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RECYCLED ASPHALT PAVEMENT AS COARSE AGGREGATE REPLACEMENT IN HIGH STRENGTH PORTLAND CEMENT CONCRETE MIXES

By

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Committee Approval

To the Graduate Faculty:

The members of the committee appointed to examine the thesis of Tara RaNae Capson find it satisfactory and recommend that it be accepted.

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Dedication

I would like to dedicate this research to Matt, Tristan and Zak.

I could not have made it through without your love and support.

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Tara RaNae Capson

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ABSTRACT

RECYCLED ASPHALT PAVEMENT AS COARSE AGGREGATE REPLACEMENT IN HIGH STRENGTH PORTLAND CEMENT CONCRETE MIXES

Thesis Abstract – Idaho State University (2014)

New construction materials utilizing recycled or bi-product waste have recently been developed to help create "greener" construction. One of these materials utilizes Recycled Asphalt Pavement (RAP) as a percentage replacement for a portion of coarse aggregate in concrete mixes. Previous studies on these concrete mixtures has shown that the RAP inclusion considerably lowers the compressive strength of the concrete; thus limiting its usefulness. However, the inclusion of RAP in High Strength Portland Cement Concrete (HSPCC) mixes has yet to be studied. Additionally, most previous studies replaced the coarse aggregate by weight, without including gradation, and used RAP from only one source.

This study considers factors which affects the strength of concrete mixes utilizing RAP as coarse aggregate replacement. The compression strength variability is compared to determine if geographical/environmental conditions of the RAP harvest location effects mechanical properties. Also, the results of gradated versus non-gradated RAP replacement in HSPCC mixes is analyzed. Six separate RAP replacement percentages are studied in HSPCC mixes to determine an ideal relationship between RAP replacement and compressive and tensile strength. Finally, this study presents the results of including Polyvinyl Alcohol Fibers (PVA) in a RAP coarse aggregate HSPCC mix.

CHAPTER 1 - INTRODUCTION

1.0 BACKGROUND AND MOTIVATION

Concrete is a key building material in bridges, buildings, parking garages, foundations, retaining walls and many other kinds of construction. It is a reliable and useful construction material that is utilized for its high compressive strength. Concrete is especially useful in areas where saturation or water is involved or where exposure to chemicals is present, due to its resistance to corrosion.

Concrete has very little strength benefits when loaded in tension. It is necessary to have both strength in compression and tension in most structural building applications. So, in order to achieve the necessary parameters in concrete that offers both compression and tension strength benefits, steel reinforcement is added to concrete in order to give strength when the member is in tension. Polyvinyl fibers, metal cages as well as other additives can be added to concrete in order to help with the tension strength parameters.

Concrete is composed of natural aggregate, cement, water and strengthening additives such as plasticizer, lime and fly ash. Utilizing recycled materials promotes the ideas and concepts of Green Engineering by re-using and recycling material, thus preserving our lands and natural resources. Green engineering embraces the concept that decisions to protect human health and the environment can have the greatest impact and cost effectiveness when applied early to the design and development phase of a process or product (EPA, 2012). Using RAP as a coarse aggregate replacement utilizes recycled natural resources otherwise mined preserving our land and resources contributing to the new wave of the future; Green Engineering.

This research promotes green engineering; re-using and recycling material to save our planet for the next generation. The concept of re-using and recycling construction materials is becoming increasingly popular as our understanding of the devastation the use of natural resources is having on the environment increases. Utilizing recycled material helps companies qualify for LEED Certification. (Brand *et al.*, 2012)

Previous studies have been carried out to determine the viability of RAP in a concrete mixture. Research conducted at Montana State University mixing asphalt with concrete for an asphalt concrete design mix to be used as a road base material only (Berry *et al.*, 2009). Optimum percentage of RAP replacement has been tested in a study conducted by Murshed Delwar, Mostafa Fahmy, and Ramzi Taha from University of Moscow Idaho in 1995. It was shown in this research that by adding RAP to concrete resultes in a decrease in compression strength and that the RAP increased ductility parameters (Delwar *et al.*, 1995). This study was conducted on regular strength PCC yielding a low strength concrete only good for low strength parameter conditions such as sidewalks, driveways, barriers, curbs, gutters and pipes. The results of these studies are the catalyst for using higher compressive strength concrete mix in the proposed study with intent to yield a compressive strength viable as a regular strength construction material. Further study of harvest location, sieve and gradation variance as well as fiber testing in HSPCC with RAP replacement has not been done.

1.1 PROBLEM DEFINITION AND SCOPE

This research proposes the replacement of RAP in high strength concrete mixes as a coarse aggregate replacement by harvest location, gradated versus not gradated, percentage replacement, and adding PVA fiber additive to percentage replacement as coarse aggregate. This study considers the factors that may affect the tensile and compression strength of concrete mixes that utilize RAP as coarse aggregate replacement for each mix listed. A detailed description of each mix and the testing method is presented in Chapters 3, 4 and 5 respectively.

The variability in compression strength is studied to determine if geography and environmental conditions of the RAP harvest location affects the mechanical properties when replacing RAP in HSPCC mix. The study also presents the results of gradated versus non-gradated RAP replacement in HSPCC mixes. Then, six separate RAP replacement percentages are studied in HSPCC mixes to determine an ideal replacement amount and the relationship between RAP replacement to compressive and tensile strengths.

Finally, the study presents the results of including Polyvinyl Alcohol Fibers (PVA) in a HSPCC mix in addition to RAP coarse aggregate replacement testing the strength parameters for both tensile and compression strength with hopes to increase the strength parameters and compensate for the possible decrease in strength from the RAP.

1.2 OBJECTIVES

In order to determine the variability in concrete strength properties from RAP concrete mixes discussed in the previous section, the four main objectives of this study are defined as:

1) Determine the variability in the compressive strength of RAP concrete utilizing gradated RAP from different harvest locations.
2) Determine the variability in the compressive strength when using gradated RAP versus non-gradated RAP.
3) Determine the variability in the tensile and compressive strength of RAP utilizing various replacement percentages of RAP for the coarse aggregate.

4) Determine the effect on tensile and compressive strength of including PVA fibers into a RAP concrete mixture.

1.3 RESEARCH TASKS & METHODOLOGY

To achieve the objectives of this study, the following tasks are streamlined:

1) Five separate locations throughout the State of Idaho are chosen and RAP is collected in the same manner from each location. The RAP is sieved and gradated in the same manner for all locations. Concrete specimens are cast using a 35% RAP replacement mix and lab testing is completed for each of the five harvest locations. Topographical data is collected for each Harvest location data including temperature, traffic count, elevation and population. The compressive strength results from the lab and the harvest location data is obtained and results are shown in Chapter 3.
2) Using a 35% RAP replacement mix, two separate locations are chosen to compare gradated versus non gradated RAP as a replacement. Concrete specimens are cast and lab testing is completed. These results are shown in Chapter 4.
3) Seven batches of concrete are cast; six using a different percentage of RAP replacement and one control batch. The RAP replacement percentages cast include 25%, 30%, 35%, 40%, 45% and 50%. Concrete cylinders are cast for all percentage batches and both tension and compression is tested for each batch. The lab data is collected and the results are presented in Chapter 4.
4) PVA fibers are added to three separate batches of RAP percent replacement mixes: 35%, 50% and 100%. Concrete cylinders are cast and both tension and compression. The lab data is collected and the results are presented in Chapter 5.

1.4 THESIS OVERVIEW

This thesis is divided into six chapters. The introduction (Chapter 1) is followed by a review of existing literature pertinent to this study (Chapter 2). Chapter 3 presents the analysis of the strength variance due to harvest location and location parameters. The analysis of the variance in strength due to gradation and RAP percentage are presented in Chapter 4. Chapter 5 presents the analysis of adding PVA fibers to RAP replacement in HSPCC. The thesis ends with a summary of conclusions and suggestions for future work. A reference page appears at the end of the thesis.

CHAPTER 2 - LITERATURE REVIEW

2.0 INTRODUCTION

This chapter presents a summary of the studies and research that is significant to this study of testing specific effects of replacing various proportions of aggregate with Recycled Aggregate Pavement (RAP) in a High Strength Portland Cement Concrete (HSPCC) mix. The specific effect being tested is the compression and tensile strength of the resulting recycled concrete mix design; to test whether or not it can maintain strength parameters with compression strength greater than 4,000 psi. This allows the new mix design to be utilized in structure applications. In other words, this enables the design mix to be used as a general construction material without limiting conditions due to the compression and tensile strength of the material.

This chapter summarizes the pertinent studies and research related to the subject matter. This chapter is broken down into eight sections. Section 2.1 summarizes the studies of using recycled aggregate, recycled asphalt pavement and the past research of replacing RAP in concrete as an aggregate replacement. Section 2.2 summarizes the effect of replacing RAP with aggregate in concrete and its ties to green engineering. Section 2.3 addresses the approach to the effects and studies addressing PVA fiber additives added as strengthener reinforcement to RAP concrete. Section 2.4 addresses the studies relevant to concrete materials, geographical location, and environmental parameters that may affect the material properties in this thesis project. Lastly, Section 2.5 summarizes the results of the compiled reviewed literature.

2.1 GREEN ENGINEERING

Presently in India, about 960 million tons of solid waste is being generated annually as by-products during industrial, mining, municipal, agricultural and other processes. Of this approximately 350 million tons are organic wastes from agricultural sources and 290 million tons are inorganic waste of industrial and mining sectors (Pappu *et al.*, 2014). Supplies of natural high quality aggregate are depleting in some areas in the world, or can be costly to transport to the construction site. Existing portland cement concrete and asphalt concrete pavements provide a source of high quality aggregate that can be recycled. Not recycling can contribute to the waste disposal and to the conservation of natural resources. (Yrjanson, 1989; and Kenai *et al*., 2002) Every year Hot Mix Asphalt (HMA) roadways are rehabilitated by milling the existing roadway and replacing the milled portion with new HMA. As a result of this practice, a tremendous amount of RAP is created. The Federal Highway Administration estimates that 100 million tons of HMA is milled each year (McGarrah, 2007).

Gondolf wrote about the geomorphic and environmental effects of mining for aggregate in natural streams and resources in 1994 (Goldolf, 1994). ‘Instream gravel mining involves the mechanical removal of gravel and sand directly from the active channel of rivers and streams. Active channel deposits are desirable as construction aggregate because they are typically durable (weak materials having been eliminated in river transport), well-sorted, and frequently located near markets or on transportation routes. Instream gravel mining commonly causes incision of the channel bed, which can propagate upstream and downstream for kilometers. As a result, bridges and other structures may be undermined, spawning gravels lost and alluvial water tables lowered. In analyzing the effects of instream gravel mining, a sediment budget analysis sheds light on the relative magnitude of gravel supply, transport and extraction. Computer models of sediment transport are simplifications of complex natural processes; they can be useful components of a sediment budget analysis but should not be relied upon alone. A historical analysis of channel change and sediment supply is needed to understand the underlying processes responsible for present conditions. While instream gravel mining can be a useful tool in flood control and river stabilization in aggrading rivers, most rivers in the developed world (certainly the vast majority below reservoirs) are not aggrading and are more prone to incision-related effects of instream gravel mining' (Goldolf, 1994).

Land mining for aggregate is a different and separate process. Aggregates commonly are available near the point of use; however availability for consumptive use is not universal. Large areas are void of sand and gravel and potential sources of crushed stone may be lacking or covered by thick overburden making surface mining uneconomical. Crushed stone, sand and gravel are often mined from open pits or quarries, although some stone is obtained from underground mines. Mining and quarrying for crushed stone and aggregate requires drilling and blasting. The sand and gravel mix can then be extracted with power equipment such as bull dozers, draglines and shovels. Broken rock, sand and gravel are loaded onto dump trucks or conveyors for transportation to a facility for processing. Aggregate is then sorted in size and even more natural resources are used to crush aggregate to appropriate size, clean aggregate free of debris so that it is ready for use according to the required standards (Langer, 1994).

Reclamation for both land mining and instream gravel mining is critical after the mining process. Natural resources in gas and oil are used as large equipment is used as the large area is rehabilitated back to as close to its natural environment as possible. The reclamation process is monitored by government facilities to ensure the area is adequately rehabilitated; however the process creates temporary environmental impacts such as increased airborne particulates, increased sediment yields in streams, increased truck traffic and noise levels, permanent change to landscape. Increased truck traffic is both an environmental concern (increased exhaust emissions) and a safety concern for local communities (Langer, 1994).

Transportation distances can have a huge impact on cost, energy and particulate emissions for concrete recycling. Hameed conducted a study in 2009 on the alternative methods that could be utilized in the procurement of coarse aggregate and the feasibility of using recycled concrete aggregate over virgin aggregate in terms of cost, energy, and particulate emissions required for production and transportation (Hameed, 2009). According to U.S. Geological Survey $74.3 billion estimated value mineral production in 2013, this is a slight decrease from $75.8 billion in 2012 (USGS, 2014). Although dollar sales decreased it was not due to less mining, the annual production mining increased in 2013, mining 14 mineral commodities worth more than $1 billion each. The increase seen in the consumption of cement, construction sand and gravel, crushed stone, and gypsum are all mineral commodities that are used exclusively in construction (USGS, 2014). According to research conducted from Hsiao, Huang, Yu and Wernick referenced in Hameeds' research; 90% of the aggregate supply has been extracted from domestic riverbeds and banks. This research concluded that using virgin aggregate instead of demolished concrete for aggregate was the least cost effective option over crushing on site with a portable crusher and hauling to an aggregate recycle facility, increasing as distance increased relative to the job site (Hameed, 2009).

