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RECYCLING CONCRETE FOR SUSTAINABLE CONSTRUCTION

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ABSTRACT

The demolition of concrete structures has made concrete debris the largest portion of the waste stream in the U.S. With landfills becoming scarcer, the need to recycle demolition debris is becoming increasingly relevant. An effective way to recycle this material is to produce recycled concrete aggregate (RCA) and use this material in the reconstruction of buildings and roads. Producing and re-using RCA will reduce landfill waste and save energy by minimizing the production and transport of natural aggregates.

The focus of this thesis is to quantify how much energy can be saved by producing and re-using RCA instead of landfilling demolition debris and using natural aggregates. However, in order to do this, a thorough understanding of RCA and the natural aggregates industry must first be addressed. Through literature review, the properties, uses, production, and criteria to use RCA was determined. The availability and energy required to produce and transport natural aggregates was also determined.

Three case studies were conducted in order to perform analysis on energy savings associated with RCA. In each case, a building was demolished and RCA was produced and re-used from the demolition debris. All of the energy inputs from the production and transportation of the RCA to its re-use site was calculated. This data was compared to the energy inputs to landfill demolition debris and produce and transport virgin aggregates to those same sites.

For each case, energy savings were seen by producing and re-using RCA. However, these savings varied greatly for each case. It was determined that variables such as re-use location, location of the quarry/distribution center and modes of transportation used in shipping were the main contributors for these differences. For this reason, it was determined that this model is effective, but that the difference in the variables can have huge impacts and are all project specific. Therefore, this analysis must be made on a case by case basis to determine if this is a sustainable practice.

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CHAPTER I

INTRODUCTION

Construction aggregates accounted for 70% by mass of all materials consumed in the United States in the late 20th Century (Mcintyre et al., 2009). Many scientists believe that concrete production alone produces 5 percent of humanity's carbon footprint (NSF, 2009). In 1998, 3,400 U.S. quarries produced 1.5 billion tons of crushed stone, in which 1.2 billion was used in construction applications (Army Corps, 2004). Aggregate consumption in the U.S. can be broken down to 10 tons per person per year, 38,000 tons per mile of new highway, or 400 tons per new home. While these aggregates are being used to construct new buildings and roadways, large amounts of concrete debris are being produced from demolishing the old ones.

It is estimated that 180 million tons of concrete debris is produced annually in the U.S., which makes it the largest portion of the solid waste stream (Mcintyre et al., 2009, Army Corps, 2004). The disposal of this debris is becoming more expensive, as landfills are becoming scarcer and transportation costs continue to increase.

The recycling of industrial minerals is an important component in the life cycle of geologic commodities in Ohio. Dozens of companies in the state are taking part in the recycling process, as it has several advantages. Recycling can reduce landfill space for disposal and decrease the transportation and handling of materials. It can decrease the cost for road base, and the products can be considered a renewable resource in an urban area. The United States Geological Survey estimated that five percent of the aggregates consumed nationally are recycled material. Reliable data on mineral recycling are lacking, but it is reasonable to expect that more than 5 million tons of recycled aggregate is used annually in the state (Wolfe, 2011).

One of the most common recycled materials and the focus of this paper is recycled concrete aggregate (RCA). RCA production was estimated at 95 million tons in the U.S. in 1996 (Mcintyre et al., 2009) and more recent estimates put this figure at 140 million tons (CMRA, 2011). As the demand for RCA continues to rise more attention must be paid to its properties, uses, and cost effectiveness.

Objectives

The objective of this thesis is to determine if recycled concrete aggregate (RCA) can be used as a sustainable building product. The properties, uses, production, and feasibility of using RCA are first going to be identified. An overall analysis will then be made to quantify the total energy consumed to produce and re-use RCA versus landfilling demolition debris and using virgin aggregates. The results of this model will determine how much energy is conserved by choosing to use RCA and determine whether or not it is a sustainable practice.

Scope

This thesis will identify both the physical and chemical properties of RCA and the advantages and disadvantages that these properties have on re-use applications. It will identify the applications that RCA can be re-used in and any potential drawbacks from its re-use. It will also identify how RCA is produced and provide examples and how it is specified in construction.

This thesis will also address the natural aggregates industry, and identify the availability of natural aggregates and the energy inputs to produce and transport them. Lastly, this thesis includes three case studies in which RCA was used. In each study, the energy inputs to produce and re-use RCA were calculated. This was compared to the energy inputs to landfill building debris and produce and transport natural aggregates to the sites where RCA was re-used. An overall analysis was made on the three studies, and conclusions were drawn on what variables contributed to the differences in energy savings between the three studies.

Outline

This document is divided into seven chapters. Chapter 1 is the introduction and describes how much building waste is being generated and recycled in recent construction practices. Chapter 2 is on the properties of RCA, and describes the physical and chemical characteristics of RCA. Chapter 3 is about the uses of RCA and the properties of the materials that RCA is used in. Chapter 4 describes how different types of RCA are produced and sized. Chapter 5 describes an example on how RCA is specified in certain applications and the criteria it must meet in order to be used. Chapter 6 describes the state of the natural aggregates industry and the availability of natural aggregates. It also discusses the production of aggregate and quantifies the energy required to produce and transport it. Chapter 7 reviews the three case studies conducted, and describes each project in depth and the procedures followed. It also includes an overall analysis on total energy conserved by using RCA and compares the results of the three case studies.

CHAPTER II

PROPERTIES OF RCA

The original use of concrete must be considered when choosing to recycle concrete. The original concrete constituents and the environmental conditions impacting it throughout its service can significantly change its physical and chemical properties. These changes in properties will directly affect the RCA's usefulness in certain applications and may eliminate its application in some cases.

Physical Properties

Mortar Content

Mortar content in RCA can be as high as 41% by volume, depending on the mixture proportions of the original concrete (Fatzhifazl, 2008). This can be highly influenced by the angularity of the originally coarse aggregate. A smoother, more rounded aggregate will typically have less attached mortar due to the fact that the concrete relies on shear resistance for bond (Hiller et al., 2011).

More important is the amount of unhydrated cement attached to the coarse aggregate of RCA. During the initial mixing process, not all of the cement in the concrete reacts with water. When the concrete is crushed and the unhydrated cement is re-exposed, it can still react with water in new applications using RCA. This can have both a positive and negative affect on new concrete made from RCA. The previously unhydrated cement in the RCA can lead to a strength increase in new concrete due to a lower water to cement ratio. It can also lead to increases in drying shrinkage, which may result in unintended stresses and premature cracking in new concrete (Hiller et al., 2011).

In recent years, there has been an increase in demand for concrete with high early strength. In order to gain early strength, the fineness and specific surface area of Portland cement has increased. (Prince, 1974). This leads to less unhydrated cement in virgin aggregate concrete applications and lessens the risk when using them as a source of RCA.

Absorption Capacity

The amount of water an aggregate can absorb is referred to as the absorption capacity. The absorption capacity of RCA can range from 2 to 10 percent (Hiller et al., 2011), which can be up to 8 times that of virgin aggregates (Army Corps, 2004). Absorption is one of the most marked physical differences between RCA and virgin aggregates. The difference in absorption capacity can be attributed to the porous mortar in RCA (ACI, 2011). Also, as the size of the RCA increases, its absorption percentage decreases significantly (**Error! Reference source not found.**).

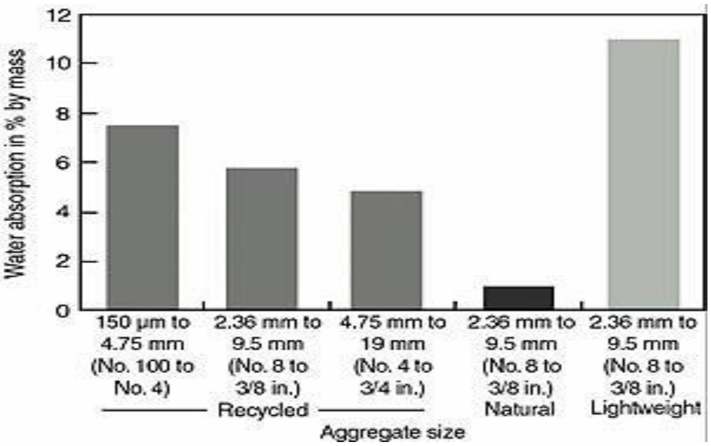

Figure 1 – Absorption Percentage of RCA and Virgin Aggregate (PCA, 2011)

Soundness

Soundness tests are an indication to an aggregate's resistance to weathering and other environmental factors. RCA typically fails the sulfate soundness test (ASTM C88–05) but passes the magnesium sulfate test (ASTM C88-05). The applicability of this test to RCA has yet to be determined(Anderson et al., 2009). Other test methods for soundness are the Los Angeles Abrasion Test (ASTM C 131-06) and the soundness test by freeze/thaw for hardened concrete (ASTM C 666-03).

Freeze Thaw Resistance

Freeze thaw resistance is dependent on factors such as absorption of the original aggregate and the pore system of the attached mortar. The pores may relieve internal pressure that may cause fracturing (Mindess, 2003). A modified soundness test by the freeze/thaw method consists of exposing aggregates of known, uniform particle size to repeated freezing and thawing cycles (ODOT, 2002).

In 2002, ODOT performed freeze/thaw testing on RCA from sources in Cleveland, Columbus, and Cincinnati using a modified version of ASTM C666 (ASTM C666 is for hardened concrete). Testing was also completed on limestone and gravel aggregate. In this test, all five aggregates were segregated into four sieves (1”, ¾”, #4, and #30). The initial weights were taken for each sieve and the aggregate was subjected to 160 freeze thaw cycles while submerged in water. The aggregates were re-sieved at three intervals during testing (54, 100, and 160 cycles), and the amount of degradation of each sample was found by re-weighing the amount retained on each sieve (ODOT, 2002).

The results of these tests indicated that RCA is not as sound or durable as virgin aggregates for particle sizes greater than the #4 sieve, with the majority of the losses occurring in the first 54 cycles. RCA losses at 54 cycles were 500% to 1,500% higher for the 1” aggregate, 200% to 700% higher for the 3/4'” sized aggregate and 20% to 50% higher for the #4 sized aggregate. For the aggregates retained on the #30 sieve, losses were 8% to 23% higher than gravel and approximately the same as limestone. The poor soundness for the larger particles can be attributed to the attached mortar fracturing and de-bonding from the aggregate, but the absence of the mortar on the smaller sized aggregates minimized these losses (ODOT, 2002).

Abrasion Loss

Abrasion loss is a measure of the pulverization that takes place for a given aggregate and is measured by the Los Angeles Abrasion Test (Anderson et al., 2009). The Los Angeles Abrasion Test consists of exposing aggregates of known gradations to abrasion, impact, and grinding actions (ODOT, 2002). A softer aggregate typically results in a higher abrasion loss, and the loss in RCA is typically higher than in virgin aggregates (Anderson et al., 2009). According to ASTM C 33, aggregates for concrete construction should have an abrasion loss of less than 50% for general construction and less than 40% for use as crushed stone under pavements (ACI Committee 555, 2001). RCA is usually within these limits recommended by ASTM (Anderson et al., 2009).

ODOT performed the Los Angeles Abrasion Test with the same five materials used in the freeze/thaw testing described above. The results of this test showed that RCA was not as sound or durable as the virgin aggregates. The losses for gravel and limestone were 21% and 36%, respectively, while the losses for the RCA ranged from 37% to 42%.

Another study, performed by Tabsh and Adelfatah (2008), showed that RCA had on average 30% more losses when The Los Angeles Abrasion (ASTM C131) Test was performed. These losses were greater for the coarse RCA that came from concrete with an initial lower strength, which suggests that higher strength concrete makes more abrasion resistant RCA.

Specific Gravity

Specific gravity is a measure of the density of aggregate. For RCA, specific gravity is lower due to the attached mortar particles on the aggregate. The mortar's porosity and entrained air structure make it a lighter material (Anderson et al., 2009).

Chemical Properties

Sulfates

Sulfate contaminants may cause disruptive expansion in concrete. Some sulfur compounds in RCA may oxidize in new concrete and produce sulfates that can lead to deleterious expansive reactions. Other types of sulfates may be less likely to participate in any further reaction in new concrete (Sagoe-Crentsil and Brown, 1998).

Plaster and gypsum wallboard are often present in RCA from buildings. This creates the possibility of sulfate attack when exposed to moisture (Army Corps, 2004). Gypsum is potentially harmful to concrete, because it can produce expansive reactions within the cement paste and can also alter concrete setting characteristics (Sagoe-Crentsil and Brown, 1998).

