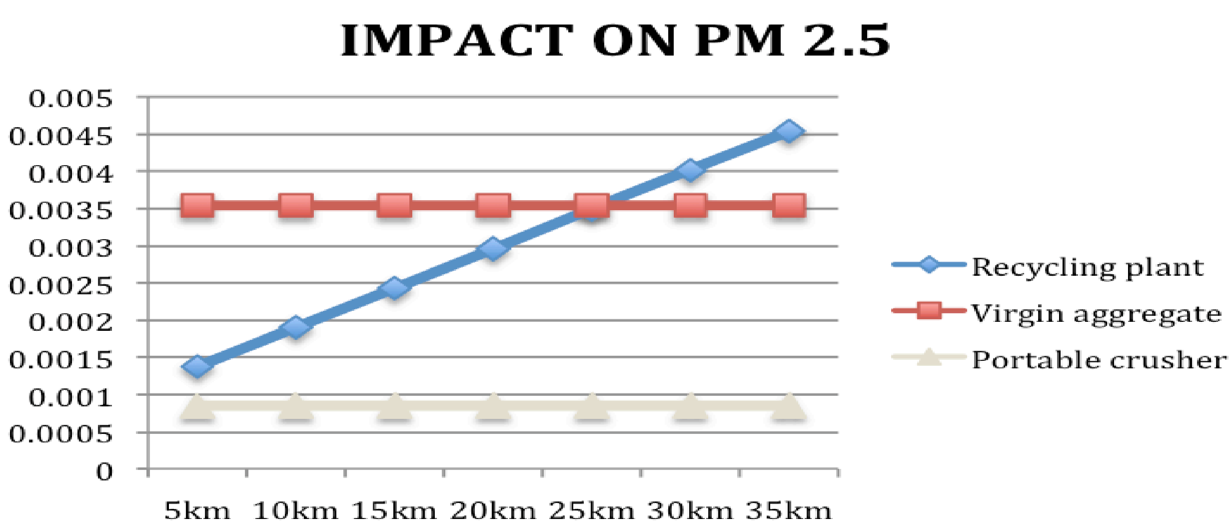

Figure 4-11. Impact on PM 2.5

Comparing the two studies in which the transportation distances between the jobsite and the recycling plant were changed at 5 km increments, shows that the second case, in which virgin aggregate is used, can become more favorable than the third case, in which recycled concrete aggregate is used after a certain distance in terms of cost, energy consumption, and particulate emissions. However, case 1 remains the preferred option. Therefore, this study shows that the transportation distances between jobsite and the source of materials (recycled concrete aggregate or virgin aggregate) has a huge impact on cost, energy consumption, and particulate emissions.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The results from this study show how different approaches can be taken for the use of demolished concrete, and how the distance for transportation for the source of concrete material plays a huge role in the selection process. Cost, energy, and particulate emissions have their own costs and benefits. Transportation for the procurement of material affects the cost, energy, and particulate emissions in their own way.

The cost for all three cases involves the cost for procurement of the material and the cost for transportation. The results show that, the first case in which a portable crusher was used to recycle the concrete was most cost effective option. And the second case in which the demolished concrete was landfilled and new virgin aggregate was bought was the least cost effective option. Therefore, using a portable crusher in which the demolished concrete is crushed onsite and which involves less transportation to and from the jobsite is the most economic option.

The major energy consumption involved in the process of obtaining recycled concrete aggregate is the energy required for the crushing and screening of demolished concrete, as well as the energy required for the transportation of the concrete material from the source to the jobsite. The three cases studied in this research show that using a portable concrete crusher onsite to crush the demolished concrete consumes the least amount of energy, and purchasing virgin aggregate is the most energy consuming. This shows that using a portable concrete crusher is the most energy efficient and environmentally friendly alternative.

The particulate emissions involved in the production and procurement of concrete are the crushing and screening of material, loading, unloading, and transfer of material and the transportation of material from the source to the jobsite. The portable crusher emitted lower amounts of particulate emissions whereas purchasing virgin aggregate produced the greatest amount. Therefore, using a portable crusher onsite emits the least amounts of particulates into the atmosphere.