The trend for the future is lending toward working on retaining our natural resources and creating sustainable energy solutions to preserve our future. If a definitive solution can be found and utilized for using RAP as a replacement for aggregate in concrete, a portion of the landfills can be saved that would have normally stored the non-biodegradable RAP in addition to saving the natural resources mined disturbing the environment when excavating for new aggregate.

2.2 PAST RESEARCH REPLACING RAP IN CONCRETE AS AN AGGREGATE REPLACEMENT

Delwar and others scientists conducted a study in 1997 adding RAP to concrete resulting in a decrease in compression strength with enhanced ductility parameters with excellent shatter resistance properties (Delwar *et al.*, 1997). Two separate water to cement (w/c) ratios were tested; 0.4 and 0.5 percent. In addition, 2 completely separate concrete mixes were tested against a control mix that had 100 percent conventional aggregate for comparison purposes. The first mix consisted of a RAP replaced in percentage increments of 0%, 25%, 50%, 75% and 100% with the fine RAP replaced at a 100% ratio. The second mix consisted of coarse RAP replaced at 100% ratio with the fine RAP replaced in percentage increments of 0%, 25%, 50%, 75% and 100%. Flexural strength tests were administered according to ASTM Standard C78-84 under three point load conditions. The research results showed that the modulus of rupture was about 685 psi, indicating that the applications of adding RAP to concrete would serve well in applications where flexural strength is more critical than compressive strength. Although, the studies showed that ductility properties did improve as the RAP additive was replaced at a higher percentage, it was also shown that as RAP increased, compression strength decreased in all mixes. For the control mix the failure type was characterized as a mortar failure and explosive conical failure. It was observed that as the RAP replacement percentages increased, the failure type was a combination of mortar and aggregate failure.

In addition to the failure break, it was observed that the specimens were able to sustain loads even after the initial failure occurred. This research shows that by adding RAP to concrete, the asphalt properties add a quality to the concrete resulting in a more pliable and ductile concrete mix (Delwar *et al*., 1997).

In a later study, Delwar and two other scientists studied varied percentages of RAP replacement aggregate on regular strength concrete. The most effective percentage of RAP aggregate replacement mixture in that design mix used was between 30% to 50% RAP replacement by volume for both coarse and fine aggregate, having results of the highest compression strengths in that range (Delwar *et al*., 1995,(1)). This research also showed an increase in ductility parameters as well as a decrease in compression strength.

The U.S. Federal Highway Administration (FHWA) and the Army Corps of Engineers conducted studies to determine the suitability and economic feasibility of using recycled aggregates from Portland Cement Concrete (PCC) (Delwar *et al*., 1995,(2)). This group of colleagues investigated varying percentages of RAP replacements of 0%, 25%, 50%, 75%, and 100% RAP replacement of coarse and fine aggregate using 2 difference water-cement (w/c) ratios of 0.4 and 0.5. Their studies concluded that recycled aggregate does not have any significant effect on the volume response of specimens to temperature and moisture effects, aggregate recycled from low strength concrete is not detrimental to the compressive strength of concrete mixtures that contain this aggregate. The use of water reducing admixtures is effective in increasing the strength of concrete mixtures that contain recycled concrete as aggregate. As recycled aggregate percent replacement increased, the air-entrainment of the admixture was increased and the unit weight and slump decreased. There results showed that fly ash can be used to improve the durability and workability of concrete made from recycled aggregates. The study concluded that concrete with high contents of replaced RAP should be suitable for non-structural strength applications such as sidewalks, gutters, road side barriers and decorative applications where a low compressive strength material is adequate.

Furthering on the research of using recycled asphalt in concrete in 2000, Huang and others studied replacing RAP in percentages similar to Delwar 1995 study using RAP replacements for both coarse and fine aggregates of 0%, 10%, 30%, 50% and 100% (Huang *et al.*, 2000). In addition to RAP replacement, silica fume was used as a replacement for cement at both 10% and 20% replacement percentages. The slump increased with low RAP replacement but decreased dramatically for high RAP replacement, especially in the high fine RAP replacement contents for both w/c ratios. However, the addition of silica fume did stabilize the slump nearly back to a zero differential from the base design control mix. Test results show a decrease in compressive and split tensile strength tests as the RAP percentage increased. The addition of RAP decreased the modulus of elasticity, however the toughness of the concrete was increased with the addition of RAP, especially that of the higher RAP replacement. The air content in this study was not affected by RAP replacement. This study concluded that the inclusion of fine RAP increased the toughness with a smaller decrease in strength (Brand *et al.*, 2012). Toughness is the area under the stress strain curve indicating the ability a material has of deforming plastically before reaching its modulus of rupture and deforming beyond structural capacity. In other words, toughness can be thought of as the ability a material has of absorbing energy and deforming without fracturing. This is an extremely valuable material property to have in the construction world and one that traditional concrete mixes lack.

Bilodeau and others studied the effect of replacing RAP in steel fiber-reinforced roller impacted concrete (RCC) in 2011 (Bilodeau *et al*., 2011). The design mix used included a 12% hydraulic binder consisting of a blend of clinker, fly ash, slag and limestone. Three RAP replacement percentages were studied: 0%, 40%, and 80%. Compressive tests were administered according to ASTM Standard C39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens as well as Split Tensile Tests performed to ASTM Standard C496 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. Both the compression and tension test results decreased as the RAP replacement increased. The compressive and tensile strength results peaked at the control design mix and decreased in strength as the RAP replacement increased. This research showed that the mixes containing RAP were more affected by temperature and frequency than the 0% RAP replacement mixes. However, this research also showed that the mixes containing RAP had visco-elastic properties while the control mix did not.

Researchers at the Montana State Transportation Department conducted research adding recycled asphalt to concrete called *asphalt concrete pavement*, to be used as a road-based material only, but not as a general construction material (Berry *et al*., 2009). The study concluded that as RAP increased, the tensile and ductility parameters increased. At the same time, the study shows a decrease of the compression strength as the RAP increased. Both fine and coarse aggregate were replaced with RAP in the following ratios: Fine RAP content 0 to 50%, Coarse RAP content 25% - 100%. The strength parameters in target were 2000 psi compressive strength at 7 days and 3000 psi compressive strength at 28 days. Their results showed a decrease in strength as the RAP increased for both compression and tension. The researchers conducted a statistical analysis of the results and it was found that the 28 day compressive strength was dependent on both the coarse and fine RAP content, while the 7 day compression test results were only dependent on the coarse RAP. This research found the fine aggregate to have a larger effect on the strength parameters than the large aggregate. It was suggested in this research that the final optimized design mix based on the research results would be a high strength concrete mix with a 20% fine RAP replacement and a 45% replacement of coarse RAP (Bermel *et al.*, 2011).

In 1997, Murshed and others investigated compressive strength results of replacing both coarse and fine aggregate with RAP in regular strength concrete. These results were compared to conventional concrete mixes without any replacements and found the compressive strength decreased with the increase of RAP content. The compressive strength results were in the range for non-structural strength applications such as sidewalks, driveways, curbs gutters, monuments and ornamental applications (Murshed *et al.*, 1997).

Al-Oraimi, Hassan and Hago performed a study in 2007 replacing coarse aggregate only with RAP in regular strength portland cement concrete with hopes in achieving a compressive strength concrete using reclaimed asphalt preserving the natural resources of mining new aggregate. In this study, normal Portland Type 1 cement was used; RAP was separated by sieving on the 5 mm sieve size into coarse and fine RAP. RAP to coarse aggregate was replaced in increments of 25, 50, 75 and 100%. Two mixes were tested at different water cement ratios of 0.4 and 0.5. The specimens were subjected to water bath cure and tested to British Standards BS 1881-116, the methods for determination of compressive strength of concrete cubes at 7, 14, 28 and 90 days. Specimens were also tested at 28 days according to ASTM Standard C469-94 Standard

Test Method for Compressive Strength of Concrete Cylinders Cast in Place in Cylindrical Molds. The results show compression strength, slump and unit weight decrease with the increase in RAP. The ratio decrease results from the control batch cubes to the RAP coarse aggregate replacement cylinders ranged from 0.77 to 0.89 for all specimens (Al-Oraimi, *et al*., 2007).

A group of scientists conducted a study on the use of recycled concrete and bricks as an aggregate in concrete (Kenai *et al*., 2002). The study used fine aggregate replacement, coarse aggregate replacement and both fine and coarse aggregate replacement. Percentages of replacement were 25, 50, 75, and 100% of the aggregate. The study recommended limiting the amount of recycled aggregate to 75% and 50% for the coarse and fine aggregate, respectively. A reduction in compressive strength was reported with the increase in recycled aggregate replacement. The study found that the relationships between tensile and compressive strength for natural aggregate concrete can be used for the recycled aggregate (Kenai *et al*., 2002).

Scientists Limbachiya, Leelewat and Dhir conducted a study in 2000 using recycled concrete as an aggregate in high strength concrete. Results indicated that up to 30% of recycled concrete aggregate had no effect on strength. At higher percentages, there was a gradual reduction in strength. The study presented a method to adjust the water cement ratio to overcome this reduction in strength. The study concluded with the adjustment of water-cement ratio, the high strength concrete made with recycled concrete aggregate may possibly have equivalent engineering and durability performance to normal high strength concrete at a 28 day break. While this study suggests potential for recycled concrete aggregate use in high-strength concrete having the strength to be used as a structural strength material, issues relating long-term performance and durability have not been considered in this study and needs to be further investigated (Limbachiya *et al*., 2000).

Brand and others presented research conducted for the Illinois Center for Transportation in August 2012. This research replaced a percentage of both fine and coarse aggregate in a design mix consisting of Fractionated Reclaimed Asphalt Pavement (FRAP) as a percent replacement of 0%, 20%, 35% and 50% of virgin coarse aggregate. The design mix included cement, slag and fly ash. The results demonstrated that up to 50% FRAP replacement it is possible to achieve a compressive strength of 3500 psi and 650 psi flexural strength at 14 days. FRAP is a washed and screened fractionated reclaimed asphalt pavement that has been further processed to produce a cleaner and more consistent product (Brand *et al*., 2012).

The Illinois Center for Transportation research has been conducted on mixing FRAP with concrete for an asphalt concrete design mix only used for roads, sidewalks and landscaping areas not intended for results of structural strength. Although the study was based on recycled aggregates from PCC using a regular strength concrete design mix and FRAP; viable information is used that can be related and utilized in this study regarding using the RAP as aggregate in a HSPCC design mix. This study shows a decrease in compression strength from the control mix to the concrete mixed using FRAP as an aggregate replacement. Test results show a decrease in tensile strength from the control mix to the concrete mix using FRAP as an aggregate replacement. Elastic and dynamic moduli properties have been documented to decrease as FRAP increases yet air content seems unaffected by FRAP replacement percentages. Producing opposite results than those presented in the Delwar study in 2000, this study results indicated that by adding FRAP to concrete may decrease the fracture toughness. This studies' rapid chloride penetration tests showed the FRAP did not alter the permeability rating of the design mix but may reduce the durability, although after 300 freeze/thaw cycles specimens rated a satisfactory durability value (Brand *et al*., 2012).

Studies presented in Chapter 2.1 shows research conducive to the relationship pertinent in the study that is being presented in this thesis. The existing research agrees that by adding recycled asphalt, recycled concrete or recycled brick to concrete in place of new aggregate, either fine, coarse, or any combination thereof, the compressive strength decreases as the replacement ratio increases. Huang and Delwar research concluded that the toughness in the concrete with replacements increases (Delwar *et al*., 1997), while the Illinois Center for Transportation Research concluded opposite than that with toughness decreasing (Brand *et. al*., 2012). The research presented by Montana State University and Limbachiya, Leelewat and Dhir show results for ductile and durability properties increased, with other studies either inconclusive or not looked at (Limbachiya *et al*., 2000; Bermel, 2011). The variability found here in results may be the difference in design mix and ingredients used in the concrete ratio mix for each study.

2.3 PVA FIBER ADDITIVES ADDED AS STRENGTHENER REINFORCEMENT TO RAP CONCRETE

It has been discussed in Section 2.1 of this study the importance of conserving our natural resources by not mining new aggregate, which additionally saves emissions of gases from fossil fuels that would otherwise be created by large mining equipment and machinery. For these reasons, many new construction materials utilizing recycled or bi-product waste have recently been developed to help create “greener” construction. The discussion continues in chapter 2.2 of this report on compression and tensile strength and the variability that may be seen when adding RAP as a recyclable material. In order to combat the compression strength deficiency in a greener concrete design mix, this study compares the results of using a high strength design mix while adding the different percentages of RAP. However, the previous studies also showed that consistency in the tensile capacity of these concrete mixes has yet to be achieved. While tensile capacity is not usually a main consideration in the specification of concrete materials, it does affect the ductile performance. In order to prevent tensile strength loss and even increase tensile strength in the high strength design mix being test, the utilization of fibers have been considered as an additive in existing studies.

Researchers Naaman, Moavenzadeh and McGarry studied the effect of stress and strain properties in fiber reinforced concrete (Naaman *et al*., 1975). The study performed a probabilistic analysis of what a stress strain curve would look like after adding fiber reinforcement and how the elongation at the neck of the curve would look like. The authors explain, "The first part of the curve up to the first structural crack (up to the peak load) contains a linear portion from zero to the initiation of cracking and a curved portion from initiation of cracking to the peak load" (Naaman *et al*., 1975).