Alkali-Silica Reaction

The reaction of RCA and alkaline water is one of great concern when using RCA in new concrete production. Alkali-silica reaction results in volumetric expansion, which increases the chances of internal fracturing and premature deterioration (Army Corps, 2004). Whenever possible, the reactivity of RCA should be determined under conventional accelerated test conditions to establish its susceptibility to Alkali-Silica reaction (Sagoe-Crentsil and Brown 1998). Some ways to combat the alkali-silica reaction are use type II cement and/or fly ash in new concrete applications.

Chlorides

In colder climates, the use of salts to control snow and ice removal affects the use of the pavements as a source for RCA. The salts deposit chloride ions onto the pavements, which can negatively impact the reinforcing steel in new concrete using RCA. When steel is in the presence of chloride ions it will form iron oxide or rust. If this happens, the structural integrity of the concrete can be in question (Army Corps, 2004).

CHAPTER III

USES OF RCA

RCA can be used as an aggregate in new concrete production, as an aggregate in new asphalt production, as a road or pavement base, as embankment fill, as a railway ballast, and as a drainage material.   RCA can come from many different sources and be exposed to many different conditions throughout its service life. For this reason, the final product in its new applications may have properties with great variability. The reasons for this must be addressed in an attempt to eliminate any question of the quality of the new product.

RCA as Aggregate in New Concrete

Compressive Strength

A 10% reduction in strength can typically be seen when using coarse RCA in place of all virgin coarseaggregate (Sagoe-Crentsilet al.,2001). However, further research has shown that this reduction can be highly variable based on the source and strength of the old concrete aggregate.

Laboratory testing performed by Tabsh and Adelfatah (2008) used RCA of different strengths to determine the effect the different RCA had on new concrete. Four mixes designs were tested using virgin aggregate, RCA from concrete having7,250 psi (50 MPa) compressive strength, RCA from concrete having 4,350 psi (30 MPa) compressive strength, and RCA from an unknown stockpile. Two different mix designs of concrete were made for these four materials, one with a designed compressive strength of 7,250 psi (50 MPa) and one with a designed compressive strength of 4,350 psi (30 MPa).

The 4,350 psi (30 MPa) mixture design showed that the concrete made from the 7,250 psi (50 MPa) RCA concrete and the concrete made from virgin aggregates were very close in compressive strength. However, the concrete made from 4,350 psi (30 MPa)coarse RCA showed a 30% strength reduction, and the unknown RCA showed a 40% strength reduction when compared to the virgin aggregate concrete. The 7,250 psi (50 MPa)mix design showed the same trend without as drastic of a drop in strength loss. The 4,350 psi (30 MPa) RCA produced concrete with a 10% strength loss, while the unknown source produced concrete with a 15% strength loss (Tabsh and Abdelfatah, 2008).

Gull (2011), also performed a similar study on compressive strength, but with the addition of an admixture. In this study, three types of concrete were made consisting of an all virgin mix, RCA in place of virgin coarse aggregate, and RCA in place of virgin aggregate with polymer-H, which acts as a water reducer and increases workability of the mix. Three separate mix designs were created for each, with different proportions of cement, sand, and coarse aggregates.

Compressive strength was lower by 8.72% and 39.36% for RCA coarse aggregate concrete when all three mix designs were considered. When comparing the virgin aggregate concrete to RCA coarse aggregate with polymer-H added, the drop in compressive strength was reduced to -3.3% (increase), and 7.78% when all three mix designs are considered (Gull ,2011).

These studies suggest that the strength and quality of the original concrete greatly affects its practical use as a coarse RCA. Also, as the strength requirements of the new concrete produced decreases, the impact of the weaker coarse RCA increases. However, the results of the study by Gull (2009) suggest that these differences can be significantly reduced or even eliminated with the addition of chemical admixtures.

Tensile Strength

In a study conducted by Sagoe-Crentsil, Brown and Taylor (2001), tensile strength of coarse RCA concretewas found to be very similar to thetensile strength of concrete using all virgin aggregate. The absence of any detrimental effects of RCA concrete is indicative of good bond characteristics between the aggregate and mortar mix. Also, the splitting-tensile to compressive strength ratio for RCA concrete is close to typically accepted values for virgin aggregate concrete (Sagoe-Crentsilet al.,2001).

Tabsh and Abdelfatah (2008) performed this same test using the same mix designs described above. Their conclusions were similar to the conclusions drawn from the compressive strength. In the case of the 7,250 psi (50 MPa) coarse RCA, the tensile strength for both mixture designs were practically the same. For the 4,350 psi (30 MPa) mixture design, the tensile strength dropped 25-30% for the 4,350 psi (30 MPa) coarse RCA and the unknown source. This trend continued for the 7,250 psi (50 MPa) mix design, but with alesssignificant drop of only 10-15%.

Gull (2011) performed the tensile test as using the criteria described above, but using only one mix design. His results showed that the drop in tensile strength was 37% when comparing RCA coarse aggregate concrete to virgin aggregate concrete and 0% when comparing the RCA coarse aggregate concrete with polymer-H to the virgin aggregate concrete at 28 days.

These studies concluded that tensile strength properties of RCA coarse aggregate concrete show similar trends to compressive strength properties, and that the differences can be reduced or eliminated with admixtures.

Drying Shrinkage

Coarse RCA concrete and virgin aggregate concrete both display similar trends with regard to rate of shrinkage. However, the coarse RCA concrete has typical published values of drying shrinkage that are 30-70 percent higher than virgin aggregate concrete (Sagoe-Crentsilet al.,2001).

Abrasion Resistance

In one study, white fused aluminum oxide was used as an abrasive material and dispensed at a constant rate between an abrasive disc and the concrete specimen. Concrete made with coarse RCA had a 12% higher abraded volume when compared to virgin aggregate concrete using basalt as its coarse aggregate (Sagoe-Crentsilet al.,2001).

Absorption

One study shows that coarse RCA concrete hadan average of 25% higherabsorption (7% total) when compared to virgin aggregate concrete using basalt as coarse aggregate. The lower porosity of the basalt aggregates restricts the rate of water absorption (Sagoe-Crentsil et al., 2001). Due to its high absorption capacity, the workability (slump) of fresh concrete is decreased when using RCA. Saturating the RCA to the saturated surface dry condition before mixing has been one way to combat this problem. However, one study has shown that the high water content inside the RCA resulted in localized bleeding, which results in a higher localized water to cement ratio, weaker interfacial transition zone, poorer fracture resistance and decreased strength (Hiller et al.,2011).

RCA as Aggregate in New Asphalt

RCA in new asphalt has been researched in several different mix designs using different portions of RCA and virgin aggregates.Due to the high absorption capacity of RCA, its use in new asphalt production can demand much higher quantities of asphalt binder. This demand increases as the percentage of RCA increases. The absorption is not as big of a problem in concrete due to the negligible cost of additional water, but can add a significant amount of cost to an asphalt mix due to the increased binder (Wen and Bhusal, 2011).

The use of RCA in HMA can also significantly reduce the flow number, tensile strength, fracture energy and TSR (tensile strength ratio), which can result in reduced resistance to rutting, fatigue, thermal cracking and moisture damage. The flow number, tensile strength and TSR values will also become increasingly affected as more RCA by percent is used in the mix design (Wen and Bhusal, 2011).

A study at Michigan Technological University concluded that RCA can be substituted for virgin aggregates at levels approaching 75%. While it was noted that some of the physical properties of the RCA HMA mixture would be affected, the Superpave specifications could still be met with only some difficulty attaining required air content. The same study also concluded that significant energy costs could be saved in the compaction process through the use of the Construction Energy Index (Hiller et al., 2011). Whether or not these cost savings can negate any cost or all cost increases due to higher binder absorption rates was not discussed, and remains to be determined.

RCA as a Base Material

A base course is defined as the layer of material immediately below the wearing surface of a pavement. The purpose of the base course is to provide stability between the surface course and subgrade. The base course will prevent overstressing of the subgrade and it can withstand the pressures imposed on it by traffic (Army Corps, 2004).

Due to the fact that RCA is angular and its unhydrated particles can re-cement, it can serve well in a dense graded base application (ACPA, 2009). The main factors in determining its acceptability as a base layer are the shear strength and stiffness, determined by the resilient modulus test. Although the stiffness is not as high when using RCA compared to virgin aggregate, it does perform well (NCHRP, 2008). Crushing operations also provide large- sized angular aggregates which create a structurally sound supporting base layer that also allows for drainage (Hiller et al.,2011).

California Bearing Ratio

The California Bearing Ratio (CBR) (ASTM D 1883-07) is relative measure of strength and moisture durability for structural design purposes using various road materials (Berthelot et al., 2010). A study carried out in Utah compared the CBR of recycled concrete from both demolished structures and from haul backs (left over concrete not used at the site and brought back to the plant). Using three test specimens for each material, the study concluded that RCA from demolished structures and haul back RCA had CBR values of 22% and 55%, respectively (Blankenagel and Guhrie, 2006).

One study conducted in Saskatchewan, Canada found that CBR values for RCA base were lower than conventional aggregate base materials. However, this result did not reflect the observed field performance of RCA base material. The study determined that recycled materials did not respond well to conventional impact compaction methods and that CBR performed by using impact compacted samples was not suitable for characterizing RCA base material (Berthelot et al.,2010).

Unconfined Compressive Strength

Using 24 test specimens, Blankenagel and Guthrie (2006)performed unconfined compressive strength tests (UCS) on both demolition and haul back RCA. The test specimens were subjected to daily UCS tests for a week to see if any recementing of the original unhydrated cement would occur. Demolition material saw a rise in strength of

130% from 0 to 3 days and a rise in strength of 180% from 0 to 7 days. Haul back materials showed increases of 150% and 190% over the same periods. The haul back material had an approximate 70% greater UCS throughout the 7 day curing period. This can most likely be attributed to greater quantity of unreacted cement and finer gradation of the haul back material. Finer material leads to greater surface area for hydration reactions and a denser mix (Blankenageland Guthrie, 2006).

Stiffness

Blankenagel and Guthrie performed stiffness testing on three samples of each material in order to determine the Young's Modulus. The increase in stiffness for the demolition and the haul back material were 390% and 940%, respectively, while the average 7 day stiffness values were 16,000 psi (110 MPa) to 21,800 psi (150 MPa), respectively. The difference in stiffness can be attributed to the greater quantity of unreacted cement and the finer gradation of the haul back material, as was the case for unconfined compressive strength (Blankenagel and Guthrie, 2006).

Resilient Modulus

The Resilient Modulus of a material is based on its recoverable strain under repeated loads. A number of factors can contribute to the resilient modulus of a base material which include moisture content, density, stress history, aggregate type, gradation, temperature, percent fines and degree of saturation (Bennert et al., 2007)

Using the AASHTO bulk stress model for comparison and following the specifications designated in AASHTO TP46-94, a 2007 study concluded that the resilient modulus under a bulk stress of 21 psi (144.7 kPa) was 36,500 psi (251.8 MPa) and

24,100 psi (166MPa)for a 100% RCA base and a dense graded aggregate base course (DGABC), respectively. Under a bulk stress of 50 psi (350kPa), the resilient modulus for RCA and DGABC was 54,500 psi (375.9 MPa) and 2,600 psi (180 MPa), respectively (Bennert et al., 2007).

This same study also performed permanent deformation tests on both RCA and DGABC. The samples were subjected to a constant confining stress of 15 psi (103 kPa) and axially loaded with a cyclic deviatoric stress of 45 psi (310kPa) for 100,000 cycles. The 100% RCA base material suffered a minimal permanent strain of .0038 mm/mm while the DGABC had a permanent strain of about .0068 mm/mm (Bennert et al., 2007).

Aluminum Swell Pressure

Several sections of roadway in Hawaii built on base courses using RCA failed as a result of aluminum swell pressure. Because of this, a case study was conducted to find out what caused this, and one of the “erupted” areas was examined extensively.

It was observed that directly below each eruption was a significant amount of white substance which was later determined to be bayerite, which is an unstable form of gibbsite ($Al(OH)_3$). This can form when impurities such as aluminum metal are present in a base course and corrode in an alkaline environment. Since moisture is almost always present in any base course containing RCA, it is likely that an alkaline environment can exist.

Further laboratory testing was conducted on the reaction of aluminum in an alkaline environment and it was found that the swell pressure can reach up to 430 kPa in just 15 minutes. If a similar pavement is subjected to that same swell pressure, the calculated deflections are consistent with the observed pavement deflections (Ooi et al., 2010). Therefore, aluminum swell pressure is a hazard when constructing a road base from RCA if aluminum is present and should be addressed.