To truly show the impact that transportation has on the results, a few changes were made and tested for varying distances. The distance from the jobsite to the recycling plant was changed and tested at 5 km increments. The new results show that at some point as the distance between the jobsite and recycling plant increases, virgin aggregate becomes a more favorable option in terms of cost, energy consumption, and particulate emissions, than using a recycled concrete aggregate from a recycling plant. The results of this study strongly show the profound impact of transportation both economically and environmentally.

Recommendation

The results of this study show how the distance and the type of aggregate production have a big impact on cost, energy, and particulate emissions. Cost in most cases determines the method of procuring aggregate. And the cost is directly proportional to the distance traveled for the procurement of aggregate. Therefore, further research has to be conducted to determine appropriate locations for the recycling plant, which minimizes the long distances traveled for the procurement of aggregate. This study did not take into consideration the duration of time taken for the use of a portable crusher. Therefore, further research has to be done taking this into account. The study also showed that transportation is the major emitter of particulate emissions followed by crushing and screening operations to a lesser extent. Particulate emissions pose serious problems for health and the atmosphere. Particulate matter of the size of 10 microns, 2.5 microns and smaller, poses bigger problems than the total suspended matter (TSP). Very little research has been done in the area of particulate emissions for construction. The EPA AP 42 has little information on emission factors for construction, hence its evaluation may not be very comprehensive. Further research on particulate emissions in the field of construction will help to better understand the problems and act to implement the particulate reduction and control strategies. Also, this study did not take into consideration the effect on pollution between crushing and screening concrete onsite (urban) and in an aggregate plant (rural). Further research in this area will help to understand and distinguish the effects of pollution between the crushing onsite and crushing in an aggregate plant. Other limitations of this study that has to be considered in the future are the site logistics, space, time, and the minimum threshold quantity of concrete required for the use of portable crusher onsite to be feasible. Further study in this area will help in the implementation of practical use of a portable crusher onsite. Other environmental factors that need to be considered for similar research are the depletion of natural resources, conservation of land use, and the impact of disposing concrete wastes to landfills.

APPENDIX A
CALCULATION FOR COST, ENERGY AND PARTICULATE EMISSION

Case 1

Recycle the demolished concrete using portable crusher, and use the same recycled concrete in the same site

COST

Cost for using portable crusher to recycle concrete onsite	5.44	/mt
Quantity of concrete to be recycled	6169	mt
cost	$33,559	
cost for installation	$5,000	
Tax 6.75%	$2,265.26	
Total Cost	$40,824.62	

ENERGY

Energy required to recycle the concrete	505,858,000	kJ
Distance from the recycling plant=	2.41	km
Energy required for transportation	12.7971	KJ
Total energy consumption	505,858,012.80	KJ
	505.858	GJ

NOTE:

Energy required to crush concrete	82	kJ/kg
Energy required for transporting material for 100Kms	265.5	kJ/kg

PARTICULATE EMISSION

Loading of material into the portable crusher

EF=[K(0.0016)(U/2.2)^1.3]/(M/2)^1.4 (Ref 13.2.4)

Where,

K=Particle size multiplier
U=Mean wind speed (m/s)
M=material moisture content (%)

Where, K=	0.35	
U=	3	m/s
M=	0.7	

EF = 0.003644189 kg/mt

E= A*EF*(1-ER/100)

Where,
A=activity rate
EF=Emission factor
ER=Emission reduction efficiency

ER= 0.03

A= 6169 mt

E= 0.218065728 kg

Crushing and screening

1. Tertiary crushing (PM10)

EF = 0.00027 kg/Mg(mt) (Ref 11.19.2.1, Table 11.19.2.1)

ER = 0.77 (Ref 11.19.2.1)

A= 6169 mt

E= 0.003830949 kg

Screening (PM 10)

EF = 0.00037 Kg/Mg

ER = 0.91

E= 0.002054277 kg

2. Tertiary crushing (PM 2.5)

EF = 0.00005 Kg/Mg

ER = 0.77

E= 0.000709435 kg

Screening (PM 2.5)

EF = 0.000025 kg/Mg

ER = 0.91

E= 0.000138803 kg

Unloading of material from the crusher

E= 0.218065728 kg

Transportation to and from the jobsite (PM 10)

E= 0.00966909 g

or

9.66909E-06 kg(negligible)

Transportation to and from the jobsite (PM 2.5)

E= 0.000754705 g

or

7.54705E-07 (Negligible)