Previous research on cementitious materials has shown that the inclusion of Polyvinyl Alcohol Fibers (PVA) into the mix matrix helps increase both tensile strength and ductility. Skourup and Erdogmus studied the effect of adding PVA fibers to reinforce mortar for masonry applications in 2010 (Skourup and Erdogmus, 2010). Fiber Reinforced Mortar (FRM) mixtures for masonry applications are designed specifically for rehabilitation, reconstruction, and strengthening of existing masonry structures. As such, low compressive strength and high ductility parameters are preferred. Results found that increased toughness, ductility and energy absorption can be achieved using FRM's in masonry joints without significantly altering the compressive capacity or aesthetics of the structure.

According to Johnston (2001) the compression strength of the mortar is not directly affected from the fibers. According to a number of studies (ACI Committee 544 1984, 1988; Skourup and Erdogmus, 2010; Lawler 2001; Banthia and Soleimani, 2005; Balaguru and Shah, 1992) macro fibers are between 0.5 and 2.5 inches and microfibers are defined as lengths less than 0.5inches. PVA fibers are shown to provide excellent reinforcing for cementitious mixtures, especially when both macrofibers and microfibers are combined (Lawler, 2001). Banthia and Soleimani study tested combinations of five separate fiber-reinforced mortar mixes were tested. The fibers used in the design mix are a various combinations of one, two or three of 18mm, 8mm and 6mm. This research concluded addition of PVA did not significantly affect the compressive strength of the mortar but did increase post-crack ductility, toughness, and energy absorption. The longer fiber provided the most significant strength increase, however the mix was the least workable. Additionally, the microfiber provided the highest first crack strength over the macrofiber (Skourup and Erdogmus, 2010).

"In micro-fracturing, strain-softening material like concrete, one parameter description of fracture is not possible and multi-parameter descriptions of fracture criterion have been proposed. In the case of fiber reinforced concrete, in addition to crack closing pressure due to aggregate interlocking, fiber bridging occurs behind the tip of propagation crack where fibers undergo bond-slip processes and provide additional closing pressures. The fracture processes in fiber reinforced cement composites are therefore even more complex … these are only crack initiation criteria" (Banthia, 1994). In this and other studies, fiber has been considered as an option for reinforcing concrete and other cementitious materials as an option for building, blocking, guarding and reinforcing areas of special terrorist interest, both U.S. and International.

Previous research yields to the conclusion that adding PVA fibers will increase the tensile strength parameters that may lack in the design mix. In order to test the effects of the PVA fibers in the HSPCC to the design mix, PVA fibers will be added to HSPCC and the results tested. Chapter 5 of this report includes details of the study.

2.4 RAP HARVEST LOCATION AND LOCATION PARAMETERS

Past research that has been related to adding or replacing RAP in cementitious materials and the effects the studies concluded on strength parameters and material properties have been discussed thus far. Additionally, the benefit of reusing and recycling material was discussed and how that directly related to utilizing RAP as a replacement for new aggregate. However, no research could be located on the location differential of RAP as a replacement of aggregate in concrete and the potential material properties changes related to their geographic location. Geographic location, including the parameters such as elevation, annual snow pack, annual precipitation, roadway type, traffic counts all may have an effect on the material properties of the RAP in the concrete as an aggregate replacement.

2.5 SUMMARY

This chapter reviews the existing literature that is pertinent to the study of replacing coarse aggregate with RAP to HSPCC design mix. From this review, several key points relevant to this study are extracted:

1) Utilizing RAP as a large aggregate replacement is an effective way to achieve green engineering and recycling. Reusing an unsustainable product saves land mining, in stream mining and fossil fuels.

2) Adding RAP in a concrete design mix may decrease the compression strength. All combinations of replacing coarse, fine or a combination of both aggregates with RAP show a relationship of decreasing compressive strength. Exact percentage variance needs to be tested.
3) Tensile strength parameter effects are inconclusive when adding or replacing aggregate with RAP in a concrete design mix. Varying results on past research concluded both an increase and decrease depending on the research. Tensile strength parameters need to be tested for each design mix.
4) Adding or replacing RAP in a concrete mix may potentially increase durability, flexibility and toughness. This increases the ability a material has of absorbing energy and deforming without fracturing, which is what currently lacks in concrete.
5) Adding PVA fibers in addition to replacing the coarse aggregate with RAP in a HSPCC may increase tensile strength and durability.
6) The effects on compression and tensile strength parameters with regard to geographic location properties in concrete mix design have yet to be studied.

CHAPTER 3 – HARVEST LOCATION AND GRADATION

3.0 INTRODUCTION

The main objectives discussed in this chapter are:

1) Determine the variability in the compressive strength between RAP concrete utilizing gradated RAP versus non-gradated.
2) Determine the variability in the compressive strength of RAP HSPCC utilizing gradated RAP from five different harvest locations around the State of Idaho.

Past research did not account for the possible variance of geographical specific location properties of the RAP. Therefore, the first stage of this research is to examine if location properties affect the compression strength of the RAP being replaced in the HSPCC. RAP is harvested from five separate Idaho locations; Bear Lake, Boise, Coeur d'Alene, Dubois, Pocatello and Wilder. The RAP is sieved, gradated, and then the RAP concrete mixture is tested for compression strength. RAP for each harvest location is set at 35% replacement for coarse aggregate. Road type, traffic counts, precipitation, temperature and snow pack for each location is analyzed and compared to the compression strength results.

Additionally, previous research did not account for the possible variance in compression strength when sieving and gradating the RAP versus not sieving and gradating the RAP being replaced in HSPCC. Therefore, further research is performed comparing the compression strength of the concrete using Pocatello and Wilder harvest locations. Each harvest location obtained 2 batches of concrete; one with RAP sieved, one without RAP sieved. RAP for this portion of research is replaced at 35% replacement for coarse aggregate.

The coarse aggregate in the control batch is sieved, gradated, and weighed according to ASTM Standard D6913, "Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis". Therefore; for the RAP for each harvest location for both the sieve testing portion of this research as well as the geographical location properties is replaced at the same weight by volume per sieve matching the control batch appropriately. The batches of concrete made at 35% RAP replacement to large aggregate are tested for compression strength using identical tests as the percentage batches; ASTM C39/C39M-12, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens" (ASTM, 2012). These tests determine if geographical location parameters or sieving the RAP change the compression strength in the HSPCC concrete.

3.1 METHODOLOGY

Because it has been shown in research conducted by Limbachiya, Berry, McGarrah, Murshed and Delwar that RAP as a concrete additive potentially decreases the compressive strength, a high strength concrete mix is used to combat the adverse effects (Limbachiya et al., 2000; Berry et al., 2012; McGarrah, 2007; Murshed et al., 1997; Delwar et al, 1997). The following sections discuss the design mix and testing methods used on the sieve gradation analysis as well as the harvest locations.

3.1.1 MIX DESIGN

The study control mix design is a high strength concrete design intended to break at 7,000 psi or greater. Due to the high strength design mix used, the mix consistency is stiff and often unmanageable; therefore a super plasticizer is utilized in order to achieve the necessary workability for reliable results. Both coarse and fine aggregate is used from local suppliers as well as Type II Portland Cement and Type “F” fly ash. These components are chosen in order to replicate a more widely used design mix. Design mix details are shown in Table 1. Appendix B shows a detailed breakdown of the mix details used for each batch.

Table 1. Control Design Mix

Design Mix Pocatello Ready Mix Used for ITD Overlay High Strength Mix 8000 psi INITIAL DESIGN MIX								
	Ingredients for 0.35 cf				Ingredients for 0.49 cf			
	5 Qty Small 4x8 Cylinders				3 Qty Large 6x12 Cylinders			
Type II Cement	8.28	lbs	3756	grams	11.6	lbs	5262	grams
Type F Fly Ash	1.46	lbs	662	grams	2.04	lbs	925	grams
Fine Agg	15.4	lbs	6985	grams	21.56	lbs	9779	grams
Course Agg	23.27	lbs	10555	grams	32.6	lbs	14787	grams
Super Gilinium Plasticizer	0.78	oz	0.78	oz	1.1	oz	1.1	oz
Water	3.57	lbs	1619	grams	5	lbs	2268	grams

The coarse aggregate replacement weight by volume is calculated from the control batch. Each location’s mix design coarse aggregate and RAP is calculated at a 35% replacement. The RAP from each harvest location replaces the coarse aggregate in the HSPCC mix. The batch design mix details used for each harvest location are found in Table 2.

Table 2. Design Mix for 35% RAP Replacement Design Mix

Design Mix for 35% RAP REPLACEMENT								
	Ingredients for 0.35 cf 5 Qty Small 4x8 Cylinders				3 Qty Large 6x12 Cylinders			
Cement	8.28	lbs	3756	grams	11.6	lbs	5262	grams
Fly Ash	1.46	lbs	662	grams	2.04	lbs	925	grams
Fine Agg	15.4	lbs	6985	grams	21.56	lbs	9779	grams
Coarse Agg	15.1255	lbs	6861	grams	21.19	lbs	9612	grams
Rap Total 35%	8.1445	lbs	3694	grams	11.41	lbs	5175	grams
Super Plasticizer	0.78	oz	0.78	oz	1.1	oz	1.1	oz
Water	3.57	lbs	1619	grams	5	lbs	2268	grams

The coarse aggregate total is separated into weight by volume per sieve for each batch tested. The coarse aggregate breakdown can be found in Table 3.

Table 3. 35% RAP Breakdown by Sieve Size

35% RAP Break Down by Sieve				
Sieve Size	5 Qty Small 4x8 Cylinders		3 Qty Large 6x12 Cylinders	
3/4"	362	grams	507	grams
5/8"	813	grams	1139	grams
1/2"	805	grams	1128	grams
3/8"	1034	grams	1449	grams
Pan	695	grams	973	grams

3.1.2 HARVEST LOCATION AND GRADATION

For the RAP harvest location variability study, RAP is collected from six locations throughout the State of Idaho: Bear Lake, Boise, Coeur d'Alene, Dubois, Pocatello and Wilder (see Figure 7). The RAP is sieved and gradated to match the gradation of the coarse aggregate used in the control mix. RAP and coarse aggregate for each harvest location is replaced at a 35% ratio of RAP to coarse aggregate by weight in the HSPCC mix. After a 28 day water bath cure, compression tests are administered. The data from the testing is collected and compared to topographical information for each location such as elevation, temperature, snow pack, traffic counts and road type for each harvest location. The lab tests and analysis for this research is performed in the Materials Laboratory at Idaho State University, Pocatello, Idaho.

Two harvest location RAP samples are chosen to be tested for the gradated RAP versus non-gradated RAP as well as testing variance in the size and quality of RAP; Wilder and Pocatello Idaho.

3.1.3 TESTING METHODS

The RAP and coarse aggregate are gradated according to ASTM D6913, "Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis" (ASTM, 2012). The concrete mixes are prepared and compacted in 4" diameter by x 8" high cylinder molds for compression testing according to ASTM C192-90, "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory" (ASTM, 2012). Five 4" x 8" cylinders are made for each harvest location batch of concrete tested. The samples are cured for 28 days in a water bath storage container according to design standard ASTM C511-09 "Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes" and then tested according to ASTM C39/C39M-12, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens" (ASTM, 2012).

A sieve analysis of the RAP is completed according to AASHTO Standard T-27 "Sieve Analysis of Fine and Coarse Aggregates" and ASTM D6913 "Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis" (ASTM, 2012).

3.2 RESULTS AND DISCUSSION

3.2.1 SIEVED VERSUS NOT-SIEVED

The RAP harvesting techniques and storage varies from location to location and therefore not all RAP from each location provides consistent results. Maintaining consistent results is necessary to provide quality controlled concrete products. RAP can vary greatly in size due to harvesting techniques alone. Figure 1 shows the large variability that can occur due to different harvesting techniques.

Figure 1. RAP Size Variability Due to Harvest Method

Each harvest location is sieved and gradated having the same mass amount tested set forth by the testing methods laid out in Section 3.1.2 of this report. Table 4 shows the results of the sieve gradation analysis.