Stabilization

When the base material is mixed with Portland cement, it can increase its strength and stiffness for better support of the surface layer(Hiller et al.,2011). Since the RCA already has unhydrated cement attached to it, the amount of cement added may be reduced from 3% to 1.5% (Guthrie, 2002).

RCA can also be mixed with asphalt binder to create a suitable base material. However, the quality of the RCA asphalt base material may be lower than a virgin asphalt material. For the RCA mix, the resilient modulus was found to be lower while the air voids were generally higher. Although of lesser quality, the RCA asphalt mix can still be constructed to meet minimum specificationsfor a base material (Hiller et al.,2011).

Alkaline Run-Off and Tufa Formations

When using RCA as a base material in roadway construction, alkaline run-off and tufa formations may raise cause for concern. Alkaline run-off is due to a high PH of water flowing through the RCA base and can present environmental hazards. Tufa formations are calcium deposits that can clog drains and filter fabrics (ODOT, 2011).

ODOT conducted research on the effects of these two phenomena by setting up a box test on one sample of limestone and three samples of RCA from three different sources; Cleveland, Cincinnati, and Columbus. The results of this test determined that the initial PH values of water running through the recycled concrete were around 11 and decreased over time, settling just above 9. The PH values of the water running through the limestone were around 8. PH level above 9 can be a concern for the environment, and it was determined that RCA should not be used as base material in low lying or wet areas due to the adverse effect on the environment (ODOT, 2011).

No tufa formations were seen in any of the test devices set up in the experiment. However, the test was conducted to room temperature and did not expose the circulating water to carbon dioxide. Carbon dioxide and decreased temperatures have both been linked to increased tufa formations (ODOT, 2011).

Other Uses of RCA

RCA can be used in a variety of other applications such as embankment fill, railway ballast, drainage and filter material and concrete block. Crushed rock fill material is typically specified to control embankment erosion. However, RCA is not commonly used as this fill material because the cost of the RCA aggregate will usually be higher than the cost of other fill material due to the fact that is of higher quality and could be used in other more suitable applications. But, if no other solutions are available RCA will work satisfactorily (Army Corps, 2004).

One of the most demanding applications for crushed stone is railroad ballast. Railway ballast consists of a coarse aggregate that provides a free- draining foundation for the track. The use of RCA in railway ballasts is limited now due to concerns of low strength, abrasion resistance, and durability (Army Corps, 2004).

RCA can be a suitable drainage material for sub-drains and dams as well as filter material for water and sewage treatment. This is also not very common, due to concerns of chemical attack from impurities in the groundwater.

CHAPTER IV

CONSTRUCTION OPERATIONS

Demolition

When demolishing concrete pavements, some preparation may be necessary. In order to prevent contamination there must be a complete removal of joint sealant, asphalt overlays, and patches (Hiller et al., 2011).

When preparation is complete, a variety of tools can be used to demolish the structure. Hand tools, which include pry bars and sledge hammers, could be used for smaller demolition jobs such masonry walls. Hand power operated tools also fall into this category, and can be used some places where normal hand tools cannot do the job but are too hard to reach for large equipment. These include pneumatic, hydraulic, electrical, and gas powered tools as well as drop hammers and blades (ACI 555, 2001).

For larger operations, vehicle mounted equipment can be used. Wrecking equipment can be mounted to backhoes and skid loaders and other large equipment. Some types of these are impact breakers/hammers,spring action hammers, wrecking balls and cranes, rotating cutter heads, concrete crushers, rippers, and a resonant frequency breaker (ACI 555, 2001).

The vehicle mounted equipment can be classified into two main categories, impact breakers (Figure 2) and resonance breakers (Figure 3). Both breaker types are effective, but each has advantages and disadvantages. Impact breakers have higher surface production rates than resonance breakers, while using a single dynamic force to fracture concrete pavement. Resonant breakers produce uniform slabs of concrete using a high-frequency low amplitude pulse to fracture the concrete. Resonance breakers also produce fewer disturbances to underlying sewers and utilities, which can be very important in urban areas (Hiller et al., 2011).

Figure 2 - Vehicle mounted impact breaker (ACI 555, 2011)

Figure 3 - Vehicle mounted resonance breaker (RMI Resonant Machines, 2011)

For very large operations, explosive blasting may be considered. This is a difficult option because concrete has a high variation in strength and also contains reinforcing steel. It has to be done under close observation (ACI 555, 2001).

The last method of demolition is from drills and saws. These use hard cutting diamond tools to drill smooth surfaces. They have minimal vibration and use water to minimize dust. However, reinforcing steel can make the concrete difficult to saw through (ACI 555, 2001).

CrushingOperations

Once concrete has been removed, the fractured slabs must be reduced in size to be used as a RCA. This may be done using a series of crushers, screens and various other tools to eliminate any contaminants that may be left.

There are three types of crushers that are typically used in RCA production (Figure 4); jaw, impact and cone crushers. Jaw crushers compress the concrete between a stationary and movable plate and concrete is then reduced in size as it travels down the length of the wedge between the two plates (CMRA 2011). Jaw crushers are typically used in primary crushing operations and bring the aggregate to a more manageable size of 3 to 4 inches (75-100 mm) (Hiller et al., 2011).

Cone crushers are typically used as secondary crushers and are designed to produce a product with a more uniform size distribution than jaw crushers (Hiller et al., 2011). Cone crushers operate by compressing the concrete between two cone shaped plates, and typically produce RCA with a maximum size of 1 ½ inches (40 mm) (CMRA, 2011).

Impact crushers can be used as primary, secondary, or tertiary crushers, depending on their size and capacity. They have a spinning rotor with bars or hammers that shoot the concrete into a plate, several plates, or rods, and typically produce aggregate with a maximum size of 2 inches(50 mm) (CMRA, 2011). An advantage to using an impact crusher is its ability to remove a larger percentage of old mortar from original aggregates when compared to the cone crusher. However, this often results in lower yield of coarse aggregate (Hiller et al., 2011).

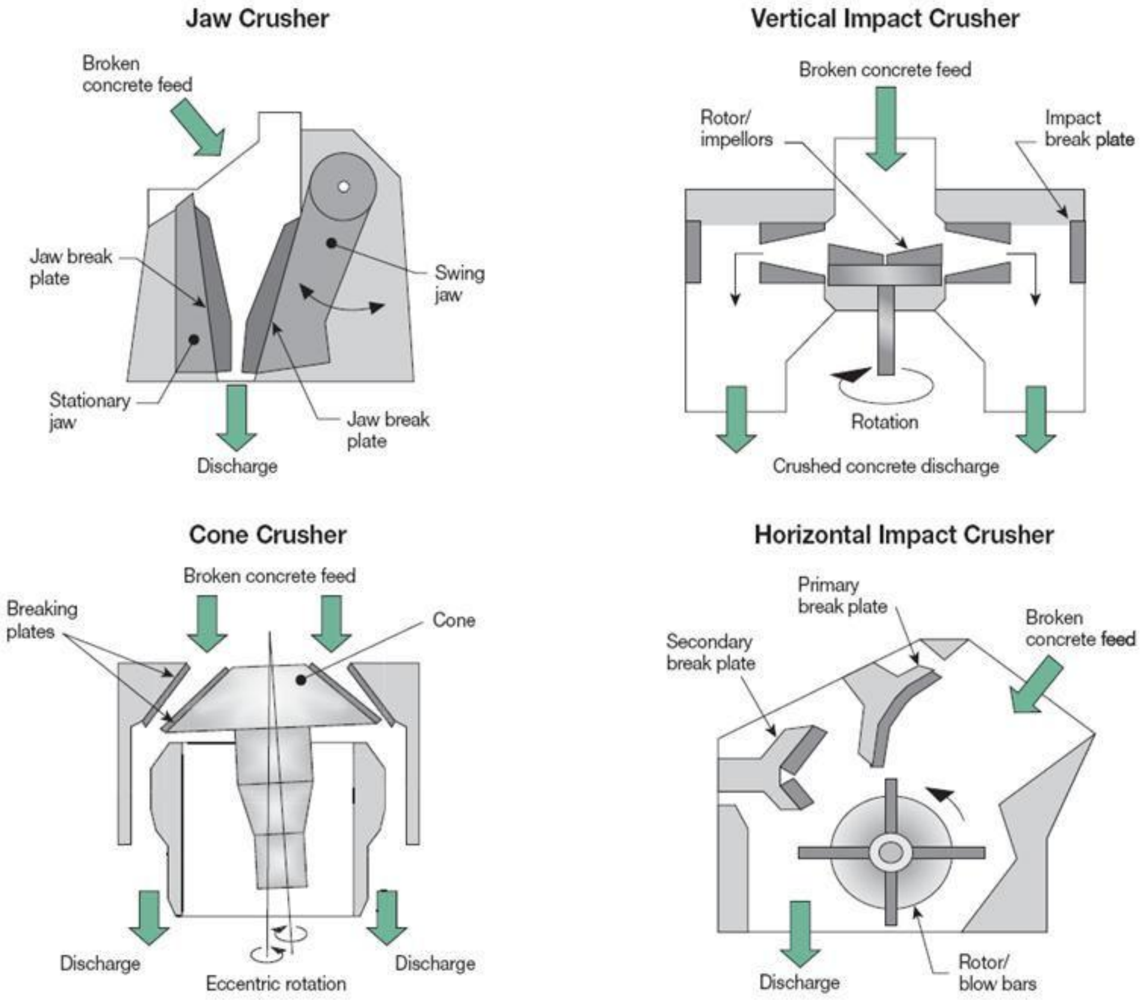

Figure 4 - Different types of crushers (ACPA, 2009)

Between any primary, secondary, or tertiary crushing, primary and secondary screens may need to be used depending on the project, equipment used and final product desired. Scalping screens are used to remove foreign particles and a fine harp deck screen is used to separate the fines from the coarse aggregate. The RCA must also be free of any dirt, clay, wood, plastic or organic materials. This can be removed by using water flotation, hand picking, air separation, or electromagnetic separation

(CMRA, 2011). Approximate amounts of contaminants in typical demolished concrete can be seen below (Figure 5).

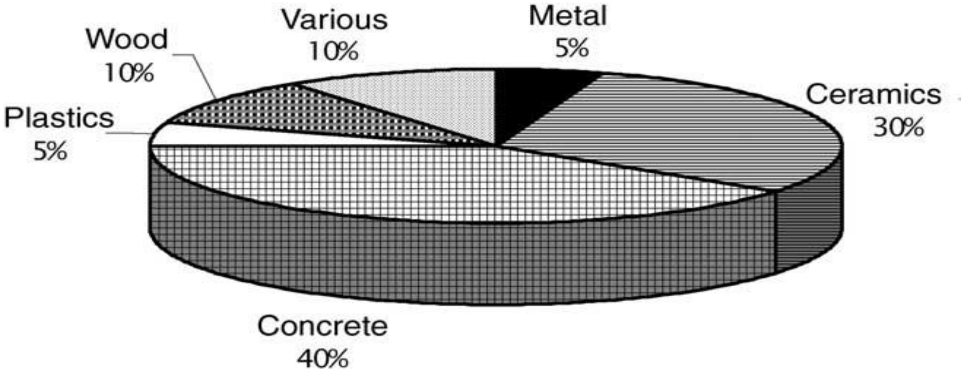

Figure 5 - Approximate composition of demolition waste (Oikonomou, 2005)

There are several problems that must be addressed during the crushing phase. Crushers have traditionally been used in mining operations to grind the material to a fine particle size. This creates some problems in getting the machines to produce a usable coarse aggregate size, gradation and yield from crushed concrete.Crushing and sizing canreduce the amount of old mortar attached to the original aggregate, but can also lead to micro-cracking or damage of the RCA. Micro-cracking can create problems with RCA/new mortar bonding and RCA concrete fracture resistance (Hiller et al.,2011).

On-site versus off-site crushing is one more thing to consider when producing RCA. On-site crushing can consist of jaw, impact and cone crushers ina mobile or portable form. A portable crusher is mounted on a rubber tire chassis and can be towed to the site by truck. Once on site, they canbe moved by loaders or tugs. A mobile crusher is carried to the site by truck and trailer and has its own onboard drive system.

Mobile crushers can move easily on sites and are advantageous when several moves are required (CMRA, 2011).