Case 2

Dispose the demolished concrete and buy virgin aggregate

COST

Cost to landfill demolished concrete per ton	$5.98	/mt
Quantity of demolished Concrete	6169	mt
Cost to landfill demolished concrete	$36,891	
Cost for buying Virgin aggregate per ton	$10.84	/mt
Quantity of virgin aggregate needed	6169	mt
Cost for buying Virgin aggregate	$66,853	
Total cost	$103,744	
Tax 6.75%	$7,003	
Total cost	$110,747	

ENERGY

Energy required to produce virgin aggregate=	505,858,000	kJ
Distance from the jobsite to the landfill=	26.5	km
Energy required to transport demolished concrete to landfill=	434,035,418	kJ
Distance from the quarry pit to the jobsite=	24.7	km
Energy required to transport VA from quarry pit to the jobsite=	404,553,767	kJ
Total Energy	1,344,447,184	kJ
	1,344.447	GJ

NOTE:

Energy required for recycling concrete 82 kJ

Energy required for transporting material for 100 Km	265.5	kJ

PARTICULATE EMISSION

Loading of material into the truck

E=	0.218065728	g

Transportation to the landfill (PM 10)

EF= [K*(s/12)^a*(S/30)^d/(M/0.5)^c]-C (Ref 13.2.2.1)

Where, EF=Emission factor (lb/VMT)
s=surface material silt content(%)
M=mean vehicle speed (Mph)
C= Vehicle emission factor fleet exhaust

K=	1.8	
s=	0.048	
a=	1	
S=	50	
d=	0.5	
M=	0.05	
c=	0.2	
C=	0.00047	(Ref 13.2.2-4)

EF=	0.014731836	(-C)
EF=	0.014261836	lb/VMT
1lb/VMT=	281.9	g/VKT
EF=	4.020411528	g/VKT
ER=	0.95	(Ref 13.2.2-5)
Quantity per truck=	36.74	mt
Total quantity of concrete=	6169	mt
No. of trips=	168	

E=	A*EF*(1-ER/100)	
E=	0.337714568	g/km

Distance to and from landfill= 52.6 Km

E=	17.76378629	g
or		
	0.017763786	kg

Transportation to the landfill (PM 2.5)

EF=	0.001473184	(-C)
C=	0.00036	(Ref 13.2.2-4)
EF=	0.001113184	lb/VMT
or		
EF=	0.313806453	g/VKT
E=	0.026359742	

Distance to and from landfill= 52.6 Km

E=	1.386522431	g
or		
	0.001386522	kg

Unloading of material into the landfill

E= 0.218065728 kg

Crushing and screening

1. Tertiary crushing (PM10)

E= 0.003830949 kg

Screening (PM 10)

E= 0.002054277 kg

2. Tertiary crushing (PM 2.5)

E= 0.000709435 kg

Screening (PM 2.5)

E= 0.000138803 kg

Loading of material into the truck

E= 0.218065728 kg

Transportation to the Construction site (PM 10)

Distance to and from the Quarry pit to the Construction site= 49.56 km

E= 16.73713401 g
or
0.016737134 kg

Transportation to the Construction site (PM 2.5)

E 1.306388815 g
or
0.001306389 kg

Unloading of material from the truck

E= 0.218065728 kg

Case 3

Dispose the demolished concrete at the recycling plant and buy new RCA from recycling plant

COST

Cost for disposing concrete at the recycling plant	4.354	/mt
Quantity of concrete to be recycled	6169	mt
Cost for disposing concrete at the recycling plant	$26,860	
Cost for buying RCA per ton	10.34	/mt
Quantity of RCA needed	6169	mt
Cost for buying RCA	$63,787	
Total Cost	$90,647	
Tax 6.75%	$6,119	
Total Cost	$96,766	

ENERGY

Energy required to recycle the concrete	505,858,000	kJ
Distance from the jobsite to the recycling plant=	2.41	km
Energy to transport demolished concrete to the recycling plant	39,472,655	kJ
Distance from the recycling plant to the jobsite=	2.41	km
Energy to transport RCA to the jobsite	39,472,655	kJ
Total Energy	584,803,310	kJ
	584.803	GJ

NOTE:

Energy required for recycling concrete	82	kJ/Kg
Energy required for transporting material for 100Kms	265.5	kJ/Kg

PARTICULATE EMISSION

Loading material into the truck

E=	0.218065728	kg

Transporting material to the Recycling plant (PM 10)