Table 4. Pocatello and Wilder Harvest Location Sieve Gradation Results

	Pocatello	Wilder
Sieve Size mm (in.)	**Individual Mass Retained, g (IMR)**	
16.0 (5/8)	87	16
12.5 (1/2)	95	131
9.5 (3/8)	241	232
4.75 (No. 4)	577	563
Sum Coarse	**1000**	**942**
2.0 (No. 10)	380	390
0.425 (No. 40)	165	200
0.210 (No. 80)	9	14
No. 100	2	2
Pan	>1	1
Sum Fine	**556**	**607**

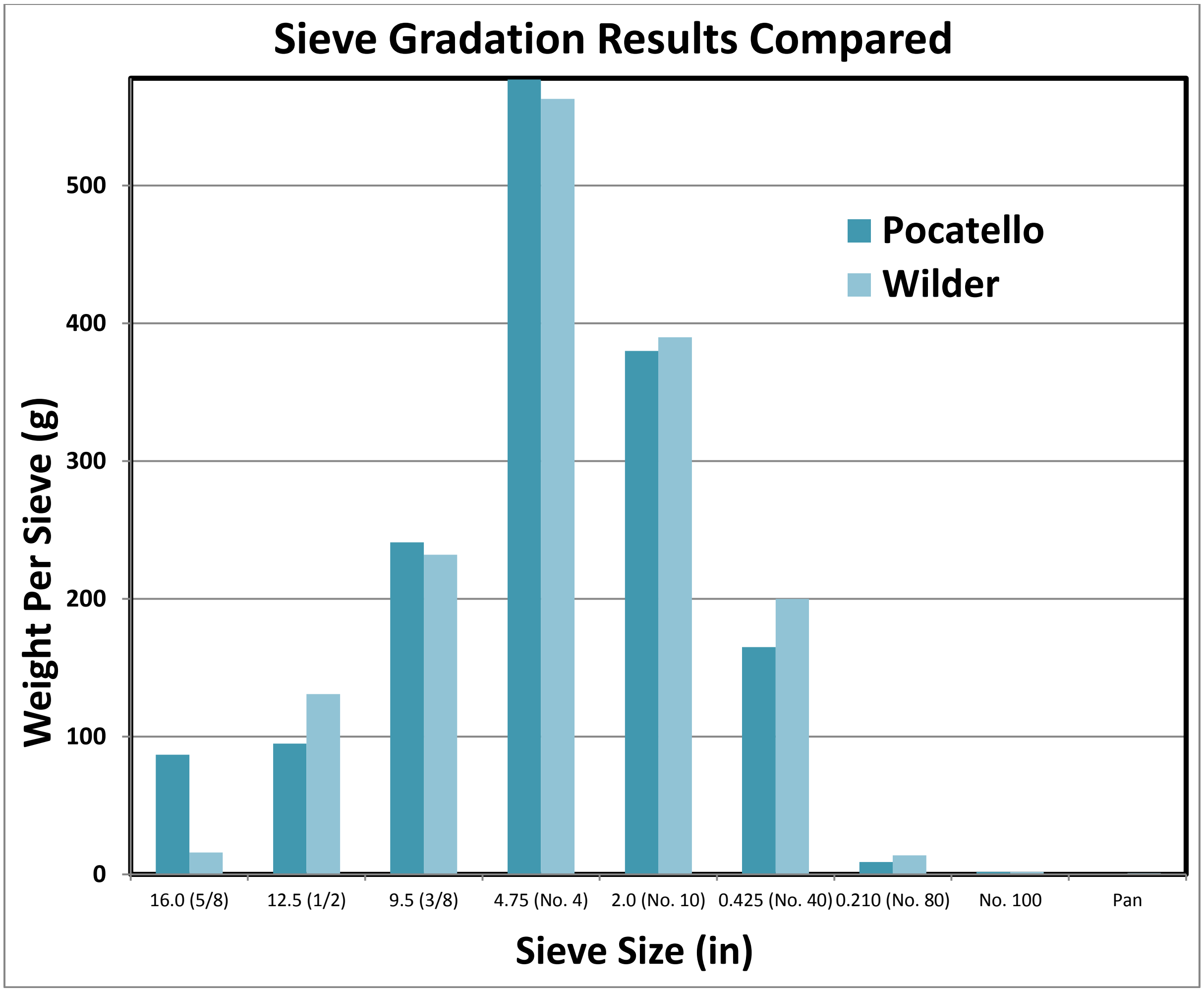

Figure 2. Sieve Gradation Results Compared

Table 4 shows that the sieve analysis does vary, but only by 8.4%. This is partially due to the fact that part of the process of AASHTO T-27 standard is to heat and dry the sample before sieving. As it is heated the asphalt that once held smaller chunks of aggregate together has relaxed and is no longer holding it as one chunk. Additionally, the aggregate that contains large amounts of asphalt coating is thinned during that process as well. The sieve analysis results are shown and compared graphically in Figure 2. As shown so far, RAP can vary greatly in size due to harvesting techniques. However, after processing the RAP to the gradation standards required, the study yielded close results. Therefore, it is shown that all RAP be processed according to AASHTO T-27 or ASTM

D6913 and checked to standard on the RAP being replaced as this provides consistent results.

Compression strength test results on the HSPCC of gradated versus non-gradated using RAP as coarse aggregate replacement are recorded and shown Table 5. The results show that there is no conclusive pattern in the compression strength when using the RAP after the sieve gradation is complete versus not performing the sieve gradation.

Table 5. Sieved and Gradated vs. Not Sieved and Gradated. Compressive Strength for 35% RAP Replacement in HSPCC Mix

RAP HARVEST LOCATION	COMPRESSIVE STRENGTH (PSI) / STD DEV (PSI)	
	GRADATED	NON GRADATED
Pocatello	3966 / 411	4265 / 903
Wilder	5598 / 364	4977 / 586

The results of the compression tests shown in Table 5 demonstrates that there is a difference in compressive strength if the RAP is sieved and gradated versus not sieved and gradated. However, based on the fact that one gradated sample is a lower compressive strength than the non-gradated and for the other sample the inverse is true, no direct conclusion about the effect of gradation on compressive strength can be made. The standard deviation is shown in Table 5 identifying the reduction in the standard deviation for the sieved and gradated replacement RAP. Figure 3 compression strength specimen breaks for Wilder Idaho. The samples are shown side by side for comparison; sieved showing on the left, non-sieved on the right. As shown in the figure, there is a large variability in the distribution and size of the RAP for each sample.

Figure 3. Sieved and Not Sieved RAP Compression Samples, Respectfully

The large variability of RAP distribution and the compression strength data results conclude that sieving the RAP and replacing it to match the same weight by volume to the control batch will yield the most consistent results.

3.2.2 HARVEST LOCATION

For the RAP harvest location variability study, RAP is collected from six locations throughout the State of Idaho: Bear Lake, Boise, Coeur d'Alene, Dubois, Pocatello and Wilder (see Figure 7). The RAP is sieved and gradated to match the gradation of the coarse aggregate used in the control mix. Additionally, RAP and coarse aggregate for each harvest location is also replaced at a 35% of RAP to coarse aggregate.

The 35% replacement RAP HSPCC samples for each of the six locations as well as the control batch are tested and the average measured compressive strengths are shown in Table 5 When sieving the Boise, Idaho harvest location, the RAP is so finely ground at harvesting that the entire RAP fell through the No. 100 sieve and therefore could not be gradated appropriately to replace the correct percentage of aggregate with the appropriate size of RAP. Figure 4 shows the sieve gradation results for Boise Idaho.

Figure 4. Results of Boise Gradation Sieve

Due to the harvest technique of the Boise RAP, the results were documented but not compared to the other RAP locations. The results of all the harvest locations are shown in Table 6 and Figure 5 shows a graphical representation of the information without including Boise.

Table 6. RAP Location Average Compression Strengths (psi) for a 35% RAP Replacement HSPCC Mix

IDAHO LOCATION	COMPRESSIVE STRENGTH AVERAGE (PSI)	STANDARD DEVIATION (PSI)
CONTROL	7041	302
BOISE	5743	132
COEUR D'ALENE	4337	702
BEAR LAKE	4357	371
POCATELLO	3966	411
WILDER	5598	364
DUBOIS	4325	220
AVERAGE	*5053*	*357*

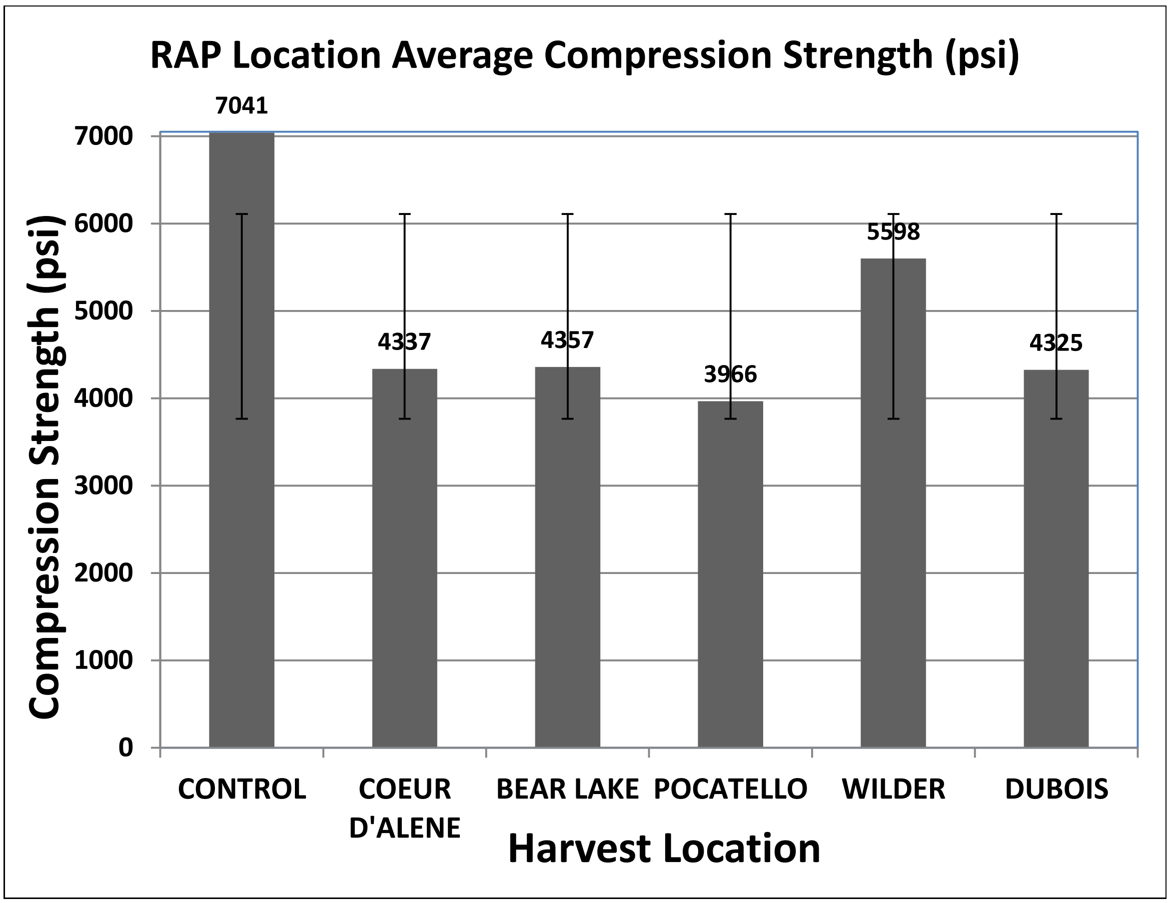

Figure 5. RAP Location Compression Strength Results

The results from Table 6, minus Boise Idaho, are shown Figure 5. Figure 5 shows compression specimen's results from each harvest location in graphical format. As shown by using a gradated RAP in the HSPCC, the variability that occurs from different harvesting techniques can by decreased by gradating and replacing the RAP at the same percentage replacement as the control mix. This yields a lower standard deviation than that of those not sieved and gradated. Figure 6 shows the typical breaks from the harvest locations. Typically, all breaks show that the concrete is well mixed and the RAP is appropriately dispersed throughout the concrete mix. The breaks also show that for each location, the failure occurs through the course aggregate as well as the RAP. This indicates the bond between RAP and cement is secure and acting like virgin aggregate would. These failure modes show the concrete mix is acting stable in compression utilizing the entirety of the strength capacity of the course aggregate as well as the cement. The RAP offers a weak point for cracking to start developing; this is combated with a higher strength cement and fly ash. Ultimately the compression sample failure modes perform well under testing. Overall, the specimen failure modes show respectable compression failure with a range of Typical Modes Failure of B, C and D. This shows a good distribution of the force applied during testing, the course aggregate and cement bond held strong allowing all material components to react to the compression force applied. Concrete is stronger and more durable when all properties of the concrete are able to react to the force applied. Figure 6 shows a standard failure mode for each of the corresponding harvest locations.

Figure 6. Location Concrete Specimens Showing Break and Aggregate (Boise, Coeur d'Alene, Bear Lake, Pocatello, Wilder, Dubois) (left to right, top to bottom)

Exploring geographical location parameter differences for harvest locations, this study performs a closer look on the impact traffic of the compressive strength of concrete when using RAP as a coarse aggregate replacement in HSPCC. Figure 7 shows a state map of Idaho identifying the RAP harvest locations (ITD, 2010). The pink stars represent the traffic counts for that exact geographic location while the green circle indicates the tested compressive strength results shown in Figure 6 for each location. As shown in Figure 7, there is a correlation between the traffic counts and the compressive strength; the higher the traffic counts the lower the compressive strength. This can be attributed to several factors: 1) over time and increased traffic duress, the material properties in the RAP break down, 2) roadway traffic weight, vibration and heat cause the modulus of elasticity of the RAP to decrease making the concrete less ductile, therefore increasing its brittleness and ultimately decreasing its capacity.