On-site crushing significantly reduces hauling costs, and can be used on relatively small projects. The smaller on-site crushers tend to increase the yield of coarse aggregate by leaving more mortar on the original aggregate. This can have a significant impact on the RCA for its future use, and the cost savings must be weighted with the quality of RCA produced from on-site crushing (Hiller et al.,2011).

Sizing and Yield

Controlling the top size of the aggregate in crushing can be easily done by adjusting the break plate distances on the jaw crusher. Overall grading, however, is much more difficult to control. Crushing operations often produce a lack of mid-range (around ½ inch or 13 mm) size aggregate, which makes it difficult to achieve gradation specifications. The lack of mid-sized material leads to smaller yields of usable RCA, as the mid-sized material governs the usage volumes and the rest of the material must be hauled off site and possibly landfilled(Hiller et al.,2011).

Overall yield can usually correlate to the top size of aggregate produced. Aggregate with a top size of 1 ½ inches (40 mm) can produce yields reaching 80% when comparing the volume of in place concrete to aggregate produced, while a top size aggregate of ¾ inches (19 mm) produces yields of 55%-60% (Hiller et al.,2011).

The yield of RCA aggregate for use as a base material versus natural aggregates must also be taken into consideration. RCA has a lower compacted unit weight than natural aggregates, and therefore can yield up to 15% more volume for an equivalent weight of natural aggregates (CMRA, 2011). This higher yield can offset some of the cost of the waste material produced in the crushing operation.

Storage

Stockpiling of RCA uses the same techniques as traditional aggregates. However, unhydrated cement can become an issue in storage stockpiles, particularly in stockpiles with large amounts of fines. Direct water exposure or even high humidity can result in cementing of the previously unhydrated cement. Therefore, fine aggregate stockpiles need to be protected when possible (Hiller et al.,2011). This whole process can be seen in the diagram below (Figure 6).

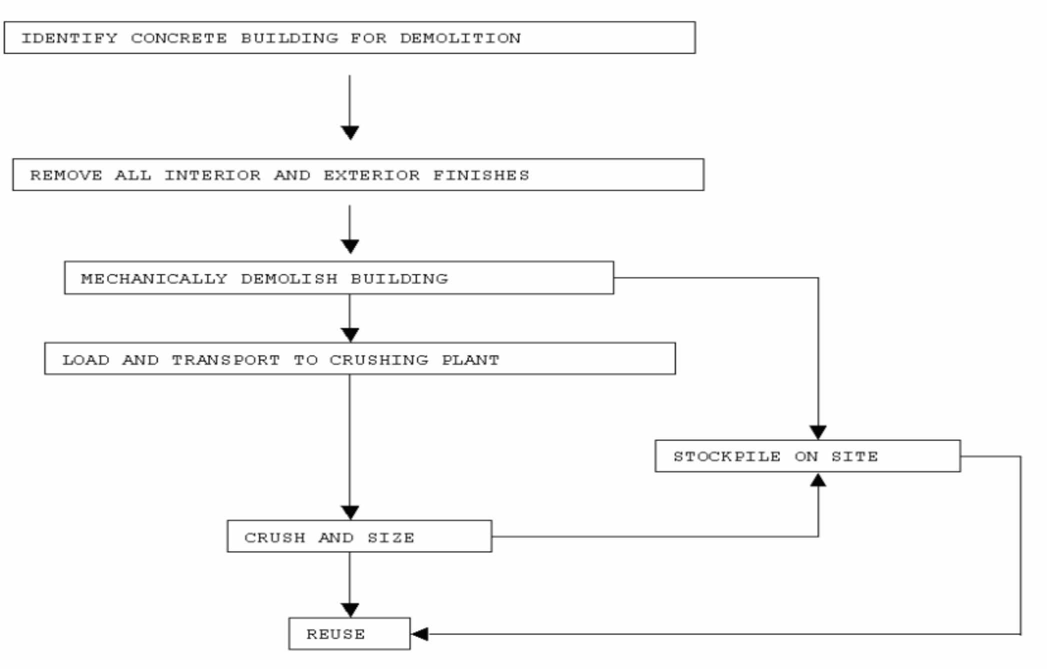

Figure 6 - Concrete structure recycling flow process (Army Corps, 2004)

CHAPTER V

SPECIFICATIONS

RCA in New Concrete Pavement (ODOT)

The ODOT specification for the use of RCA in new concrete pavements can be found in supplement 1117 titled “Concrete Using Recycled Coarse Aggregate for Concrete Pavement and Incidental Items.” This specification includes details regarding pavement surveys (1117.02), aggregate requirements (1117.03), new concrete (1117.04), mix design submittal (1117.05), testing procedures (1117.06), and controls section (1117.07) for new concrete pavements made from RCA.

The pavement survey section specifies that all concrete to be recycled should be analyzed for material related distress such as alkali silica reaction or D-cracking. All pavements that are identified to have D-cracking should be processed to a #8 gradation (2.38 mm) to be used as RCA.

The aggregate requirements section specifies that all concrete to be recycled for use as RCA in new pavements should originally be from an ODOT source, and that concrete should not be inter-mingled from different ODOT sources.

Further requirements state that any steel, joint sealants, clay or other contaminants must be removed, and that the RCA must have consistent quality and properties. This section also outlines the requirements for coarse RCA (RCA as a fine aggregate should not be used), which consist of the following:

1) Insure that the RCA meets the quality requirements of 703.02-B, except:
    a. Percent of Wear, Los Angeles test, maximum 50%
    b. Amount passing the No. 200 (75µm) sieve, maximum 1.5%
    c. Chloride Content (AASHTO T 260), maximum 0.6 lbs/yd3 in new concrete
    d. Specific Gravity variability, maximum 0.100
    e. Absorption variability, maximum 0.8%

2) Use only material passing 703.13. For each coarse aggregate gradation and each different source provide a sample of the RCA material to the Department for testing. Allow 10 weeks for testing.

3) Process the coarse RCA to meet the gradation requirements of the accepted mix design in 1117.04 and 1117.05.

4) Use only coarse RCA with absorption of 7.0% or less.

5) Provide coarse RCA with an asphalt content of 1.0% or less.

The concrete produced from RCA must also meet certain specifications (1117.04) since its properties will be different from concrete using virgin aggregates. The submittal of the mix design (1117.05) specifies what needs to be submitted to the engineer for preliminary acceptance, and the testing section (1117.06) specifies how to test the proposed mix design for final acceptance.The controls section (1117.07) discusses how to develop and implement a quality control plan for aggregate production that details the production procedures, testing methods, and testing frequencies that will assure consistent material. It will assure that the recycled concrete aggregate meets the requirements of the specification.

Although ODOT has these specifications in place, a conversation with ODOT's Dale Crowl revealed that no one in the state has been able to produce RCA that met these specifications. Crowl stated that the main specification concrete manufacturers could not meet was the absorption percentage of 7 percent or less. Another problem cited by Crowl was the concrete manufacturers' inability to filter out all the contaminants. Crowl stated that the equipment needed to reduce contaminant levels to make an acceptable product would require too much of an investment.

Recycled Concrete as Base Material (ODOT)

The process for which base material can be laid and compacted can be found in section 304 of ODOT's Construction and Materials Specification. The common term used to describe base material used by ODOT and installed using the procedures used in item 304 is ODOT #304 base material. The actual aggregate specification for #304 is found in section 703.17 of the Construction and Materials Specification Manual (ODOT 2010).

Section 703.17 specifies that #304 base material must consist of crushed carbonate stone, crushed gravel, crushed air cooled blast furnace slag, granulated slag and open hearth slag. Therefore, the use of recycled concrete aggregate as #304 base material is not permitted on ODOT projects (ODOT, 2010).

Other Uses (ODOT)

While section 703 restricts the use of RCA as base material, it allows it for use in some other applications. Section 703.11 permits the use of RCA without wear testing or sodium soundness testing requirements if the contractor provides information proving the original material met this specification at the time it was initially used. Its use as structural backfill should be excluded around aluminum or pipe or aluminum coated steel pipe, and the RCA should not contain more than 2 percent steel.

Section 703.16 allows the use of RCA in embankment construction. The section specifies that RCA should be furnished with the reinforcing steel cut to a maximum of 1 inch (25 mm) outside the pieces of RCA. It also specifies that at least 30 percent of the blend should be natural soils or natural granular materials.

Section 703.18 allows the use of RCA materials for items 410 (traffic compacted surface), 411 (stabilized crushed aggregate), and 617 (reconditioning shoulders). If using RCA, the specification number that the material was originally constructed under and the applicable material requirements of the original construction item must be provided. If the original requirements meet or exceed the requirements of section 703.18 then the shale, sodium soundness, and Los Angeles Abrasion Test for RCA may be waived. RCA must also be free of any steel.

CHAPTER VI

NATURAL RESOURCES

In order to look at recycled concrete as a sustainable building product, the state of the virgin aggregate industry in a specific region must first be analyzed. The availability of virgin aggregates in a specific region and the distance the aggregate must be transported will significantly affect its cost. With money as a driving factor in most decisions, aggregate availability will significantly affect the decision to specify the use of recycled concrete products. Furthermore, before evaluating the decision making processes of engineers, crushing companies and contractors, a sense of aggregate availability and the driving factors to use recycled concrete must be understood.

Since 1837 the Ohio Department of Natural Resources has been collecting data on the state's economic geology. Limestone producers started submitting data in 1885, while sandstone and sand and gravel producers started reporting in the early 1900's. Historical data on the production of these minerals is available from 1942 to today.

Each operator in the state must submit an annual report to the Ohio Geological Survey, which includes information on the commodity extracted at each location and other information on employment, production, use, distribution, value, and other facts relative to the mineral. All of the information gathered from producers is published in "The Report on Ohio's Mineral Industries: An Annual Summary of the State's Economic Geology", or MIR (Wolfe, 2011).

Limestone and Dolomite

There are currently 99 operations owned by 53 companies in Ohio that produce or sell limestone and dolomite. Most of the production comes from the western half or mid-east portion of the state (Figure 7). Estimated sales in 2010 totaled 50,079,000 tons (Figure 8), which is up 12.7 percent from 2009. The total value of limestone and dolomite sold in 2010 was $436,248,000 (Figure 8) with an average price per ton of $8.71. In 2010, the primary use of limestone and dolomite was road construction and resurfacing. Other uses were for asphaltic concrete, Portland cement concrete, commercial building and the production of lime (Wolfe, 2011).

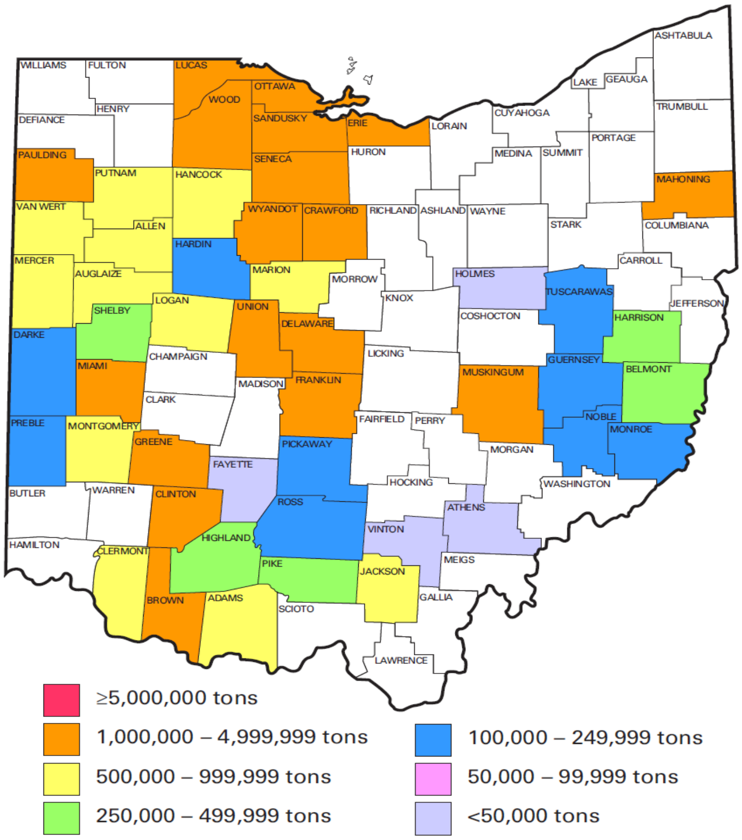

Figure 7 - Sales of limestone and dolomite in Ohio in 2010, by county (Wolfe, 2011).