E=	0.337714568	g

Distance to and from the recycling plant= 4.82 km

E=		1.627784219	g
	or		
		0.001627784	kg

Transporting material to the recycling plant (PM 2.5)

E=		0.127053957	g
	or		
		0.000127054	kg

Unloading material at the recycling plant

E=	0.218065728	kg

Crushing and screening

1. Tertiary crushing (PM10)

E=	0.003830949	kg

Screening (PM 10)

E=	0.002054277	kg

2. Tertiary crushing (PM 2.5)

E=	0.000709435	kg

Screening (PM 2.5)

E= 0.000138803 kg

Loading material into the truck

E= 0.218065728 kg

Transportation of material to the Construction site (PM 10)

E= 1.627784219 g
or
0.001627784 kg

Transportation of material to the Construction site (PM 2.5)

E= 0.127053957 g
or
0.000127054 kg

Unloading of material at the Construction site

E= 0.218065728 kg

APPENDIX B
IMPACT OF TRANSPORTATION ON COST, ENERGY AND PARTICULATE EMISSION

Distance between the jobsite and recycling plant= 5 km

Dispose the demolished concrete at the recycling plant and buy new RCA from recycling plant

Distance between the jobsite and recycling plant=	5km	
COST		
Cost for disposing concrete at the recycling plant	4.604	/mt
Quantity of concrete to be recycled	6169	mt
Cost for disposing concrete at the recycling plant	$28,402	
Cost for buying RCA per ton	10.55	/mt
Quantity of RCA needed	6169	mt
Cost for buying RCA	$65,108	
Total Cost	$93,510	
Tax 6.75%	$6,312	
Total Cost	$99,822	
ENERGY		
Energy required to recycle the concrete	505,858,000	kJ
Distance from the jobsite to the recycling plant=	5.00	km
Energy to transport demolished concrete to the recycling plant	81,893,475	kJ
Distance from the recycling plant to the jobsite=	5.00	km
Energy to transport RCA to the jobsite	81,893,475	kJ
Total Energy	669,644,950	kJ
	669.645	GJ

NOTE:

Energy required for recycling concrete	82	kJ/Kg
Energy required for transporting material for 100Kms	265.5	kJ/Kg

PARTICULATE EMISSION

Loading material into the truck

E= 0.218065728 kg

Transporting material to the Recycling plant (PM 10)

E= 0.337714568

Distance to and from the recycling plant= 10 km

E= 3.377145683 g
or
0.003377146 kg

Transporting material to the recycling plant (PM 2.5)

E= 0.26359742 g
or
0.000263597 kg

Unloading material at the recycling plant

E= 0.218065728 kg

Crushing and screening

1. Tertiary crushing (PM10)

E= 0.003830949 kg

Screening (PM 10)

E= 0.002054277 kg

2. Tertiary crushing (PM 2.5)

E=	0.000709435	kg

Screening (PM 2.5)

E=	0.000138803	kg

Loading material into the truck

E=	0.218065728	kg

Transportation of material to the Construction site (PM 10)

E=		3.377145683	g
	or		
		0.003377146	kg

Transportation of material to the Construction site (PM 2.5)

E=		0.26359742	g
	or		
		0.000263597	kg

Unloading of material at the Construction site

E=	0.218065728	kg

Distance between the jobsite and recycling plant= 10 km

Dispose the demolished concrete at the recycling plant and buy new RCA from recycling plant

Distance between the jobsite and recycling plant=	10km	
COST		
Cost for disposing concrete at the recycling plant	4.854	/mt
Quantity of concrete to be recycled	6169	mt
Cost for disposing concrete at the recycling plant	$29,944	
Cost for buying RCA per ton	10.84	/mt
Quantity of RCA needed	6169	mt
Cost for buying RCA	$66,872	
Total Cost	$96,816	
Tax 6.75%	$6,535	
Total Cost	$103,351	
ENERGY		
Energy required to recycle the concrete	505,858,000	kJ
Distance from the jobsite to the recycling plant=	10.00	km
Energy to transport demolished concrete to the recycling plant	163,786,950	kJ
Distance from the recycling plant to the jobsite=	10.00	km
Energy to transport RCA to the jobsite	163,786,950	kJ
Total Energy	833,431,900	kJ
	833.432	GJ

NOTE:

Energy required for recycling concrete	82	kJ/Kg

Energy required for transporting material for 100Kms		265.5	kJ/Kg

PARTICULATE EMISSION

Loading material into the truck

E=		0.218065728	kg

Transporting material to the Recycling plant (PM 10)

E=		0.337714568	
Distance to and from the recycling plant=		20	km
E=		6.754291367	g
	or		
		0.006754291	kg

Transporting material to the recycling plant (PM 2.5)

E=		0.527194841	g
	or		
		0.000527195	kg

Unloading material at the recycling plant

E=		0.218065728	kg

Crushing and screening

1. Tertiary crushing (PM10)

E=	0.003830949	kg

Screening (PM 10)

E=	0.002054277	kg

2. Tertiary crushing (PM 2.5)

E=	0.000709435	kg

Screening (PM 2.5)

E= 0.000138803 kg

Loading material into the truck
E= 0.218065728 kg

Transportation of material to the Construction site (PM 10)

E= 6.754291367 g
or
0.006754291 kg

Transportation of material to the Construction site (PM 2.5)

E= 0.527194841 g
or
0.000527195 kg

Unloading of material at the Construction site

E= 0.218065728 kg

Distance between the jobsite and recycling plant= 15 km

Dispose the demolished concrete at the recycling plant and buy new RCA from recycling plant

Distance between the jobsite and recycling plant=	15km	
COST		
Cost for disposing concrete at the recycling plant	5.104	/mt
Quantity of concrete to be recycled	6169	mt
Cost for disposing concrete at the recycling plant	$31,487	
Cost for buying RCA per ton	11.09	/mt
Quantity of RCA needed	6169	mt
Cost for buying RCA	$68,414	
Total Cost	$99,901	
Tax 6.75%	$6,743	
Total Cost	$106,644	
ENERGY		
Energy required to recycle the concrete	505,858,000	kJ
Distance from the jobsite to the recycling plant=	15.00	km
Energy to transport demolished concrete to the recycling plant	245,680,425	kJ
Distance from the recycling plant to the jobsite=	15.00	km
Energy to transport RCA to the jobsite	245,680,425	kJ
Total Energy	997,218,850	kJ
	997.219	GJ

NOTE:

Energy required for recycling concrete	82	kJ/Kg
Energy required for transporting material for 100Kms	265.5	kJ/Kg

PARTICULATE EMISSION

Loading material into the truck

E= 0.218065728 kg

Transporting material to the Recycling plant (PM 10)

E= 0.337714568

Distance to and from the recycling plant= 30 km

E= 10.13143705 g
or
0.010131437 kg

Transporting material to the recycling plant (PM 2.5)

E= 0.790792261 g
or
0.000790792 kg

Unloading material at the recycling plant

E= 0.218065728 kg

Crushing and screening

1. Tertiary crushing (PM10)

E= 0.003830949 kg

Screening (PM 10)

E= 0.002054277 kg

2. Tertiary crushing (PM 2.5)

E= 0.000709435 kg

Screening (PM 2.5)

E= 0.000138803 kg

Loading material into the truck
E= 0.218065728 kg

Transportation of material to the Construction site (PM 10)

E= 10.13143705 g
or
0.010131437 kg

Transportation of material to the Construction site (PM 2.5)

E= 0.790792261 g
or
0.000790792 kg

Unloading of material at the Construction site

E= 0.218065728 kg

Distance between the jobsite and recycling plant= 20 km

Dispose the demolished concrete at the recycling plant and buy new RCA from recycling plant

Distance between the jobsite and recycling plant= 20km

COST

Cost for disposing concrete at the recycling plant	5.354	/mt
Quantity of concrete to be recycled	6169	mt
Cost for disposing concrete at the recycling plant	$33,029	
Cost for buying RCA per ton	11.34	/mt
Quantity of RCA needed	6169	mt
Cost for buying RCA	$69,956	
Total Cost	$102,985	
Tax 6.75%	$6,952	
Total Cost	$109,937	

ENERGY

Energy required to recycle the concrete	505,858,000	kJ
Distance from the jobsite to the recycling plant=	20.00	km
Energy to transport demolished concrete to the recycling plant	327,573,900	kJ
Distance from the recycling plant to the jobsite=	20.00	km
Energy to transport RCA to the jobsite	327,573,900	kJ
Total Energy	1,161,005,800	kJ
	1,161.006	GJ