RAP is collected from two different types of roadways that are maintained by the Idaho Transportation Department. Three RAP harvest locations are from an Interstate and three RAP harvest locations are from a State Highway. The compression strength from each road type is compared and the results are shown in Table 7. Harvest Location Compression Strength Results. These results are plotted showing the increase and decrease of each harvest location and the type of road the RAP is collected from (shown in Figure 8. Interstate and State Highway RAP Concrete Compressive Strength Comparison (psi)

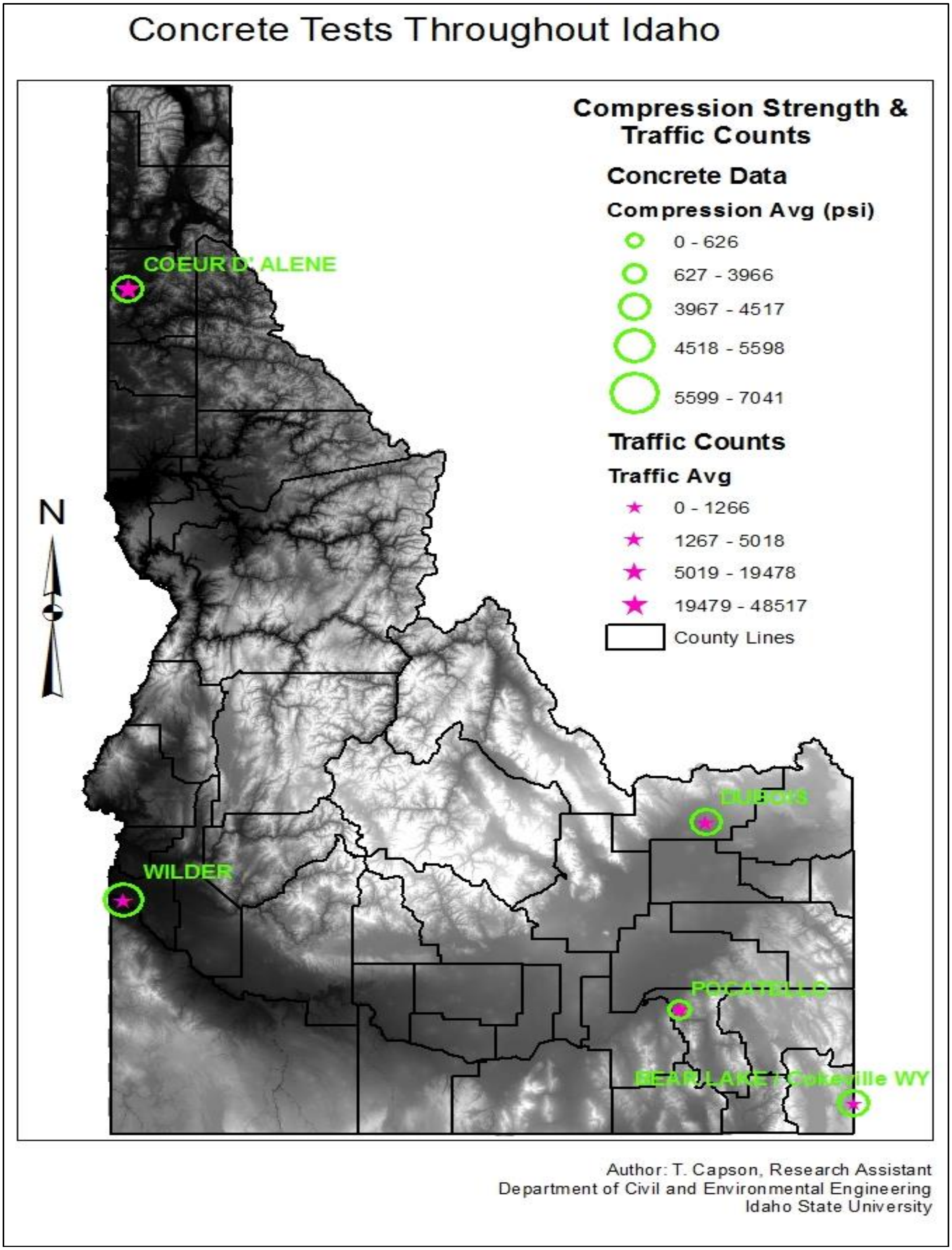

Figure 7. RAP Harvest Locations with Corresponding Average Compression Strengths (psi) for a 35% RAP Replacement HSPCC Mix and Traffic Counts

Table 7. Harvest Location Compression Strength Results

HARVEST NAME	LOCATION	ROAD TYPE	MILLED DATE	TIME IN STORAGE (YEARS)	TIME IN SERVICE (YRS)	AVG COMPRESSION STRENGTH (PSI)
COEUR D' ALENE	I-80	INTERSTATE	2009	3	8	4337
POCATELLO	I-15	INTERSTATE	2009	3	15	3966
DUBOIS	I-15	INTERSTATE	2012	0	17	4325
WILDER	US-95	HIGHWAY	2012	0	16	5598
BEAR LAKE	US-189	HIGHWAY	2012	0	16	4357
BOISE	US-95	HIGHWAY	2012	0	6	5743

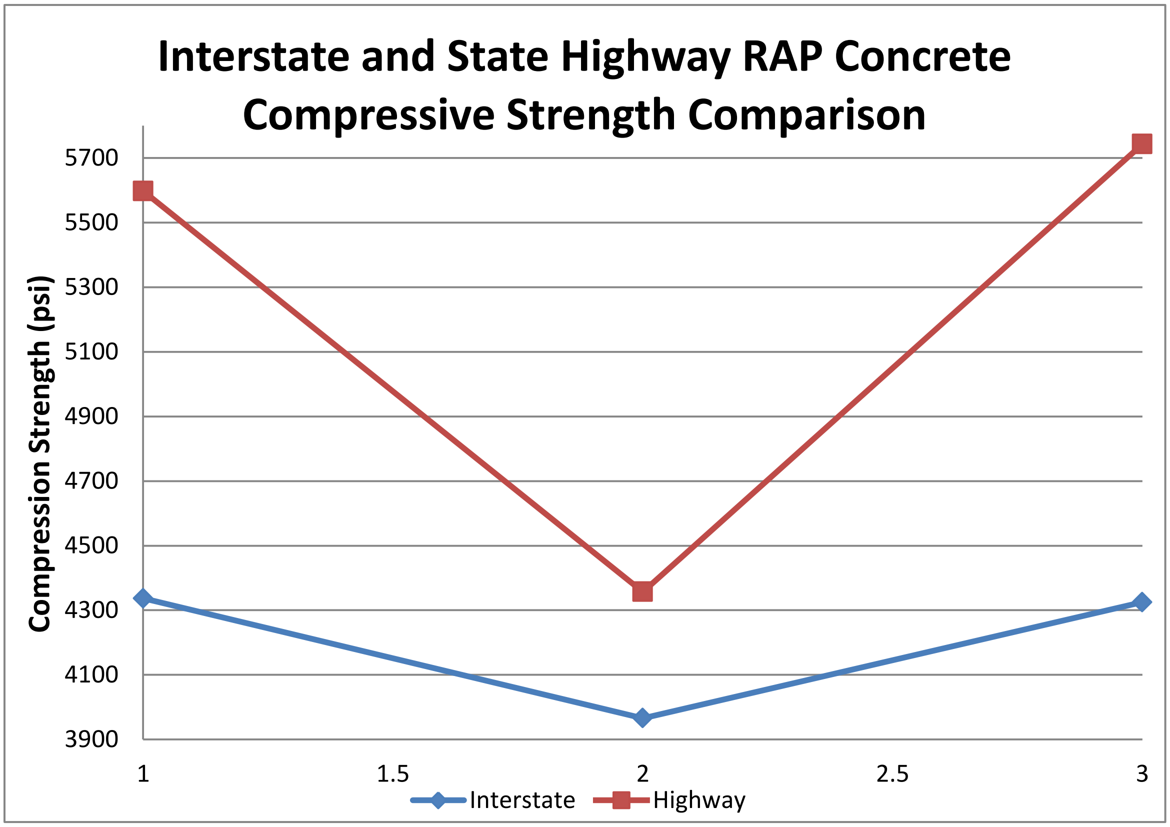

Figure 8. Interstate and State Highway RAP Concrete Compressive Strength Comparison (psi)

Table 7 and Figure 8 show that the State Highway RAP yields a higher compressive strength than the Interstate RAP. These results can be attributed to the quality of asphalt used and the amount of traffic seen for each road type. According to the Idaho Transportation Department, the specifications for roadway asphalt must be a higher quality for the interstates than that for the state highways; however interstates get considerably more traffic than do state highways as shown in Figure 7. It is also possible the better quality asphalt does not necessarily have a direct impact on the compression strength of the HSPCC due to the fact that compression strength comes predominately from the aggregate in the concrete mix, not the asphalt. This data supports the traffic count and compression strength relationship results. Additionally, the strength of the compression is not supported from the asphalt of the RAP, but the aggregate in the RAP. The traffic breaks down the aggregate in the road even though the asphalt is of higher quality.

Table 8. Snow Pack, Temperature, Elevation, Annual Precipitation and Corresponding Compression Strength Harvest Location Results

	Avg Compression Strength (psi)	Avg Jan. (deg)	Avg July (deg)	Elevation (ft)	Annual Precipitation (in)	Snow Pack (in)
COEUR D' ALENE	4337	20-30	70-80	2188	25	29.6
POCATELLO	3966	10-20	70-80	4462	13	66.4
DUBOIS	4325	10-20	70-80	5148	13	36.9
WILDER	5598	20-30	80-90	2428	11	19.2
BEAR LAKE	4357	10-20	70-80	5925	21	53.9

Table 8 shows the snow pack, average temperature, elevation and annual precipitation results for each location and the corresponding compressive strength (IDWR, 2014). Snow pack for each geographic location is collected and compared to the compressive strength tests.

As shown, the compressive strength for Wilder, Idaho exhibited the strongest compressive strength results of 5598 psi having the lowest snow pack of 19.2 inches; contrary the Pocatello Idaho location shows the least compression strength of 3966 psi with the largest snow pack of 66.4 inches. However, the harvest locations Bear Lake, Dubois and Coeur D'Alene Idaho show variable snow pack amounts with corresponding variable compression strengths. This contradicts the trend set forth in the Wilder and Pocatello locations with the largest locations yielding the smallest compression strength. Therefore, no direct conclusion can be correlated between the snow pack for each location and the compression strength.

July temperatures can be categorized in two categories; 70–80 and 80–90 degrees. All harvest locations except Wilder, Idaho fit in the 70-80 category. The compression strength varies from 3966 to 4357 psi in that category with wilder having compression strength of 5598 psi. January temperatures can be categorized in two categories; 10-20 and 20-30 degrees. Pocatello, Dubois and Bear Lake Idaho fall in the 20-30 degree category while Coeur D'Alene and Wilder fall in the 20-30 degree category. Each category contains a large variance of compression strength therefore no direct conclusion can be construed on temperature directly affecting the compression strength of concrete.

Elevation for each harvest location is listed in Table 8. The resulting strongest compressive strength shown from the Wilder is at the mid to lowest elevation of all the harvest locations. The next highest compression strength comes from the highest elevation harvest location. There is no direct conclusion in the compressive strength results correlating the elevation to the compressive strength. Lastly, the annual precipitation for each location shows the corresponding compressive strengths are variable in the strength with regards to the total annual precipitation for each location. Coeur D'Alene has the most annual precipitation of 25 inches with a corresponding compressive strength of 4337 psi. Second to the most annual precipitation is 21 psi with corresponding compression strength of 4357 psi is at Bear Lake harvest location. The lowest annual precipitation is at the Wilder location with a compressive strength of 5598 psi. The remaining Pocatello and Dubois harvest locations have an annual precipitation of 13 inches with compression strength of 3966 and 4325 psi, respectively. No direct correlation can be made on the compressive strength of the RAP in HSPCC and elevation the RAP is collected.

3.3 SUMMARY OF CONCLUSIONS

As shown in Section 3.2, sieving, gradating and replacing the RAP at the same percentage as the design mix eliminates the variability found from different harvest locations and differential harvesting techniques. Data is inconclusive if gradating RAP increased or decreased the compressive strength of the HSPCC but lowered the standard deviation. Further testing will need to be performed in order to adequately prove the conclusion of the influence if sieving and grading RAP increases or decreases the compression strength of the HSPCC.

Traffic counts in regards to geographic location do have an effect on the compression strength of the HSPCC. As the traffic counts increase, the compression strength of the HSPCC decreases. Temperature, elevation, annual precipitation and snow pack do not have an effect on the compression strength; however, the type of road impacted the compression strength of the HSPCC. State Highway RAP yielded a stronger HSPCC, while the Interstate RAP yielded weaker compression strength in HSPCC. Theoretically, this is due to the breakdown of the aggregate in the asphalt; however further testing will need to be done in order to conclude the results. Geographic location parameter testing in other states and countries should be done in order to concur with these results.

Therefore, it is recommended to use sieved and gradated RAP from a highway as a RAP replacement in HSPCC.

CHAPTER 4 - RECYCLED ASPHALT PAVEMENT PERCENTAGE

4.0 INTRODUCTION

The main objective in this chapter is:

- Determine the variability in the compressive strength of RAP concrete utilizing varying replacement percentages of RAP for the coarse aggregate.

This chapter discusses the variability in compression and tensile strength relative to the percentage of Recycled Asphalt Pavement (RAP) replaced in the High Strength Portland Cement Concrete (HSPCC). The purpose is to gauge exactly and to what extent mixing certain ratios of RAP and HSPCC will increase or decrease the strength parameters of this new RAP high strength concrete mix and to identify which ratio is optimal for the strongest compression and tensile strength.

In order to address the disadvantages and to improve the results from previous research discussed in Chapter 2, testing is performed on compression and tensile strength results using a HSPCC mix replacing large aggregate with a percentage of RAP by weight. Six sample batches of HSPCC with varying percentage of RAP replacement of the coarse aggregate are prepared and tested. The first batch starts at 25% RAP replacement of large aggregate, increasing in 5% increments, until 50% RAP to large aggregate replacement is met. Additionally, a control batch with no RAP replacement is prepared to use for comparison for a total of seven separate concrete mix batches. Research on the compression and tension strength parameters of HSPCC with percentages of RAP replacement are documented in this chapter.

In order to study the objective set forth in this chapter, analysis is performed on concrete samples for compression and tensile strength are constructed and tested in the Materials Laboratory at Idaho State University.

4.1 METHODOLOGY

The study results tie into the research conducted and presented in this paper linking the study of replacing coarse aggregate with a greener option with hope for a structural strength concrete while utilizing an economic replacement for the aggregate. A study performed in 2012 closely resembles this research but uses Fractionated Recycled Asphalt Pavement (FRAP) (Brand *et al*., 2012). The differences in FRAP versus RAP is that RAP is not washed and cleaned, therefore can be utilized directly from the plant without further cleaning process; thus saving more natural resources and increasing the green aspect of using RAP instead of FRAP. Both studies process the RAP so that the size of the coarse aggregate replacement is consistent, however the design mixes are different and results are also different. Table 9 shows the difference in the two mix designs. The Illinois Center for Transportation design mix will be referred to as Mix 1 and the design mix used in this study is referred to as Study Design Mix (Brand *et al*., 2012).