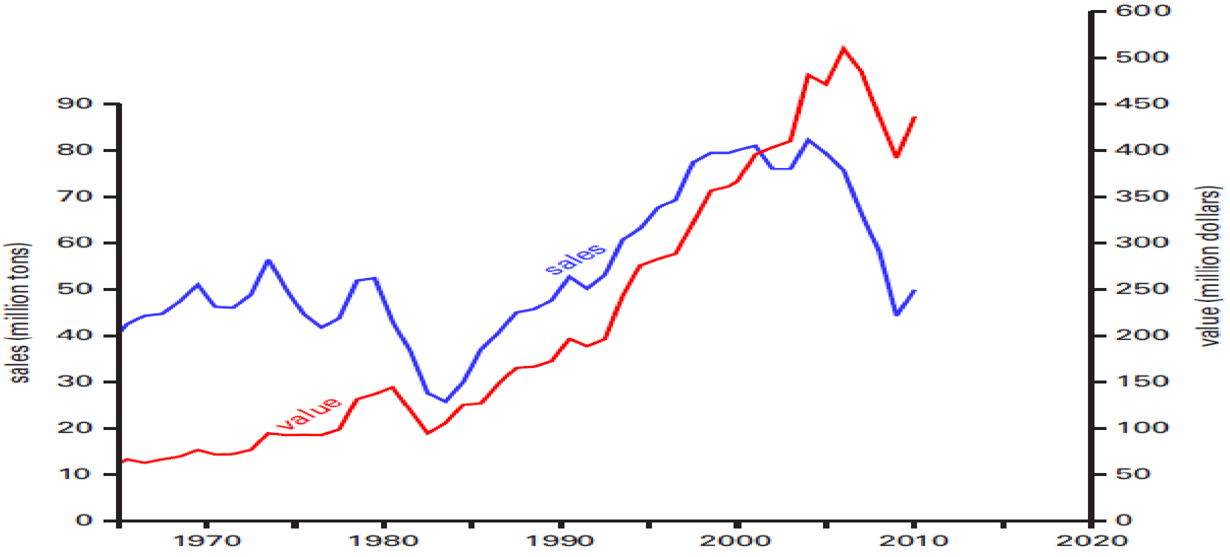

Figure 8 - Sales and value of limestone and dolomite in Ohio (Wolfe, 2011).

From Figure 8, it can be seen that the relationship between sales and value of limestone and dolomite do not have a linear correlation. By dividing the historical value of the mineral by the historical sales, one can obtain a historical price per ton. For example, in 1990 the price per ton was approximately $4.00, and in 2000 the price increased to roughly $4.63. Before considering any adjustments for inflation, this shows a 15.8% increase in price/ton from 1990 to 2000 and an 88.1% increase in price/ton between 2000 and 2010.

Sand and Gravel

There are currently 227 operations owned by 157 companies in Ohio that produce or sell sand and gravel.Sales on Ohio are spread throughout the state and are shown in Figure 9. Estimated sales of sand and gravel totaled 27,015,000 tons in 2010 (Figure 10), with sand accounting for 15,001,000 tons and gravel accounting for 12,014,000 tons. This is a 3.9% drop in production from 2009 and ranks Ohio eleventh nationally in the production of sand and gravel out of 50 producing states and Puerto Rico. The total value of sand and gravel sold in 2010 was $170,937,000 (Figure 10), with an average price per ton of $6.32. Major uses of sand and gravel in 2010 were commercial and residential building, Portland cement concrete, asphaltic concrete, and road construction and resurfacing (Wolfe, 2011).

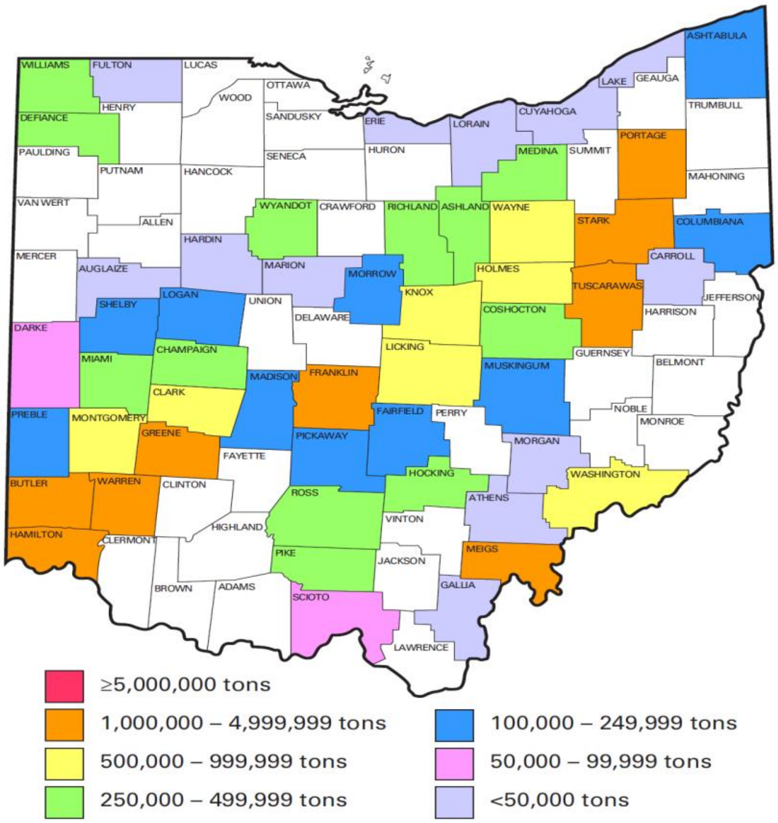

Figure 9 - Sales of sand and gravel in Ohio in 2010, by county (Wolfe, 2011)

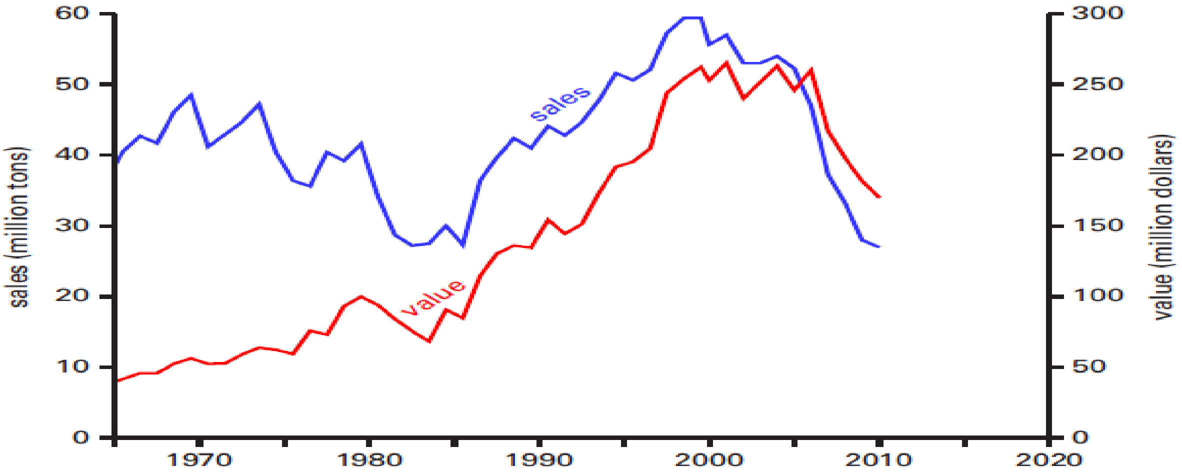

Figure 10 - Sales and value of sand and gravel in Ohio (Wolfe, 2011)

From Figure 10, it can be seen that the sales and value of sand and gravel are not linearly correlated. In 1990, the price per ton was approximately \$3.38, and in 2000 the price per ton was approximately \$5.60. Before adjusting for inflation, this shows a 65.7% increase in price per ton from 1990 to 2000 and a 12.9% increase in price per ton from 2000 to 2010.

Limestone Quarrying and Processing

Introduction

In 2010, nearly 49 million tons of limestone were produced from quarries in the state of Ohio (Wolfe, 2011), making it the most commonly produced aggregate in the state. Since limestone is typically the main competitor of recycled concrete products, the process to quarry and process this aggregate must be examined. All of the equipment to quarry and process limestone will be evaluated as well as the total energy consumed by these pieces of equipment.

Quarrying

The quarrying process can have significant differences based on whether the aggregate is coming from the surface or underground mine. In the U.S., the predominant and more cost effective method is quarrying from the surface (Shahriar et al., 2007). For this reason, limestone quarrying from the surface is what will be considered for this thesis.

The surface quarrying process starts with the removal of the overburden, which can be top soil, sub-soil, or any rock overlying the limestone. This material must then be handled and stored, and in some cases, can be sold as fill material. In many locations, overburden removal is best done in the summer, when the soil is drier and more able to bear the weight of the earth-moving equipment (Oates, 1998).

The next step in this process is the drilling and blasting of the in place limestone rock. This process is typically the lowest in cost relative to the subsequent operations (Oates, 1998) and can be done using several different types of equipment. Drilling is typically done using tricone rotary drills, long hole percussion drills and churn drills (BCS, 2002). Most limestone quarries use a “down-the-hole” rotary hammer drill, which provides a high level of accuracy and a fast drilling rate. The percussive drills are lower in capital cost, but often to be slower, less accurate and noisier (Oates, 2008).

Blasting may also be used in smaller operations (BCS, 2002), which include a high explosive (i.e. TNT) to initiate the blast and a blasting agent (ammonium nitrate and fuel oil), which provides the main explosive effort. The force of the explosion is usually contained within the hole by “stemming” the top of the hole using fine stone. The “stemming technique also reduces the noise level produced by the blast (Oates, 1998).

In some cases, secondary breaking is necessary when the boulders produced are too large to haul or feed into the crushing plant. This can be done by secondary blasting methods, hydraulic hammers or drop balls (Oates, 1998).

Once the limestone has been separated from the quarry, it must be loaded and hauled to the processing facility. Hydraulic shovel and rubber-tired front end loaders are typically used in these operations, due to the fact that hydraulic shovels have a large digging power and the front end loaders are highly maneuverable.   The hauling of the material can be major variable cost in the production. This is usually done using a rigid-bodied dump truck, but articulated dump trucks are often favored in smaller quarries due to the fact that they are more maneuverable (Oates, 1998)

Processing

The processing operation can typically be broken down into five categories: crushing, sizing, benefication, storage/loading and transportation.   Virtually all of the size reduction in processing is done using crushers. Similar to crushing recycled concrete, crushers can be used as primary, secondary, or tertiary crushers, which can consist of jaw, impact, and cone crushers. In most productions, crushers are chosen to produce the required amount of aggregate-sized particles, without over-production of fines (Oates, 1998)

The sizing of limestone is used to produce accurately sized aggregates, segregate coarse particles from fine particles, and reduce impurities often contained in finer fractions. Different types of screens can be used for this process, which include inclined vibrating screens, horizontal vibrating screens, trommel screens, grizzly screens, ball deck screens and probability screens.

The benefication of limestone refers to improving the physical and chemical quality of the limestone products. This can consist of scalping and additional screening, washing and scrubbing, and sorting (Oates, 1998). Whether or not this needs to be done depends on the state of the limestone after initial sizing.

The greatest tonnage of limestone is stored on the ground in uncovered stockpiles. This storage is usually done using conveyors, particularly radial conveyors, which can service three to four stockpiles each consisting of a different grade of limestone. Some problems that may arise from this include further breaking of the limestone as it falls from the conveyor and dust coming off of the falling stream of stone. (Oates, 1998)

The transport of limestone can often amount to over 50% of the delivered price. In many cases where the location is favorable, limestone from the quarry can be delivered directly to the local users, which can be relatively cheap. Transportation by rail can be a cost effective method of transporting the final product, and becomes increasingly more cost efficient as the distance from the quarry to the customer is increased. Also, if the quarry is near a navigable waterway, a barge can be utilized at a relatively low cost per ton if the customers have suitable reception facilities (Oates, 1998).

Energy Required to Produce Limestone

In order to do future analysis, the total energy used per ton of limestone produced must be addressed. In 2002, the BCS corporation produced a report for the U.S. Department of Energy which broke down the process outlined above and analyzed the energy inputs for each step. Using the “SHERPA Mine Estimating Cost Model” and the “Mine and Mill Equipment Cost, an Estimators Guide”, BCS was able to estimate the total BTU per ton of limestone produced for both the quarrying and processing operations. The hypothetical mine operates with a 10 years and has a 15 million ton output at the end of its service life. The mine runs 250 days a year with two shifts per day of nine hours, giving it a daily production of 6,000 tons per day and a daily waste production of 300 tons. The mined material must travel 150 feet at a gradient of 7 percent (BCS, 2002). The total energy inputs for the quarrying operation can be seen inTable Iand the total energy inputs for the processing operation can be seen in Table II.