NOTE:
Energy required for recycling concrete 82 kJ/Kg

Energy required for transporting material for 100Kms 265.5 kJ/Kg
PARTICULATE EMISSION

Loading material into the truck

E= 0.218065728 kg

Transporting material to the Recycling plant (PM 10)

E= 0.337714568

Distance to and from the recycling plant= 40 km

E= 13.50858273 g
or
0.013508583 kg

Transporting material to the recycling plant (PM 2.5)

E= 1.054389681 g
or
0.00105439 kg

Unloading material at the recycling plant

E= 0.218065728 kg

Crushing and screening

1. Tertiary crushing (PM10)

E= 0.003830949 kg

Screening (PM 10)

E= 0.002054277 kg

2. Tertiary crushing (PM 2.5)

E= 0.000709435 kg

Screening (PM 2.5)

E=	0.000138803	kg

Loading material into the truck

E=	0.218065728	kg

Transportation of material to the Construction site (PM 10)

E=	13.50858273	g
or		
	0.013508583	kg

Transportation of material to the Construction site (PM 2.5)

E=	1.054389681	g
or		
	0.00105439	kg

Unloading of material at the Construction site

E=	0.218065728	kg

Distance between the jobsite and recycling plant= 25 km

Dispose the demolished concrete at the recycling plant and buy new RCA from recycling plant

Distance between the jobsite and recycling plant=	25km	
COST		
Cost for disposing concrete at the recycling plant	5.604	/mt
Quantity of concrete to be recycled	6169	mt
Cost for disposing concrete at the recycling plant	$34,571	
Cost for buying RCA per ton	11.59	/mt
Quantity of RCA needed	6169	mt
Cost for buying RCA	$71,499	
Total Cost	$106,070	
Tax 6.75%	$7,160	
Total Cost	$113,229	
ENERGY		
Energy required to recycle the concrete	505,858,000	kJ
Distance from the jobsite to the recycling plant=	25.00	km
Energy to transport demolished concrete to the recycling plant	409,467,375	kJ
Distance from the recycling plant to the jobsite=	25.00	km
Energy to transport RCA to the jobsite	409,467,375	kJ
Total Energy	1,324,792,750	kJ
	1,324.793	GJ

NOTE:

Energy required for recycling concrete	82	kJ/Kg

Energy required for transporting material for 100Kms 265.5 kJ/Kg

PARTICULATE EMISSION

Loading material into the truck

E= 0.218065728 kg

Transporting material to the Recycling plant (PM 10)

E= 0.337714568

Distance to and from the recycling plant= 50 km

E= 16.88572842 g
or
0.016885728 kg

Transporting material to the recycling plant (PM 2.5)

E= 1.317987102 g
or
0.001317987 kg

Unloading material at the recycling plant

E= 0.218065728 kg

Crushing and screening

1. Tertiary crushing (PM10)

E= 0.003830949 kg

Screening (PM 10)

E= 0.002054277 kg

2. Tertiary crushing (PM 2.5)

E= 0.000709435 kg

Screening (PM 2.5)

E=	0.000138803	kg

Loading material into the truck

E=	0.218065728	kg

Transportation of material to the Construction site (PM 10)

E=	16.88572842	g
or		
	0.016885728	kg

Transportation of material to the Construction site (PM 2.5)

E=	1.317987102	g
or		
	0.001317987	kg

Unloading of material at the Construction site

E=	0.218065728	kg

Distance between the jobsite and recycling plant= 30 km

Dispose the demolished concrete at the recycling plant and buy new RCA from recycling plant

Distance between the jobsite and recycling plant=	30km	
COST		
Cost for disposing concrete at the recycling plant	5.854	/mt
Quantity of concrete to be recycled	6169	mt
Cost for disposing concrete at the recycling plant	$36,113	
Cost for buying RCA per ton	11.84	/mt
Quantity of RCA needed	6169	mt
Cost for buying RCA	$73,041	
Total Cost	$109,154	
Tax 6.75%	$7,368	
Total Cost	$116,522	
ENERGY		
Energy required to recycle the concrete	505,858,000	kJ
Distance from the jobsite to the recycling plant=	30.00	km
Energy to transport demolished concrete to the recycling plant	491,360,850	kJ
Distance from the recycling plant to the jobsite=	30.00	km
Energy to transport RCA to the jobsite	491,360,850	kJ
Total Energy	1,488,579,700	kJ
	1,488.580	GJ