Table 9. Design Mix Differences

MATERIAL	MIX 1	STUDY DESIGN MIX
PORTLAND CEMENT TYPE	TYPE 1	TYPE 2
COARSE AGGREGATE REPLACEMENT	YES	YES
FINE AGGREGATE REPLACEMENT	NO	NO
FLYASH CLASSIFICATION	CLASS C	CLASS F
RECYCLED ASPHALT PAVEMENT (RAP)	WASHED	NOT WASHED
PVA FIBER ADDITIVE	NO	YES
PLASTICIZER ADDITIVE		SUPER GILINIUM

As shown in Chapter 3, sieving the RAP into the appropriate gradations directly affects the strength of the concrete and in order to control the outcome of the concrete mix, sieve gradations must be performed and replaced at the appropriate percentage to match the coarse aggregate the RAP is replacing. The exact percentages of the large aggregate from the control batch are matched when preparing each sample batch set forth in this chapter.

4.1.1 MIX DESIGN

All percentage batches prepared and tested are made with RAP collected from the Idaho Transportation Department District 5 Office in Pocatello, Idaho. Due to the high strength design mix used, Super Gilineum 1481 plasticizer is used in order to achieve necessary workability. Coarse and fine aggregate from local suppliers is also used. Type II Portland cement and Type "F" fly ash is used in order to replicate a more widely used design mix. A no air entrained design mix is used, however air from the mixer used is calculated into the design mix. Design control mix details can be found in Table 10 and Table 11. The control mix is used to calculate RAP percentage replacements starting at 25%, increasing in 5% increments, ending with 50% coarse aggregate replacement totaling 7 batches including the control batch. Table 10 and Table 11 outlines the design mix details used for 0.35 and 0.49 cubic foot of concrete, respectfully. Table 12 and Table 13 show detail information on the sieve breakdown for the 0.35 and 0.49 cubic foot mixes, respectfully.

Table 10. Design Mix Compression Details

Design Mix Pocatello Ready Mix Used for ITD Overlay High Strength Mix 8000 psi						
	Ingredients for 0.35 cf 5 Qty Small 4x8 Cylinders					
Cement	**8.28**	**lbs**	**3756**	**grams**		
Fly Ash	**1.46**	**lbs**	**662**	**grams**		
Fine Agg	**15.4**	**lbs**	**6985**	**grams**		
Coarse Agg	**23.27**	**lbs**	**10555**	**grams**		
Super Plasticizer	**0.78**	**oz**	**0.78**	**oz**		
Water	**3.57**	**lbs**	**1619**	**grams**		

Table 11. Control Design Mix Tensile Details

Design Mix Pocatello Ready Mix Used for ITD Overlay High Strength Mix 8000 psi				
	Ingredients for 0.49 cf 3 Qty Large 6x12 Cylinders			
Cement	**11.6**	**lbs**	**5262**	**grams**
Fly Ash	**2.04**	**lbs**	**925**	**grams**
Fine Agg	**21.56**	**lbs**	**9779**	**grams**
Coarse Agg	**32.6**	**lbs**	**14787**	**grams**
Super Plasticizer	**1.1**	**oz**	**1.1**	**oz**
Water	**5**	**lbs**	**2268**	**grams**

Table 12. Sieve Breakdown for Small Cylinder Batch

RAP Break Down by Sieve						
	5 Qty Small 4x8 Cylinders (grams)					
RAP %	**25**	**30**	35	40	45	50
3/4"	259	310	362	414	465	517
5/8"	581	697	813	929	1045	1161
1/2"	575	690	805	920	1035	1151
3/8"	739	887	1034	1182	1330	1478
Pan	496	595	695	794	893	992

Table 13. Sieve Breakdown for Large Cylinder Batch

RAP Break Down by Sieve						
	3 Qty Large 6x12 Cylinders (grams)					
RAP %	25	30	35	40	45	50
3/4"	362	435	507	580	652	725
5/8"	813	976	1139	1301	1464	1627
1/2"	806	967	1128	1289	1451	1612
3/8"	1035	1242	1449	1656	1863	2070
Pan	695	834	973	1112	1251	1390

4.1.2 TESTING METHODS

The RAP and coarse aggregate are gradated according to ASTM D6913, "Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis" (ASTM, 2012). The concrete mixes are prepared and compacted in 4" diameter by x 8" high cylinder molds for compression testing according to ASTM C192-90, "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory" (ASTM, 2012). Five 4" x 8" cylinders are made for each batch of concrete tested. The samples are cured for 28 days in a water bath storage container according to design standard ASTM C511-09 "Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes" and then tested according to ASTM C39/C39M-12, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens" and ASTM C496 / C496M – 11, "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens" (ACI, 2012).

Six sample batches of HSPCC with varying percentage of RAP replacement of the coarse aggregate are prepared and tested. The first batch starts at 25% RAP replacement and increases in 5% increments up to 50%. Additionally, a control batch with no RAP replacement is prepared for comparison. After curing, the samples are tested for both compression as well as tensile strength in a Gilson Concrete Testing Machine. Figure 9 shows the compression test setup on the left and the split cylinder test setup on the right.

Figure 9. Compression and Tensile Test

Each compression batch of concrete has a set of five (5) 4”x8” cylinders while the split cylinder tests have a set of three (3) 6”x12” cylinders. All batches are made by the same standards as set forth in Section 4.2 of this chapter, and are made in the same manner in the controlled environment of the Materials Laboratory at Idaho State University.

4.2 RESULTS AND DISCUSSION

Figure 10 shows a saw-cut sample cylinder with 35% RAP replacement for large aggregate. The cylinder is saw cut to better view the mix of virgin aggregate to RAP. The saw-cut also shows a good distribution of the RAP across the cross-section.

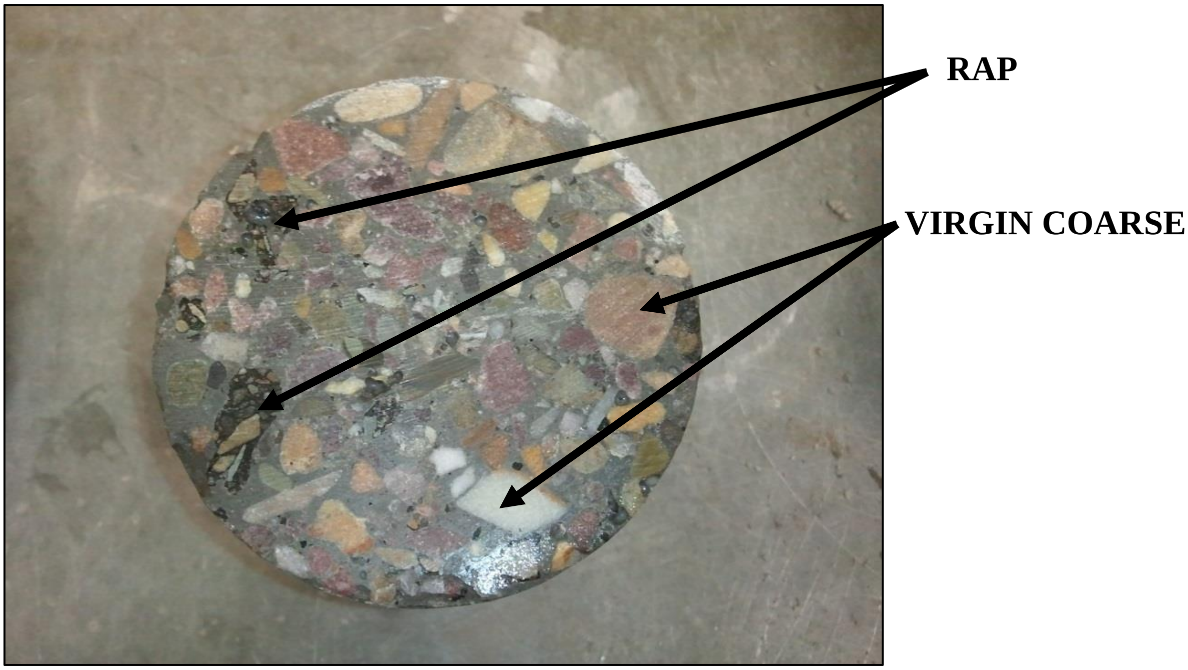

Figure 10. Cylinder Saw Cut Showing RAP and Aggregate

Data from the individual cylinders for the compression and split cylinder tests performed are shown in Table 14. The lab results from the 35% RAP replacement batch have a much lower compressive strength than anticipated after performing the percentage batches and comparing the results. This anomaly may be attributed to the fact that the 35% replacement mix is cast at a different time (the same time as the varying location study) than the other percentage replacement mixes. In order to either confirm or deny the low compression strength test results for the 35% RAP replacement percentage, a second batch of 35% RAP replacement batch is prepared and tested. The results of the second compression strength test for the 35% RAP replacement averaged compression strength is 3966 psi, decreasing the compression strength by 8% from the original batch. This is a small decrease is strength from the 1st batch, but confirms that the 35% batch compression strength results are in the range of 4000 psi. However, the compression strength test results still ranged the furthest from the linear regression line showing the greatest varying from the normal standard deviation of all the design mixes.

Table 14. Compression and Tensile Strength Individual Cylinder Results

POCATELLO RAP % BATCHES	Compression Strength Per Cylinder (psi)						% Reduced from Control	Split Tensile Strength Per Cylinder (psi)				% Reduced from Control
	1	2	3	4	5	**Avg**		1	2	3	**Avg**	
Control	6631	6722	7206	7317	7329	7041		540	611	587	579	
25	6334	5568	6067	6122	5925	6003	15%	510	549	520	526	5%
30	4869	6033	5436	5147	4970	5291	25%	630	647	607	628	-12%
35	4407	3208	3954	4031	4231	4505	36%	433	442	452	443	24%
40	3708	5222	5063	5391	4952	4867	31%	558	496	439	497	14%
45	4874	4746	4408	4882	4942	4770	32%	556	501	416	491	13%
50	4667	4671	3652	4936	4630	4511	36%	444	515	529	496	11%
35[2]	4260	3820	3810	3991	3950	3966	44%	-	-	-	-	-

The break type for each individual cylinder is recorded. The break type is then checked in correspondence with the strength of the concrete. The lower compression strength cylinder specimens may be caused by the failure starting at and around the RAP rather than regular aggregate. The RAP in the cylinder has coincidentally patterned a shear failure plane for the compression strength to act along causing a premature break. This is avoidable when using industrial machines ensuring an even mix of the concrete, therefore possibly increasing the overall compression and tensile strength of the design mix. Figure 11 shows the difference in break type on the 40% RAP replacement batch. The left hand picture shows a shear break with a compressive strength of 3708 psi and the right hand side picture shows a conical break with a compressive strength of 5391 psi.

Figure 11. RAP Samples Shear and Conical Breaks for 40% RAP

As expected from the results of previously published studies, the results from the laboratory tests show that the RAP inclusion does decrease the compressive strength in concrete mixes (Brand et al., 2012). However, by utilizing a HSPCC mix, a compressive strength of 4500 psi or greater is maintained with all RAP replacement percentages except for the first batch of 35% replacement percentage. This anomaly may be attributed to the fact that the 35% replacement mix is cast at a different time (the same time as the Harvest Location Study discussed in Chapter 3 of this study) than the other percentage replacement mixes.

If the results from Table 14 are plotted with the first 35% mix added as a point and the second 35% mix falling in the natural regression line of the other percentage data (See Figure 12. Average Compression & Tensile Strength (psi) for Various RAP Replacement Percentages), it shows that a negative linear relationship exists between the RAP replacement percentage and the average compressive strength exists. From the plot an equation can be developed which can be used to predict the compressive strength based on a proposed RAP replacement percentage. The linear equation developed is y = -

46.405x+6641.7, with a low R^2 value of 0.2763. This shows that the decrease in compressive strength is almost 50 psi for every percent of RAP added to the design mix.