Equipment (Number of Units)	Daily Hours/Unit	Single Unit (BTU/ton)	All Units (BTU/hour)	All Units (BTU/day)	All Units (BTU/ton
Percussion Drill (6)	18	928	1,860,000	33,480,000	5,580
Hydraulic Shovel (1)	14	5,140	2,200,000	30,800,000	5,133
Rear Dump Truck (3)	18	1,220	1,220,000	21,960,000	3,660
Bulldozer (3)	18	1,030	1,030,000	18,540,000	3,090
Pick-up Truck (3)	12	679	1,010,000	12,120,000	2,020
Water Tanker (1)	8	1,060	796,000	6,368,000	1,061
Service Truck (2)	9	509	679,000	6,111,000	1,019
Lighting Plant (4)	18	15	20,000	360,000	60
Front-End Loader (1)	3	170	339,000	1,017,000	170
Bulk Truck (1)	2	113	339,000	678,000	113
Pumps (2)	18	1,020	679,000	12,222,000	2,037
Grader (1)	0.1	6	339,000	33,900	6
Total				**144,000,000**	**24,000**

Table I - Energy Consumption for Quarrying Operaion (BCS,2002)

Equipment (Number of Units)	Daily Hours/Unit	Single Unit (BTU/ton)	All Units (BTU/hour)	All Units (BTU/day)	All Units (BTU/ton
Teriary Crushing (1)	18	1,660	552,000	9,936,000	1,656
Secondary Crushing (1)	18	995	332,000	5,976,000	996
Screens (1)	18	332	111,000	1,998,000	333
Conveyor (1)	18	165	55,000	990,000	165
Total				**18,900,000**	**3,150**

Table II - Energy Consumption for Processing Operation (BCS, 2002)

It can be seen from the tables that the total energy need for both the quarrying and processing operations is estimated at 27,150 BTU per ton. It is important to note that the energy consumption for the calcining process was neglected because this process is only needed when the desired end product is lime. Since the analysis made with this data only concerns aggregates that can be used in competition with RCA, we are not concerned with processing associated with lime production.

Energy Required to Transport Limestone

A report published in 2009 by the Texas Transportation Institute researched the energy requirements for the transportation of goods by truck, rail and barge. The results of this study showed the differences in energy demand based on the carrying capacities for the three modes of transportation.

The study used an average carrying capacity of 25 tons for trucks, 110 tons for rail, and 1750 tons for a barge. In order to compare trucks to rail and barge, the truck carrying capacity was multiplied by the EPA estimated 6.2 mpg to determine ton*miles per gallon, since this is how rail and freight modes are measured. Data for the rail industry was compiled by averaging ton*miles per gallon from nine different sources, taking empty backhaul, spillage, idling and assembly into account. For a barge, the Tennessee Valley Authority developed software to track fuel consumption, reported tonnages, and miles traveled on waterways under the jurisdiction of the Army Corps. Since total mileage was reported, and fuel consumption was tested against IRS fuel tax data (Kruse et al., 2009), it is assumed that the return trip and any fuel losses are taken into account for the barge operation.

The results of this study concluded that the ton*miles per gallon for truck, rail and barge were 155, 413, and 576, respectively (Kruse et al., 2009). This data will be used further in this paper to draw comparisons among case studies.

CHAPTER VII

CASE STUDIES CONDUCTED ON RCA

Introduction

Three case studies were conducted to determine energy savings by producing and re-using RCA versus landfilling demolition debris and using virgin aggregates. In each case, a structure was demolished and the demolition debris was crushed either on or off site to produce RCA. The RCA was either then re-used on site or transported to a re-use site.

If RCA was not produced and re-used then all of the demolition debris from these projects would have been transported to a landfill. Also, natural aggregates would have been used at the re-use sites where the RCA was used.

The total energy consumption for both of these processes was calculated for each of the three case studies. All of the information obtained was from personal correspondence with representatives from the three companies and from research of the locations of the relevant sites and distances between them. The data previously discussed for production and transportation of virgin aggregate was also used in the analysis.

Independence Case Study: Cold Storage Building, Cleveland Ohio

Independence Excavating was started in 1956 in Cleveland, Ohio. Since then, they have grown to form many other sister companies and provide services throughout the Midwest. Independence recently completed a project in which they demolished the Cleveland Cold Storage building and used the waste material from that demolition to produce recycled concrete aggregate through one of their sister companies, Independence Recycling. Independence agreed to provide the details of this operation in order to perform a case study on the production of the recycled concrete aggregate from the demolition waste.

The Cleveland Cold Storage building was built in 1927-1928 and was used as food distribution warehouse for the Cleveland area for many years. By the end of the twentieth century this building was obsolete and vacant, serving only as a advertising billboard (Figure 11).

Figure 11 - The Cleveland Cold Storage Building on West 14th Street (Campbell, 2010)

In order to make way for Cleveland's new innerbelt bridge, the cold storage building was purchased by the Ohio Department of Transportation, and Independence Excavating was awarded the contract to demolish the structure. This case study will analyze the fuel consumed to haul the material off site, produce RCA and deliver RCA to its final destination and compare it to the hypothetical fuel consumption of landfilling the material and using virgin aggregates at that same destination.

In 2011, Independence Excavating began on the demolition of the structure. It took a total of 8 weeks to demolish the structure (Figure 12) with demo crews working 8 hours a day.A total of 50,000 tons of material was hauled off of the site to a nearby location on Carter Road in Cleveland, which is about a mile away from the demolition site.

Figure 12 - Demolition of the Cleveland Cold Storage Building

(http://www.mousemedicine.com/2011/07/wrecking-ball.html, 2011)

Independence said that their dump trucks get approximately 6 miles to the gallon when fully loaded and can carry 15 to 18 tons per load. Assuming an average value of 16.5 tons per load, the total fuel consumption to haul the demolition debris to the recycling facility was calculated (Table III).

Transport to Recycling Center	1	miles
Waste	50000	tons
Truck Capacity	16.5	tons
MPG of Dump Truck	6	mpg
Number of Truck trips	3030	trips
Miles to recycle	6061	miles
Gallons used to Transport	1010	gal

Table III - Fuel Consumption to Transport Demolition Debris to Carter Road Recycling Facility

Independence had set up a mobile crushing plant at the Carter Road site (Figure 13), which takes four people approximately three days to mobilize. The material was placed into a large stockpile (Figure 14) when it arrived on site where it was then ready to process.

Figure 13 - Independence's Carter Road mobile crushing plant

Figure 14 - Waste material stockpiled at Carter Road Site

From the waste stockpiles, the material is separated by a processor (Figure 15), so it could then be picked up by a loader and placed into the horizontal impact crusher (Figure 16).

Figure 15 - Processor separating demolition material

Figure 16 – Demolition material being loaded into horizontal impact crusher

The demolition material was then crushed and screened to separate the different sizes using a 3 deck horizontal screening plant. The different sized material was then sent onto different conveyors to stockpile the different sized RCA. During this operation Independence produced a “dirty” 304 base material (Figure 17), #1’s and #2’s (Figure 18), #57’s (Figure 19) and a “clean” fine material (Figure 20). During this whole process a magnet was used to screen out any steel and a laborer worked on the conveyor, picking out any contaminants by hand.

Figure 17 - "Dirty" #304 RCA base material

Figure 18 - #1 and #2 RCA

Figure 19 - #57 RCA

Figure 20 - "Clean" RCA fines

The term “dirty” is used to describe a material that is loaded and processed with clay or sand from the demolition. The screening plant separated the clay and sand from the #1’s, #2’s and the #57’s, allowing the clay and sand to be mixed into the #304 base material. However, when producing “clean” RCA fines, the demolition material was first processed through a grizzly plant (Figure 21). This separated the clay and sand from the large pieces of concrete debris before it was crushed, assuring that all the fine material passing through the screening plant was RCA.

Figure 21 - Grizzly plant used to separate clay and sand from demolition debris before crushing

Independence provided all of the equipment information used during this crushing process. Since the material was still being crushed during this case study, the duration of the crushing process was estimated by Independence and the amount of material crushed was assumed to equal the estimated amount of demolition debris (approximately 50,000 tons).

It was estimated that it would take Independence 28 working days to crush the material, and it was assumed that they would be working 8 hour days during this process. Using the estimated fuel consumption given by Independence, the amount of total fuel consumption to crush all of the demolition debris was estimated (Table IV).

Equipment					
		gal/day	Duration (days)	Consumption (gals)	
CAT 980G Loader		80	28	2240	
13 Hazemag Horizontal Impact Crusher		80	28	2240	
Skidsteer Loader		10	28	280	
Cat 245 Excavators with processors		160	28	4480	
250 KW Kentucky Generator/Storage Trailer		80	28	2240	
	48" x 55' Screen fed Conveyor			11480	total
	6' x 20' 3 deck horizontal screening plant				
	Belt Magnet				
	30" by 50' Return Conveyor				
	Transfer Conveyor with Scale				
	30" x 100' Portable Radial Stacker				

Table IV - Total fuel consumption to produce 50,000 tons of RCA

Had the demolition debris not been sent to the Carter Road site to be processed into RCA, it would have been transported to the nearest construction and demolition (C and D) landfill. The closest landfill to the demolition site was on East 49th Street in

Cuyahoga Heights and was approximately 6 miles away. The total fuel consumption to transport to the landfill was then calculated and can be seen in Table V.

Transport to Landfill	6	miles
Waste	50000	tons
Truck Capacity	16.5	tons
MPG of Dump Truck	6	mpg
Number of Truck trips	3030	trips
Miles Landfill	36364	miles
Gallons used to Transport	6061	gal

Table V - Total Fuel Consumption to Transport Demolition Debris to Debris to Landfill

Once the RCA was processed and ready for distribution, it was sent to nearby projects to be used for various applications. The majority of the material (30,000 tons) was used for the new innerbelt bridge project as sub-base and backfill. The balance of the material was sent to the Flats East Bank, Cleveland Medical Mart, Horseshoe Casino and Cleveland State University housing projects.

The nearest limestone supplier to all of these projects is directly across the Cuyahoga River from the Carter Road recycling facility. Therefore, the total energy used to transport the RCA to the new projects would be almost identical to transport virgin aggregates and would cancel each other out in the overall analysis.

The transport of the virgin aggregate from the quarry to the distribution center was also considered in the analysis. The distribution center is owned by Lafarge and operates directly on the Cuyahoga River. While they were unavailable for comment on how there limestone was transported to them and what quarry it came from, it is reasonable to assume that it was barged in, since it is directly connected to a navigable waterway. Also, by referring to Wolfe's map of Limestone production in Ohio, it can be seen that the closest quarries with barge access are located in Sandusky, which is about 60 miles away via waterway. These assumptions are reasonable based on the fact that rail is 28.3% less fuel efficient (Kruse, 2009), and therefore barging is probably more economical, and also because the lowest priced aggregate will most likely come from the nearest quarry.

Using the ton*miles per gallon for a barge previously discussed, the total fuel consumption for the transport of aggregate to this site was found (Table VI).

Ton*Miles per Gallon	576
Total Miles	60
Tons per Gallon	9.6
Gallons per Ton	0.1042

Table VI - Fuel Consumption to Barge Aggregate to the Distribution Center

The overall fuel consumption for both cases was calculated by converting the gallons of diesel consumed to BTU and summing the different processes for each operation. In order to compare the energy inputs, all energy consumption was converted to BTU/ton in order to have compatible units, and a total energy savings of 23,763 BTU/ton, or 40.6%, was found by recycling and re-using (Table VII).

Crushing				**Transport to Recycling Faicility**			
Fuel Consumed		11480	gals	Fuel Consumed		1010	gals
RCA Produced		50000	tons	Amount Stockpiled		50000	tons
Gallons/Ton		0.2296		Gallons/Ton		0.0202	
BTU/Ton		31846		BTU/Ton		2802	
Landfilling				**Quarrying of Virgin Aggregate**			
Fuel Consumed		6061	gals	BTU/ton	27150		
Material Landfilled		50000	tons				
Gallons/Ton		0.12122		**Barging to Distibution Center**			
BTU/Ton		16813					
				BTU/ton	14447		
Totals							
BTU/ton to recycle and re-use			34647				
BTU/ton to not recycle			58410				
BTU/ton Difference			23763				

Table VII - Total Energy Inputs for Each Operation

Fortuna Case Study- CVS in Tallmadge, Ohio

Fortuna Construction was started in 1985 in Cleveland, Ohio and currently employs about 40 employees in their downtown Cleveland office. Fortuna specializes in sewer and site development work, doing most of their work within a 60 mile radius of Cleveland. Fortuna also does a significant amount of construction debris crushing and concrete recycling, often acting as a subcontractor utilizing a mobile crushing plant to go to different locations and crushing material for other companies.