NOTE:

Energy required for recycling concrete 82 kJ/Kg

Energy required for transporting material for 100Kms	265.5	kJ/Kg

PARTICULATE EMISSION

Loading material into the truck

E= 0.218065728 kg

Transporting material to the Recycling plant (PM 10)

E= 0.337714568

Distance to and from the recycling plant= 60 km

E= 20.2628741 g
or
0.020262874 kg

Transporting material to the recycling plant (PM 2.5)

E= 1.581584522 g
or
0.001581585 kg

Unloading material at the recycling plant

E= 0.218065728 kg

Crushing and screening

1. Tertiary crushing (PM10)

E= 0.003830949 kg

Screening (PM 10)

E= 0.002054277 kg

2. Tertiary crushing (PM 2.5)

E= 0.000709435 kg

Screening (PM 2.5)

E=	0.000138803	kg

Loading material into the truck

E=	0.218065728	kg

Transportation of material to the Construction site (PM 10)

E=	20.2628741	g
or		
	0.020262874	kg

Transportation of material to the Construction site (PM 2.5)

E=	1.581584522	g
or		
	0.001581585	kg

Unloading of material at the Construction site

E=	0.218065728	kg

Distance between the jobsite and recycling plant= 35 km

Dispose the demolished concrete at the recycling plant and buy new RCA from recycling plant

Distance between the jobsite and recycling plant= 35km

COST

Cost for disposing concrete at the recycling plant	6.104	/mt
Quantity of concrete to be recycled	6169	mt
Cost for disposing concrete at the recycling plant	$37,656	
Cost for buying RCA per ton	12.09	/mt
Quantity of RCA needed	6169	mt
Cost for buying RCA	$74,583	
Total Cost	$112,239	
Tax 6.75%	$7,576	
Total Cost	**$119,815**	

ENERGY

Energy required to recycle the concrete	505,858,000	kJ
Distance from the jobsite to the recycling plant=	35.00	km
Energy to transport demolished concrete to the recycling plant	573,254,325	kJ
Distance from the recycling plant to the jobsite=	35.00	km
Energy to transport RCA to the jobsite	573,254,325	kJ
Total Energy	1,652,366,650	kJ
	1,652.367	GJ

NOTE:
Energy required for recycling concrete 82 kJ/Kg

Energy required for transporting material for 100Kms	265.5	kJ/Kg

PARTICULATE EMISSION

Loading material into the truck

E= 0.218065728 kg

Transporting material to the Recycling plant (PM 10)

E= 0.337714568

Distance to and from the recycling plant= 70 km

E= 23.64001978 g
or
0.02364002 kg

Transporting material to the recycling plant (PM 2.5)

E= 1.845181942 g
or
0.001845182 kg

Unloading material at the recycling plant

E= 0.218065728 kg

Crushing and screening

1. Tertiary crushing (PM10)

E= 0.003830949 kg

Screening (PM 10)

E= 0.002054277 kg

2. Tertiary crushing (PM 2.5)

E= 0.000709435 kg

Screening (PM 2.5)

E= 0.000138803 kg

Loading material into the truck

E= 0.218065728 kg

Transportation of material to the Construction site (PM 10)

E= 23.64001978 g

or

0.02364002 kg

Transportation of material to the Construction site (PM 2.5)

E= 1.845181942 g

or

0.001845182 kg

Unloading of material at the Construction site

E= 0.218065728 kg

Summary

DISTANCE BETWEEN THE JOBSITE AND RECYCLING PLANT							
	5km	10km	15km	20km	25km	30km	35km
COST ($)	$99,822	$103,351	$106,644	$109,937	$113,229	$116,522	$119,815
ENERGY (MJ)	669.645	833.432	997.219	1,161.006	1,324.793	1,488.580	1,652.367
TOTAL PM (kg)	0.87226	0.87226	0.87226	0.87226	0.87226	0.87226	0.87226
PM 10(kg)	0.01264	0.01939	0.02615	0.03290	0.03966	0.04641	0.05317
PM 2.5(kg)	0.00138	0.00190	0.00243	0.00296	0.00348	0.00401	0.00454

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BIOGRAPHICAL SKETCH

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