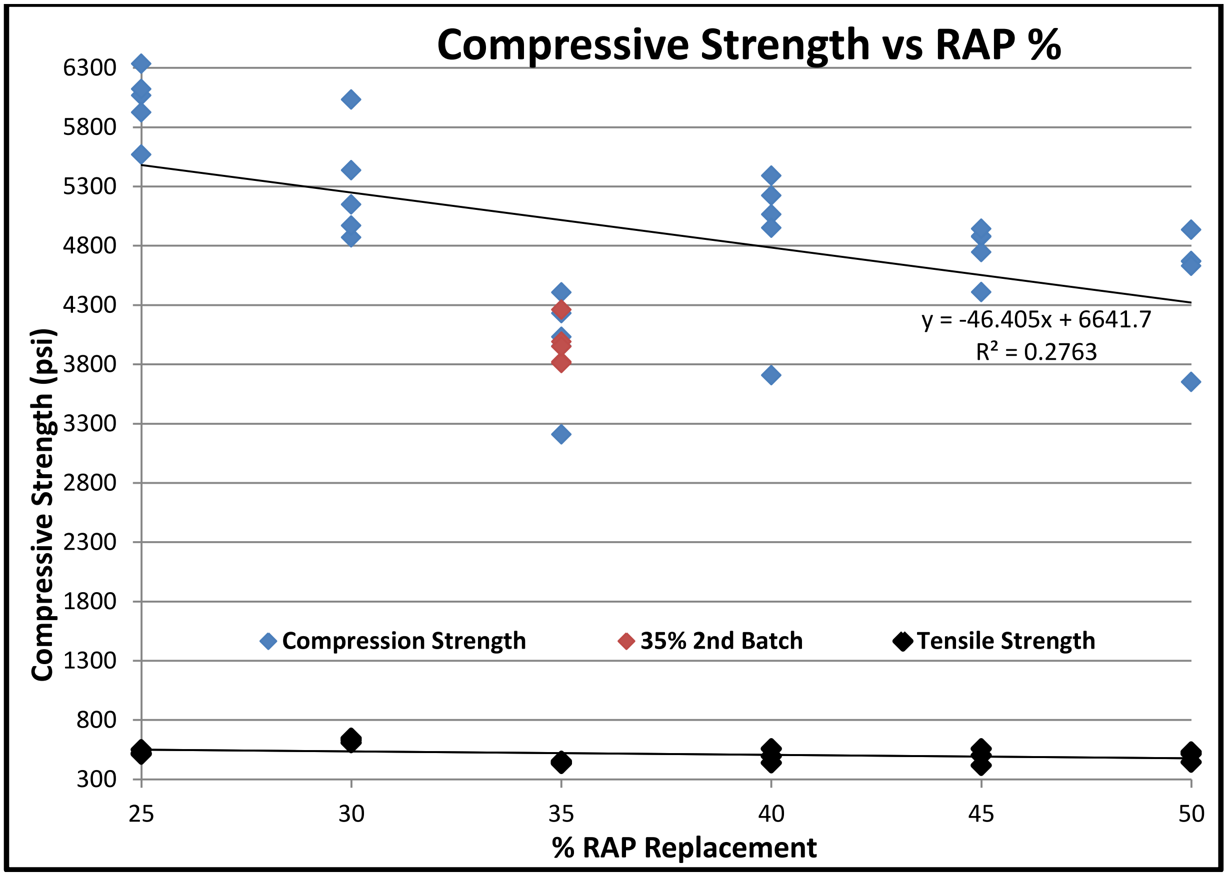

Figure 12. Average Compression & Tensile Strength (psi) for Various RAP Replacement Percentages

Figure 12 documents the second design mix including the 35% RAP replacement data. The 35% point is still the furthest off the trend line than data results from the other RAP replacement percentages. This shows that for reasons not yet understood, the 35% RAP replacement design mix is the greatest variation off the normal, exhibiting the weakest compression and tensile strength parameters than that of the other design mixes tested. Further testing needs to be performed in order to establish the foundation of source and cause producing the lower compression strength. Additional studies are necessary to determine if this is in fact the case or if for some reason a 35% replacement mix behaves differently.

Taking the theory that the 35% mix behaves differently than the other mixes for reasons unknown at this point, the data without 35% RAP test results are plotted and shown in Figure 13. This graph shows the results without any results of the 35% RAP replacement as coarse aggregate. The best fit linear equation line fits better with an R^2 value of 0.5666 and an equation of y = 53.74x + 7130.7.

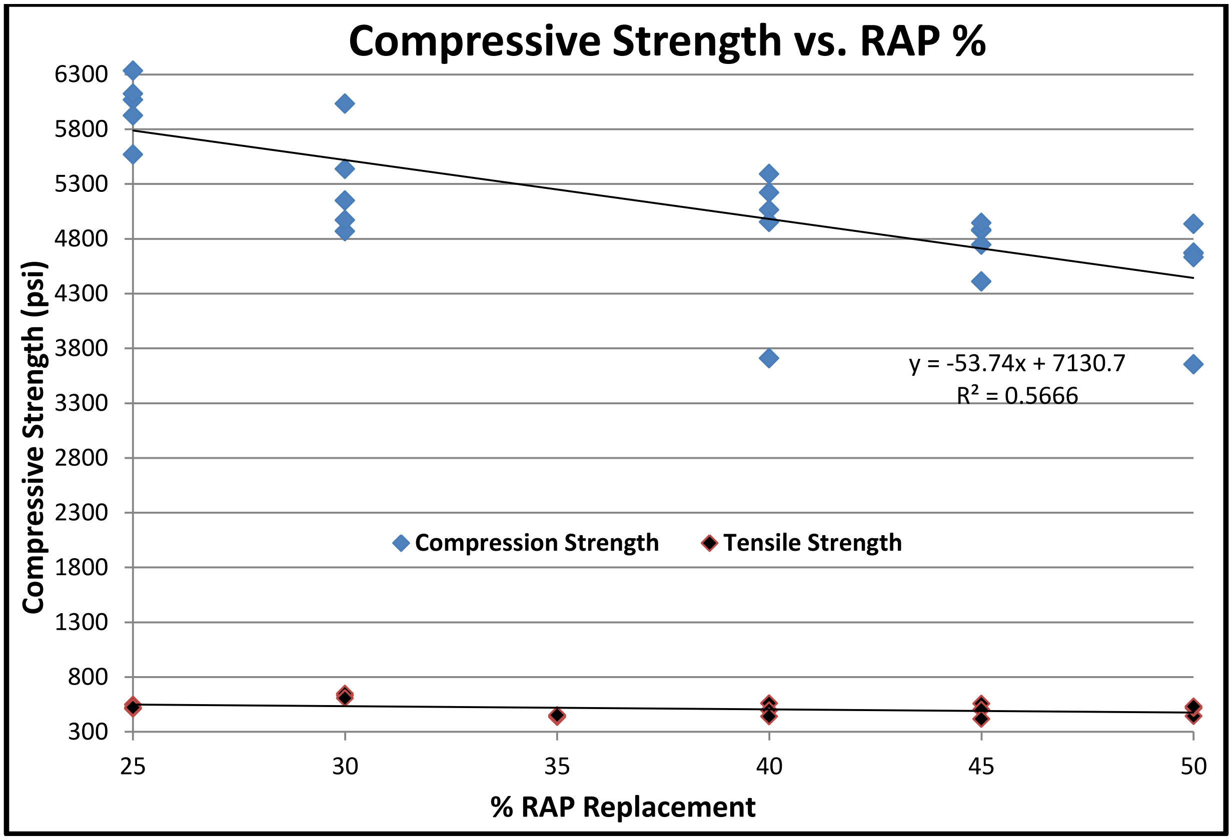

Figure 13. Average Compression & Tensile Strength (psi) for Various RAP Replacement Percentages – Excluding 35%

Despite this one anomaly, the fact that by using a HSPCC mix, a fifty percent RAP replacement for coarse aggregate can be done and still achieve a compressive strength of 4500 psi, demonstrates that a useable RAP concrete mix can be produced. From the tests results, no apparent direct correlation between the tensile strength results and the RAP percentage replacement exists. However, by comparing the RAP results to the control batch, it may be determined that utilizing the RAP as replacement does not adversely affect the tensile capacity of the concrete.

4.3 SUMMARY OF CONCLUSIONS

This chapter concludes that a method for producing useable compressive strength concrete that utilizes RAP as a percentage replacement for coarse aggregate in HSPCC has been provided in this study. Results conclude that it is feasible to have a greener mix design of concrete using RAP as a replacement of coarse aggregate while maintaining strength in concrete that is strong enough to be utilized in structural applications.

Sieving the RAP into the appropriate gradations directly affects the strength of the concrete and in order to control the outcome of the concrete mix, sieve gradations must be performed and replaced at the appropriate percentage to match the coarse aggregate the RAP is replacing.

The compression strength parameters for the RAP replacement percentage follows a linear regression line with the equation equal to $y = -46.405x + 6641.7$. The R^2value is 0.2763 including 35% RAP coarse aggregate replacement and an equation of $y = 53.74x + 7130.7$ with the best fit linear equation line having an R^2 value of 0.5666 without 35% replacement. For all RAP replacements tested, these equations show direct correlation with the decrease in compression strength with the RAP replacement percentage yields a design mix that enables re-creation and utilization as green engineering demands increase. This also allows mix designers to carry out cost/benefit analysis of utilizing RAP in their designs and to leverage that against green design requirements.

Further studies need to be conducted in replacing the fine aggregate with RAP as well as replacing a mixture of both the fine and coarse aggregate of RAP and the percentage associated with that. In addition, percentages with mixtures must be considered with further research evaluated on mix and design when using RAP as a replacement in all types of concrete, not just HSPCC.

Finally, while this study showed that it is possible to produce structural viable RAP in HSPCC; further study needs to be conducted on the durability and long term performance of these mixes.

CHAPTER 5 - POLYVINYL ALCOHOL (PVA) FIBER ADDITIVE

5.0 INTRODUCTION

The objective of this chapter is:

- Determine the variability of strength parameter in both compression and tension of a RAP HSPCC Mix with the addition of Polyvinyl Alcohol (PVA) Fibers.

This chapter presents the results of a feasibility study to determine the material behavior when utilizing RAP in a HSPCC mix by replacing a portion of the coarse aggregate by both weight and gradation for RAP and by including PVA in the mix matrix. In order to test this objective, two separate mix designs are prepared and tested in order to assess the effects and variance of strength parameters using PVA fibers as an additive while also replacing the coarse aggregate of the HSPCC concrete mix with a percentage RAP. The Pocatello RAP is used in all PVA added mix designs. Samples with various RAP coarse aggregate replacement percentages of 25%, 50% and 75% as well as PVA fibers are created and tested to determine their compressive and tensile strengths. These results are compared to previously studied mixes with the same RAP replacement percentages but without the PVA fibers. Section 5.3 outlines the results concluded from this data of this report.

5.1 METHODOLOGY

PVA fibers are utilized in structural applications as a method for controlling plastic shrinkage, thermal cracking, and improving abrasion resistance of cementations materials. PVA fibers are known for their high tensile strength and modulus of elasticity. When used in the correct application, PVA fibers increase tensile strength and ductility. Figure 14 shows PVA fibers of both sizes tested in this variability study.

Figure 14. PVA 6mm (RECS7) and 8mm (RECS15) Fiber Size

5.1.1 MIX DESIGN

Chapter five's objective is to observe the effects of including PVA fibers into a RAP HSPCC mix. In order to observe the effect of including PVA fibers into a RAP HSPCC mix, two mix designs are tested using fiber as an additive.

The first PVA and RAP design mix is detailed out in Appendix A2. This mix uses a combination of two fibers to attain a 3% by volume addition of PVA fibers added to the HSPCC mix design. Half of the fibers added to the mix are NYCON-PVA RMS702 5 denier, monofilament PVA fibers, 6mm. The other half are NYCON-PVA RECS15 8 denier, monofilament PVA fibers, 8mm. A 1% increase in water content is added to the cement mix to increase workability (Skourup and Erdogmus, 2010).

Due to the mix being over stiff and unworkable from the fiber content, the water content is increased even more from the first batch to compensate for the unmanageability. The second PVA and RAP design mix is detailed out in Appendix A2. The water to cement ratio content is increased from 1% to 10% by volume. The second design mix added a 1% by volume PVA fiber mix compared to the first fiber design mix batch adding a 3% by volume replacement. Additionally, only the longer 8 mm fibers are used in this second mix compared to the first design mix of a 50/50 blend of 8 mm and 6 mm PVA fiber. The fibers added are NYCON-PVA RECS15 8 denier, monofilament PVA fibers, 8mm. Table 15 outlines the differences in the two fiber batches. The mix design that is used for the PVA fiber additive research is the same design mixed already detailed in Chapter 3.

Table 15. PVA RAP Mix Design Differences

Fiber RAP Mix Design Differences		
	Mix 1	**Mix 2**
Mix Design*	Same	Same
Water Content (Increase)	1%	10%
% Total PVA Fibers By Volume	3%	1%
6mm Fibers	Yes	No
8mm Fibers	Yes - 50%	Yes - 50%
** Mix Design Details in Appendix A*		

5.1.2 SAMPLE PREPARATION

Three sample batches are prepared for each mix using 35%, 50% and a 75% RAP replacement of coarse aggregate. The 35% & 50% batches are made in order to directly compare the HSPCC mixes with corresponding RAP replacement percentages without the PVA fibers. The 75% RAP replacement batch with PVA fibers is constructed based on the assumption that including PVA fibers in the mix would allow for greater percentages of RAP replacement. A control batch is made for comparison that includes the RAP replacement to large aggregate for each percentage tested with no PVA fibers added.

All samples are cured in a lime water bath for 28 days before testing according to design standard ASTM C511-09 “Standard Specification for Mixing Rooms, Moist

Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes” and then tested according to ASTM C39/C39M-12, “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens” as well as ASTM C496/C496M-11, “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens” (ASTM, 2012). The second fiber mix is removed from the water 72 hours before testing to allow for draining. This is due to the excessive amount of moisture absorbed in the PVA fibers from the water bath cure.

5.1.3 TESTING METHODS

The concrete mixes are prepared and compacted in 4” diameter by 8” high cylinder molds for compression testing, and 6” diameter by 12” high cylinder molds for split tensile testing according to ASTM C192-90, “Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory” (ASTM, 2012). The RAP is sieved and gradated according to ASTM D6913, “Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis” and replaced in each percent accordingly (ASTM, 2012). Five 4” diameter by 8” high cylinders and three 6” diameter by 12” high cylinders are made for each batch of concrete tested. The samples are cured for 28 days in a water bath storage container according to design standard ASTM C511 “Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes” and then tested according to ASTM C39/C39M-12, “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens” as well as ASTM C496/C496M-11, “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens” (ASTM, 2012). The second batch of fiber design mix is taken out 72 hours prior to breaking to allow for water drainage (ACI, 2005).

5.2 RESULTS AND DISCUSSION

Table 16 shows the results of PVA Fiber Additive for both the first and second design mix.