The case study performed for this paper was for a job in Tallmadge, Ohio that was completed in 2006. The site consisted of an old concrete factory and was to be the new home for a CVS/pharmacy. Fortuna completed the demolition work on the factory and used a mobile crushing plant to recycle the debris material on site for re-use on the same job. This case study will breakdown the fuel used to produce all the RCA generated from the crushing operation and compare it to the hypothetical fuel usage if the demolition debris had not been recycled and limestone had been used for the construction of the CVS site. Some cost estimates will also be made comparing the two processes.

Fortuna began demolition of the concrete factory in 2006 and completed it three weeks later, working an average of 45 hours per week. From this demolition, Fortuna produced approximately 7500 tons of demolition debris, which was never taken off the site. The closest C and D landfill to this site is Summit C and D disposal, which is approximately 12 miles away. Using trucks with a carrying capacity of 22 tons and a fuel consumption of 4.5 MPG, it would have taken 1,818 gallons of diesel fuel to transport this material to the landfilland would have resulted in $5,000 of additional fuel cost. This landfill would have also charged Fortuna $8.00 a cubic yard to dump the demolition waste. With a truck carrying capacity of 12 cubic yards, this would have resulted in an additional charge of approximately $33,000 bringing the total additional cost to about $38,000 to landfill (Table VIII).

Haul to landfill	12	miles
Waste	7500	tons
Truck Capacity	22	tons
MPG of Truck	4.5	MPG
Number of Truck Trips	341	trips
Total Miles to Landfill	8182	miles
Fuel Used to Landfill	1818	gals
Cost of Diesel	$ 2.75	per gal
Truck Capacity	12	CY
Tipping Fee	$ 8.00	per CY
Total Tipping Fees	$ 32,727.27	
Extra Fuel Cost to Landfill	$ 5,000.00	
Total Cost to Landfill	$ 37,727.27	

Table VIII - Fuel consumption and additional costs to landfill demolition debris from CVS site

Fortuna set up a mobile crushing plant on the site, taking approximately four days to mobilize all of the equipment. It took Fortuna approximately four additional days to crush all of the demolition debris and turn it into RCA. Fortuna estimated that they worked approximately 45 hours a week during this operation, which results in an estimate of 36 hours to crush all of the demolition debris.Fortuna crushed the material to #304, #1, and #2 gradations and supplied all of the information on what equipment they had used and how much fuel each piece of equipment consumed. Using this data (Table IX), it was estimated that it took approximately 1,620 gallons of diesel fuel to process the RCA.

			gph	Hours	Fuel Used (gals)	
Eagle 1200 Crusher			16	36	576	
	60' Conveyor					
	30' Conveyor					
CAT 345 Excavator			13	36	468	
CAT 330 Excavator with hoe ram			10	36	360	
WA500 Komatsu Wheel Loader			6	36	216	
					1,620	Totals

Table IX - Fuel used to produce 7500 tons of RCA at CVS site

Once the material was processed, Fortuna re-used the RCA on site. The #1's and #2's were used to stabilize any soft spots in the ground and the #304 material was used to backfill utility trenches and as a base material for the new parking lot. Fortuna said that all the demolition material was processed and re-used and that there was a shortage of a couple hundred tons, which was hauled to the site. Due to lack of information and the small amount of material this will be neglected in the analysis.

Had Fortuna not recycled the material they would have had to haul limestone to the site for backfill and base material. The closest aggregate supplier Fortuna would have used is National Lime and Stone (NLS), which is located in Akron and is about 9 miles away from the site. Since no data was obtained from NLS on the trucks used to haul the material to the site, it was assumed that the NLS trucks operated in a similar fashion to the trucks Fortuna would have used (4.5 MPG and 22 ton carrying capacity). NLS also charges different prices for different gradations, and the amount of each gradation used on this project was unknown, so the average price of $20.00 a ton was used as the cost for the limestone aggregate.

Using the information obtained and the assumptions made, it would have taken 1,364 gallons of diesel to transport the aggregate to the site. The additional cost for the limestone aggregate would have been about $150,000(Table X). Additional fuel cost is neglected because that will be a cost to the aggregate provider.

Material Needed	7500	tons
Truck Capacity	22	tons
Trips	341	
Distance to Supplier	9	miles
MPG of Truck	4.5	MPG
Total Miles	6136	miles
Fuel Consumed	1364	gals
Cost of Limestone	$ 20.00	per ton
Total Cost of Limestone	$ 150,000.00	

Table X - Fuel consumption and additional cost to use virgin aggregate on CVS site

The transport of the virgin aggregate to the distribution center was also considered in this study. The National Lime and Stone Company stated that their limestone was railed in from a quarry in Carey, Ohio, which is about 100 miles away. Based on the ton*miles per gallon of rail previously mentioned, the overall fuel consumption to transport the material was calculated (Table XI).

Ton*Miles per Gallon	413
Total Miles	100
Tons per Gallon	4.13
Gallons per Ton	0.242131

Table XI - Fuel Consumption to Rail Limestone to Distribution Center

Using all of this information, analysis was made on the total energy inputs for the recycling operation versus landfilling and using virgin aggregates for construction. The total energy used to recycle was compared to the energy that would have been used to landfill the construction debris, quarry, process and transport the virgin aggregate to the site. The fuelconsumed for the separate operations was converted to BTUs to perform the analysis, which showed an energy savings of 89,620 BTU/ton, or 74.9%, (Table XII) by recycling for this project.

Recycling			**Landfilling**		
Fuel Consumed	1620	gals	Fuel Consumed	1818	gals
RCA Produced	7500	tons	Material Landfilled	7500	tons
Gallons/Ton	0.216		Gallons/Ton	0.2424	
BTU/Ton	29959		BTU/Ton	33621	
Aggregate Supply			**Quarrying**		
Fuel Consumed	1364	gals	BTU/Ton	27150	
Gallons/Ton	0.1819				
BTU/Ton	25225		**Rail to Distribution Center**		
			BTU/Ton	33583	
Totals					
BTU/ton to Recycle		29959			
BTU/ton to Not Recyle		119579			
Difference		89620			

Table XII - Energy savings in BTU/ton by recycling for CVS project

A general model for total cost was also developed for this operation. Since the cost/value of equipment, mobilization, labor and overhead is data that is specific and proprietary to the contractor, only the cost for landfilling and virgin limestone were considered (Table XIII). An industry standard value for cost/ton to produceRCA can be used for a similar size contractor if further analysis is to be considered for a total cost comparison.

Landfilling			**Virgin Aggregate**		
Fuel Cost	$ 5,000.00		Material Needed	7500	tons
Tipping Fees	$ 32,727.27		Material Cost	$ 150,000.00	
Total Cost	$ 37,727.27				
Total Cost	$ 187,727.27				

Table XIII - Additional costs associated with not recycling and reusing RCA

Recycled Materials Company Case Study: Stapleton Airport, Denver Colorado

The Recycled Materials Company is headquartered in Arvada, Colorado and currently employs over 100 people. They have been in the recycling industry for 20 years and in that time have recycled more than 40,000,000 tons of concrete and asphalt to meet specifications for re-use in the market. They operate a fleet of mobile and portable crushing units and heavy equipment that they utilize in many large scale projects, one of which will be investigated in this study.

The project being investigated in this case study is the demolition and production of RCA from the parking garage at the Stapleton Airport in Denver, Colorado. The garage was demolished and the debris was crushed on site to produce RCA. Some of this material was re-used on site while the balance of the material was hauled away and re-used on a nearby road and also sold to contactors for various projects. This investigation tracked the energy inputs from the production of RCA on site, transport to the storage facility, and transport to the re-use location. The investigation also tracks the energy inputs for the hypothetical situation of using virgin aggregates at both locations in place of the RCA.

Demolition of the parking structure was completed in May of 2011 (Figure **22** - Demolition of the Stapleton Airport Parking GarageFigure 22) and crushed on site to produce RCA (Figure 23).

Figure 22 - Demolition of the Stapleton Airport Parking Garage

Figure 23 - Recycling of Construction Debris at Stapleton Airport

The crushing operation took approximately 373 hours to complete with a production rate of about 230 tons per hour, yielding about 86,000 tons of RCA material.

The equipment used and total fuel consumption to produce this material can be seen in Table XIV.

	gph	Hours	Fuel Used (gals)	
Retek 1313i Impact Crusher	12.5	373	4662.5	
Powerscreen Chiefton 2100	7.5	373	2797.5	
(2) Caterpillar 966 Loaders	9	373	6714	
			14174	total

Table XIV - Equipment Used and Fuel Consumption to Produce RCA at the Stapleton Airport

The RCA produced consisted of CDOT Class VI (road base)aggregate (53%), 2"x3/4" drain rock (28%) and 4"x2" stabilization rock (19%). The material produced was considered to be a clean material. A magnet was used to pull out any reinforcing steel and laborers were stationed at each conveyor to pull out any debris that remained prior to the loading of the RCA into the trucks.

Since the RCA produced was of different gradations, the Recycled Materials Company provided us with a truck capacity for each different gradation. Before any analysis was made, an equivalent truck capacity was found to produce an average capacity for each truck based on the percentage of each gradation produced and the truck capacity for that gradation (Table XV).

Material	Percentage	Truck Capacity (tons)	Equivalent Capacity	
Class VI	53	23	20.93	tons
2"x3/4"	28	19		
4"x2"	19	18		

Table XV - Equivalent Truck Capacity at Stapleton Airport

Some of the material was re-used at the Stapleton Airport (11,000 tons), but a large majority (75,000 tons) of the material was taken to a nearby recycling facility. The facility is located on East 56th Avenue in Denver, approximately 4 miles away from the site. Using the equivalent truck capacity found, the total fuel used to transport this material was found (Table XVI).

Haul to Stockpile	4	miles
Waste	75000	tons
Truck Capacity	20.93	tons
MPG of Truck	5	MPG
Number of Truck Trips	3583	trips
Total Miles to Stockpile	28667	miles
Fuel Used to Stockpile	5733	gals

Table XVI - Fuel Used to Transport RCA to Recycling Center

From the recycling facility, the RCA was used to widen a nearby road and also sold to various contractors for other projects in the area. For this study, only the RCA used at the nearby road was considered due to the fact that it was a large quantity of the material and there was a lack of information of material distribution to other projects. The material used for this project was the Class VI aggregate (39,750 tons) and was transported to East 56th Avenue to widen a road between Quebec and Havana Street, which was approximately one mile away from the recycling center. The total fuel consumption for the transport of this material is shown in Table XVII.

Material Needed on Road Site	39750	tons
Truck Capacity	23	tons
Trips	1728	
Distance to Stockpile	1	miles
MPG of Truck	5	MPG
Total Miles	3457	miles
Fuel Consumed	691	gals

Table XVII - Fuel Consumption to Transport RCA to East 56th Avenue Project

If the demolition debris from the parking structure had not been recycled, it would have been transported to the nearest landfill facility. The Recycled Materials Company noted that the nearest landfill they would have used was Republic Services on Tower Road, which is approximately 14 miles away from the Stapleton Airport location. The total fuel consumption used to transport all of the demolition debris to this location can be seen in Table XVIII.

Haul to landfill	14	miles
Waste	86000	tons
Truck Capacity	20.93	tons
MPG of Truck	5	MPG
Number of Truck Trips	4109	trips
Total Miles to Landfill	115050	miles
Fuel Used to Landfill	23010	gals

Table XVIII - Fuel Used to Transport Stapleton Demolition Debris to Landfill

The next step in the analysis was to determine the total fuel consumption for the hypothetical case of using virgin aggregate at both the Stapleton Airport and East 56th Avenue sites. The Recycled Materials Company stated that the aggregate supplier they would have used is Albert Frei and Sons in Idaho Springs, who owns a quarry approximately 44.5 miles from the Stapleton Airport and 49 miles from the East 56th Avenue site. It is important to note that this is not the closest aggregate supplier to both sites, but is the cheapest aggregate supplier in the area. Since the purpose of the study is to investigate where the material would have came from, this is the supplier that was used for analysis.

It was assumed that Albert Frei and Sons would have used trucks with similar carrying capacities and fuel consumption rates to The Recycled Materials Company trucks. The fuel consumption for the transport of aggregate to the Stapleton Airport and East 56th Avenue sites can be seen in Table XIX and Table XX, respectively.

Material Needed on Demo Site	11000	tons
Truck Capacity	23	tons
Trips	478	
Distance to Supplier	44.5	miles
MPG of Truck	5	MPG
Total Miles	42565	miles
Fuel Consumed	8513	gals

Table XIX - Fuel Consumption to Supply Virgin Aggregate to Stapleton Airport Site

Material Needed on Road Site	39750	tons
Truck Capacity	23	tons
Trips	1728	
Distance to Supplier	49	miles
MPG of Truck	5	MPG
Total Miles	169370	miles
Fuel Consumed	33874	gals

Table XX - Fuel Consumption to Provide Virgin Aggregate to East 56th Avenue Site

Using this information, analysis was then performed to determine the total fuel used to recycle and re-use versus landfilling the demolition debris and using virgin aggregate. The total amount of recycled material produced was not all used in the scope of this study. In order to perform analysis, the gallons of fuel used per ton of RCA produced and per ton of virgin limestone needed was calculated and converted to BTUs per ton in order to draw comparisons.

For the recycling operation, the energy inputs include crushing, transportation to the recycling facility and transportation to East 56th Avenue site and can be summarized in Table XXI.

Crushing				Transport to Recycling Faicility				Transport to East 56th Avenue			
Fuel Consumed		14174	gals	Fuel Consumed		5733	gals	Fuel Consumed		691	gals
RCA Produced		86000	tons	Amount Stockpiled		75000	tons	Amount Delivered		39750	tons
Gallons/Ton		0.164814		Gallons/Ton		0.07644		Gallons/Ton		0.017384	
BTU/Ton		22860		BTU/Ton		10602		BTU/Ton		2411	

Table XXI - Summary of Fuel Consumption to Produce and Transport RCA

For the case of using virgin aggregates, the energy inputs include landfilling the demolition debris, transportation of virgin aggregate to the Stapleton Airport, transportation of virgin aggregate to the East 56th Avenue site and the limestone quarrying process, as previously determined (Table XXII).

Landfilling				**Virgin Aggregate to Road**			
Fuel Consumed		23010	gals	Fuel Consumed		33874	gals
Material Landfilled		86000	tons	Material Needed		39750	tons
Gallons/Ton		0.267558		Gallons/Ton		0.852176	
BTU/Ton		37110		BTU/Ton		118197	
Virigin Aggregate to Demo Site				**Quarrying of Virgin Aggregate**			
Fuel Consumed		8513	gals	BTU/ton	27150		
Material Needed		11000	tons				
Gallons/Ton		0.773909					
BTU/Ton		107341					

Table XXII - Summary of Fuel Consumption to Landfill and Use Virgin Aggregate

The energy inputs for all processes in both operations were added together and a total BTU/ton was found for both cases. It was determined that by recycling the demolition debris and re-using it as RCA at both sites, an approximate energy savings of 253,925 BTUs/ton, or 87.6%, was observed (Table XXIII).

Totals			
BTU/ton to recycle and re-use			35873
BTU/ton to not recycle			289798
BTU/ton Difference			253925

Table XXIII - Total Energy Savings to Recycle Demolition Debris from Stapleton Airport

Case Study Conclusions

Summary

The case studies conducted showed the energy consumption to produce and transport RCA for the various demolition jobs discussed. The study also showed the energy consumption for the hypothetical case of landfilling all of the demolition debris and using virgin limestone aggregate in place of the RCA. By comparing these two methods, recycling demolition debris could produce an energy savings of varying magnitude for each project (Table XXIV).

	Energy Savings (BTU/ton)	% Savings
Independence: Cleveland Cold Storage Building	23763	40.6
Fortuna: CVS	89620	74.9
Recycled Materials Company: Stapleton Airport Parking Garage	253925	87.6

Table XXIV - Summary of Energy Savings for Each Project

There are large differences in energy savings for each project, which are determined by the crushing operations, project location, the location of stockpiles or crushing facilities, the location of landfills, location of aggregate suppliers and transportation methods. By dividing the total amount of fuel used by the total amount of RCA produced, a set of data for energy consumption for the crushing operation alone can be seen for each case (Table XXV).

	Energy Consumed	
Independence: Cleveland Cold Storage Building	31846	BTU/ton
Fortuna: CVS	29959	BTU/ton
Recycled Materials Company: Stapleton Airport Parking Garage	22860	BTU/ton

Table XXV - Summary of Energy Consumed in the Crushing Process for Each Case Study

It can be seen that there are some differences in energy consumption for the crushing process, but they are not large enough to account for the difference in the three different case studies. Because of this it can be determined that the large differences can be attributed to the location of the demolition projects and the locations of the sites relevant to this study.

The location of where the demolition debris or the RCA went to after demolition or crushing and the location of where the RCA went to after stockpiling was first considered. The distance and energy consumption were calculated (Table XXVI) for these processes which contribute to the energy consumption for the case of re-using RCA. Because Fortuna had re-used all of the demolition material on site, there was no energy consumption for transportation. Also, in the Independence case study, since the re-use location was equidistant from the stockpile and aggregate supplier, there was no energy consumption attributed to the transport of the RCA to the re-use site.

			Miles to Stockpile	BTU/ton to Stockpile	Miles to Re-Use	BTU/ton to Re-use
Independence			1	2802	0	0
Fortuna			0	0	0	0
Recycled Materials Company			4	10602	1	2411

Table XXVI- Distance and Energy Consumption for Transport to Stockpile/Crushing Centers and Re-use sites

It can be seen from these data that there were some differences in energy consumption for the three cases, but the distance traveled was relatively short and did not produce significant enough energy differences to account for the overall difference in energy consumption.

Another thing to consider is the transport of the demolition debris to the nearest landfill and the transport of virgin aggregate to the re-use site. The distance and energy consumption was calculated for all three cases (Table XXVII) and contribute to the energy consumption for the hypothetical case of not crushing the demolition debris and re-using it as RCA.

	Miles to Landfill	BTU/ton to Landfill	Miles to Supplier	BTU/ton for Supply
Independence	6	16813	0	0
Fortuna	12	33621	9	25225
Recycled Materials Company (1)	14	37110	49	118197
Recycled Materials Company (2)			44.5	107341

Table XXVII – Distance and Energy Consumption for Transport to Landfill and Aggregate Suppliers

As was the case with the transport of the RCA to the re-use site, the transport of the virgin aggregate was not considered in the Independence case since the aggregate supplier and RCA stockpile is equidistant to the re-use site. Also, the Recycled Materials Company case study involved two sites where the material was re-used, which is reflected in the data. The quarrying process was not considered when comparing the three case studies since it was constant for all three.

It can be seen there is some difference in energy consumption related to the transport of the demolition debris to the landfill, but the major difference can be seen in the transport of virgin aggregate to the re-use site.

The last thing to consider is the transportation of the virgin aggregate from the quarry to the distribution center, which is summarized in Table XXVIII.

	Miles to Quarry	Mode of Transport	BTU/Ton to Transport
Independence	60	Barge	14447
Fortuna	100	Rail	33583
Recycled Materials Company	0	None	0

Table XXVIII - Summary of Energy Required to Transport Limestone from Quarry to Distribution Center

Since the limestone for the Stapleton Airport is hypothetically shipped directly from the quarry, this step is skipped in the distribution line for that case study. The other two studies show that there are significant energy demands associated with the barge and rail operations. However, in the case of the Stapleton Airport, the energy demand to transport the limestone via truck from the quarry directly to the site greatly outweighs any energy savings by eliminating a step in the distribution line. In the case of the Stapleton Airport, the absence of a navigable waterway or a rail line greatly outweighs the fact that the quarry is closest to the final destination when considering all three cases.

CHAPTER VIII

OVERALL CONCLUSIONS AND RECOMMENDATIONS

Concrete demolition waste is the largest contributor to the solid waste stream in the U.S. This waste is taking up landfill space that is becoming less abundant, and can be usefully converted to recycled concrete aggregate.

The properties of recycled concrete aggregate can present some challenges in its re-use applications, but a thorough knowledge of any potential drawbacks can eliminate unsuitable material for consideration and only promote the use of RCA for applications where it can meet specifications. Properties such as mortar content, absorption, and soundness can be evaluated on a case by case basis depending on the source of the recycled material.

RCA can be useful in many different ways. It can be used as an aggregate in new concrete or asphalt, as a base material under parking lots and roadways, railway ballast, or fill and drainage material. With each type of application, using RCA may present some challenges, but knowledge of the performance of RCA in these applications and the criteria that need to be met can ensure that it is only used in the proper applications.

The use of RCA in many of these applications is becoming increasingly important. Limestone and other natural aggregates are traditionally used as aggregate in new concrete and as base material. These aggregates are becomingly increasingly expensive and less common in some areas, making the transportation of these materials energy demanding.

By taking a close look into everything that goes into the production and transport of natural aggregates, one can get a better understanding of how much energy is required to generate these materials. This information can then be used to draw comparisons between the energy consumed to use natural aggregates versus using recycled concrete aggregate.

By performing the three case studies discussed in this thesis, a comparison of the energy demands of using natural aggregates and recycled concrete aggregates was generated. Using the energy consumption for both cases allowed for the determination of RCA as a sustainable building product. The results of the analysis showed that in each case energy was saved by using RCA in lieu of natural aggregates. However the degree of savings varied greatly between the three studies performed.

The main difference in energy consumption for both operations considered is highly dependent on location and mode of transportation. As the distance to the recycling center from the demolition site decreases, and as the distance from the landfill to the demolition site increases, the total energy saved by re-using RCA will increase dramatically. Also, the proximity of the project site to a fuel efficient mode of transportation (rail or barge) will drastically affect energy savings.

Based on these findings, the recommendation would be to always use RCA where it is practical. The practicality will depend on the properties of the recycled material and what it is to be used for and must be addressed on a case by case basis. It will also depend on where the recycled material is being hauled in from and where the nearest natural aggregate distribution center is located. By using RCA in the situations described, it will reduce energy demand and can be considered a sustainable building product.

Considerations

Several considerations must be made to the analysis of this data and the conclusions drawn, which are as follows:

1. The energy consumption to demolish the structures mentioned was not considered. Unless the decision to demolish the structure is influenced by the fact that it will be processed into RCA, the energy consumption for demolition will have no relevance in this study, as the building will be demolished in the same fashion for both operations. The buildings demolished for the case studies mentioned were done so out of need for the land the buildings were occupying.
2. None of the energy required for construction in the re-use applications was considered. The construction practices to re-use the RCA or use virgin aggregate were assumed to be the same.

3. Only the energy consumed to run the equipment for both the crushing of the RCA and the limestone quarrying and processing operations was considered. No energy inputs to manufacture and maintain the equipment were considered.
4. No energy consumption was considered on the manufacturing of the trucks, trains, or barges for transport.
5. The wear and tear on roads was not considered in this study. If fewer miles are traveled by trucks for transport then the pavements the trucks travel on will have a longer service life before they need to be repaired or replaced.
6. The energy consumed to manufacture and run a piece of equipment to handle and move material at the landfill was not considered in this study.
7. Re-using RCA will eliminate the waste material in a landfill. Aside from the machinery used to run the landfill, there is no way to quantify energy savings by eliminating landfill waste, which should be considered when looking at the two options.

Further Research

The results of this study show that RCA has many suitable applications, and when used in those applications, can significantly reduce energy demand. However, there are still many drawbacks to using RCA based on its varying physical and chemical properties and to what effect these properties will have in its re-use application.

The varying properties of RCA will usually depend on the source it is coming from and what application the original concrete was used in. Based on the numerous applications in which we use concrete, the properties of its recycled product are often unpredictable.

Further research can be done to determine the properties of recycled concrete coming from original concrete used in a certain application. For example, concrete that was used in pavements may produce a recycled product with similar properties, whereas concrete used in foundation or building structures may produce a recycled material with a completely different set of properties.

By determining the properties of recycled material depending on its original use, a type of grading system could be established for recycled products coming from a specific source. If the RCA is classified into a specific grade, it can be used only in applications where it can meet the quality standards of the desired end product.

Since there are certain applications such as road base or aggregate in new concrete that would require concrete to have a higher quality, the higher grade RCA could be used in those applications. The lower grade RCA could be used in situations where the quality criteria are not as stringent, such as backfill or pipe bedding.

This would help eliminate many of the drawbacks of using the product and could possibly be the launching pad for the more widespread use of RCA.

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