Table 16. RAP and PVA Fiber Strength Test Results

PVA FIBER & RAP REPLACEMENT RESULTS												
COMPRESSION								**TENSION**				
Cylinder #	*1*	*2*	*3*	*4*	*5*	*AVG*	*Std Dev*	*1*	*2*	*3*	*AVG*	*Std Dev*
CONTROL	7364	6351	7324	6694	7008	6948	384	939	825	1108	957	101
35%	2345	2563	2982	2815	2954	2732	223	502	518	607	543	40
50%	1543	1281	1439	1303	1540	1421	102	643	625	653	640	10
75%	2854	2499	2069	2318	2525	2453	236	537	515	607	553	34
Std Dev						2439.1			*Std Dev*		194.3	

As shown in Table 16 the strength values are not as high as anticipated or expected. Due to the saturation of the PVA fibers, the compression cylinders do not react as predicted. The test breaks do not react as PVA fiber reinforced concrete should act and the test results show that. Figure 15 shows a typical split cylinder specimen with fibers. The figure shows the fibers as the “fuzzy” exterior on the break side of the specimen. The fuzzy in the specimens is the fiber that is saturated from the water bath curing.

Figure 15. PVA Fibers in Split Tensile Test Specimen

The cylinders are also still saturated from the water bath and cause premature and unreliable results for both tension and compression strength tests administered. Under testing conditions, the cylinders failed on the wet side; the dry side is unbroken and intact. In fact, the compression strength on the machine would still read and increase while the wet side crumbled. Examples of this are shown in Figure 16. The four pictures show four separate cylinder breaks and how the wet portion of the cylinder softly crumbled under low pressure applied to the cylinder, while the dry side is still intact; mechanically and structurally capable of withstanding greater force.

Figure 16. PVA and RAP Fiber Design Mix 1

The second PVA and RAP fiber design mix compression and tension tests conducted on three separate batches of HSPCC as well, again the 35%, 50% & 75% of RAP replacement. All sets are taken out of the water 72 hours prior to breaking to allow for draining and compensate for oversaturation to the PVA fibers. The data is recorded and shown in Table 17.

Table 17. PVA Fiber & RAP Replacement Results

PVA FIBER & RAP REPLACEMENT RESULTS												
COMPRESSION								TENSION				
Cylinder #	*1*	*2*	*3*	*4*	*5*	*AVG*	*Std Dev*	*1*	*2*	*3*	*AVG*	*Std Dev*
CONTROL	7364	6351	7324	6694	7008	6948	351	939	825	1108	957	101
35%	4154	4263	4611	4572	4984	4517	267	664	624	779	689	57
50%	2915	5061	3882	4240	4467	4113	649	565	614	486	555	46
75%	2189	1722	2608	2466	1895	2176	304	587	542	570	567	16
					Std Dev	1960.4				*Std Dev*	187.0	

As shown from the compressive and tensile strengths listed in Table 17 the results from the second batch of fiber reinforced concrete using the longer 8 mm fibers and increasing the water content make a stronger, more functional concrete. It is shown in these results that the strength of the concrete increased dramatically, verifying that drying out the cylinders due to the saturation of PVA fibers is necessary. There is the possibility that the cylinders may have been over dry and further research will need to be tested in order to determine the exact amount of dry time required for testing concrete with fiber additive. Figure 17 shows pictures taken of the breaks from the second design mix of fiber additive and RAP replacement. The breaks shown correlate with the stronger compressive and tensile strength breaks. The top pictures show the control batch and the bottom pictures show the 75% batch.

Figure 17. PVA and RAP Fiber Design Mix 2

The tensile strengths of the second design mix of concrete tested for batches are considerably stronger than the first batch. The tensile strength results for the Control, 35%, 50%, 75% batches averaged 957, 689, 555, 567 psi respectively. This is a 65.29% increase from the control batch without fiber, a 55.53% increase from 35% mix without fiber and a 12.01% increase in the 50% mix without fiber. Table 18. Average Tensile Strength Results - PVA Fiber Additive shows the tension comparison results of the PVA HSPCC fiber batches and compares them to the non-fiber batches presented in Chapter 4 of this report.

Table 18. Average Tensile Strength Results - PVA Fiber Additive

Comparison of Results Tension Fiber vs. Non Fiber (psi)			
RAP %	RAP Only (psi)	PVA & RAP Batch 1 (psi)	PVA & RAP Batch 2 (psi)
35%	443	523	689
50%	496	640	555
75%	----	553	567

The compression strength averages for one mix design are as follows: 6948, 4517, 4113, 2176 psi respectively which is 1.3% decrease in compression strength from the control batch without fiber, a 12.2% increase from the 35% RAP percentage replacement without fiber and 9.7% decrease in the 50% RAP percentage replacement without fiber. From these results, the data cannot fully establish if the addition of PVA fibers increase or decrease the compression strength. More testing is necessary in order to fully conclude the variability adding PVA fibers to HSPCC will do. Table 19 shows the compression results of the PVA HSPCC fiber batches compared to the non-fiber batches outlined in Chapter 4.

Table 19. Average Compression Strength Results PVA Fiber

Comparison of Result Compression Fiber vs. Non Fiber (psi)			
RAP%	RAP Only (psi)	PVA & RAP Batch 1 (psi)	PVA & RAP Batch 2 (psi)
35%	3966	2732	4517
50%	4511	1421	4113
75%	------	2453	2176

The tensile and compressive strength results for HSPCC without PVA fibers added are detailed in Chapters 4 of this report.

5.3 SUMMARY OF CONCLUSIONS

This chapter concludes that adding PVA fibers to HSPCC with RAP replaced at 25%, 50% and 75% will increase the tensile strength while not compromising the compression strength of the concrete. This chapter also concludes that adding PVA fibers added to an HSPCC mix has little effect on the compression strength. It does change the compression strength a small amount; however, there is no direct conclusion if it increases or decreases the compressive strength of the mix.

In order to maintain workability when adding PVA fibers to the HSPCC mix, the water content must dramatically increase in percentage by weight for workability and strength. The more successful mix using PVA fibers has 10% water content increase resulting in a reasonable amount of workability. However, more testing will need to be performed in order to determine what water contents offer the best results when working with HSPCC concrete with a PVA fiber additive.

This research concludes that in order to maintain good results when using a PVA fiber as an additive to HSPCC using RAP as a large aggregate replacement, the samples must be allowed to drain from the water bath prior to testing. Further testing needs to be conducted in order to achieve the correct range of drying hours allotted per specimen. It is clearly shown from the test results of the first fiber design mix that the results are poor due to the intense saturation of the PVA fibers from the water bath. Utilizing this information, it is found that the design standard ASTM C511-09 “Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes” may need to be evaluated for the addition of a separate content subchapter for the process of water bathing concrete cylinders with PVA fibers as an additive. It is suggested from the test results that the PVA fiber additive specimens must be treated differently than the specimens without PVA fibers (ASTM 2012).

Additional studies need to be done regarding fine tuning the water content percentage by weight, studying various percentages of PVA fibers as an additive of weight by volume, optimizing RAP % and PVA fiber % matrix, and lastly durability and long term performance.

CHAPTER 6 - SUMMARY, CONCLUSIONS AND FUTURE WORK

6.0 INTRODUCTION

This studies objective is to determine the variability in High Strength Portland Cement Concrete (HSPCC) strength properties when adding Recycled Asphalt Pavement (RAP) while maintaining strength properties to be used in structural applications. This study tested the variability in the compressive strength of RAP concrete utilizing gradated RAP from different harvest locations, the variability in the compressive strength when using gradated RAP versus non-gradated RAP, the variability in the tensile and compressive strength of RAP utilizing various replacement percentages of RAP for the coarse aggregate and the effect on tensile and compressive strength including Polyvinyl Alcohol Fibers (PVA) fibers into a HSPCC RAP concrete mixture.

This study results conclude that it is feasible to have a greener mix design of concrete using RAP as a replacement of coarse aggregate while maintaining necessary strength in concrete to be utilized in structural applications.

To do that, this study considers the following factors on the compression and tensile strength parameters of concrete mixes utilizing RAP as coarse aggregate replacement in high strength concrete mixes:

6.1 SUMMARY OF CONCLUSIONS

6.1.1 HARVEST LOCATION AND GRADATION

Gradated versus non-gradated RAP replacement results are compared for compression strength testes in High Strength Portland Cement Concrete (HSPCC) mixes.

The results for gradating and replacing the RAP at the same percentage as the design mix eliminates the variability found from harvesting techniques. However, data is inconclusive if gradating RAP increased or decreased the compressive strength of the HSPCC, but decreases the standard deviation.

Sieving the RAP into the appropriate gradations directly affects the strength of the concrete and in order to control the outcome of the concrete mix, sieve gradations must be performed and replaced at the appropriate percentage to match the coarse aggregate the RAP is replacing. This eliminates the variance of aggregate replacement and the large variance in strength parameters directly affected from that.

Compression strength variability is compared to determine if geographical/environmental conditions of the RAP harvest location effects mechanical properties. Harvest Locations of Bear Lake, Boise, Coeur d'Alene, Dubois, Wilder, and Pocatello, Idaho are tested.

The results for the compression strength of the geographical/environmental location where the RAP is collected and used as a replacement in the HSPCC as a coarse aggregate replacement show traffic counts do have an effect on the compression strength of the HSPCC. As the traffic counts increase, the compression strength of the HSPCC decreases. Temperature, elevation, annual precipitation, and snow pack did not have an effect on the compression strength; however, the type of road impacted the compression strength of the HSPCC. State Highway RAP yielded a stronger HSPCC, while the Interstate RAP yielded weaker compression strength in HSPCC.

6.1.2 RECYCLED ASPHALT PAVEMENT PERCENTAGE

Six separate RAP replacement percentages are studied in HSPCC mixes to determine an ideal relationship between RAP replacement and compressive and tensile strength. RAP to coarse aggregate replaced at 25%, 30%, 35%, 40%, 45% and 50% plus a control batch is tested. The compression strength parameters for the RAP replacement percentage follows a linear regression line with the equation equal to y = -46.405x + 6641.7. The R^2value is 0.2763 including 35% RAP coarse aggregate replacement and an equation of y = 53.74x + 7130.7 with the best fit linear equation line having an R^2 value of 0.5666 without 35% replacement.

For all RAP replacements tested, these equations show direct correlation with the decrease in compression strength with the RAP replacement percentage yields a design mix that enables re-creation and utilization as green engineering demands increase. This also allows mix designers to carry out cost/benefit analysis of utilizing RAP in their designs and to leverage that against green design requirements.

6.1.3 POLYVINYL ALCOHOL FIBER ADDITIVE

RAP replacement percentages are studied in HSPCC mixes adding PVA to test strength variability in both tension and compression.

PVA fibers added to an HSPCC mix have little effect on the compression strength. It does change the compression strength a small amount; however there is no direct conclusion if it increases or decreases the compressive strength of the mix. The compression strength averages for one mix design are as follows: 6948, 4517, 4113, 2176 psi respectively which is 1.3% decrease in compression strength from the control batch without fiber, a 12.2% increase from the 35% RAP percentage replacement without fiber and 9.7% decrease in the 50% RAP percentage replacement without fiber. From these results, the data cannot fully establish if the addition of PVA fibers increase or decrease the compression strength.

In order to maintain workability when adding PVA fibers to the HSPCC mix, the water content must dramatically increase in percentage by weight for workability and strength. The second batch using PVA fibers with the 10% water content increase has a reasonable amount of workability.

This research concludes that in order to maintain good results when using a PVA fiber as an additive to HSPCC using RAP as a large aggregate replacement, the samples must be allowed to drain from water bath prior to testing. It is clearly shown from the test results of the first fiber design mix that are not good results due to the intense saturation of the PVA fibers from the water bath. Utilizing this information, it is found that the design standard ASTM C511-09 “Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes” may need to be evaluated for the addition of a separate content subchapter for the process of water bathing concrete cylinders with PVA fibers as an additive (ASTM, 2012). It is suggested from the test results that the PVA fiber additive specimens must be treated differently than the specimens without PVA fibers.

6.2 RECOMMENDATIONS FOR FUTURE WORK

Further testing will need to be performed in order to adequately prove the conclusion of the influence if sieving and grading RAP increases or decreases the compression strength of the HSPCC.

Theoretically, the compressive strength differential in in geographic location of RAP is due to the breakdown of the aggregate in the asphalt; however further testing will need to be done in order to conclude the results. Additional topographic and GIS testing in other states and countries will need to be done in order to conclude the results that higher traffic counts lower compression strength and Interstate RAP yields a lower compressive strength. Also, more testing needs to be done in order to further conclude that elevation, snow-pack, precipitation has no effect on the structural strength of the

RAP. Compressive strength tests on regular and low strength concrete as well as different percentage replacements other than 35% RAP coarse aggregate replacement need to be performed in order to verify the results of the location portion of this study.

Further studies need to be conducted in replacing the fine aggregate and various matrix of coarse and fine aggregate with HSPCC using RAP as aggregate replacement as well as replacing a mixture of both the fine and coarse aggregate of RAP and the PVA fibers and all percentages of each matrix associated with that. In addition, percentages with mixtures must be considered with further research evaluated on mix and design when using RAP as a replacement in all types of concrete, not just HSPCC.

More in depth investigation and studies need to be conducted on Alkali Silica Reaction (ASR) of this design mix and any variance the design mix used may or may not have a negative or positive impact to the ASR reaction in the mix.

Finally, while this study showed that it is possible to produce structural viable RAP in HSPCC; further study needs to be conducted on the durability and long term performance of these mixes.

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APPENDICES

APPENDIX A: LAB DATA AND RESULTS

APPENDIX A.1 COMPRESSION AND TENSILE STRENGTH INDIVIDUAL CYLINDER RESULTS

Batch	Compression Strengths Per Cylinder (psi)					Tensile Strengths Per Cylinder (psi)		
Control	6631	6722	7206	7317	7329	540	611	587
25%	6334	5568	6067	6122	5925	510	549	520
30%	4869	6033	5436	5147	4970	630	647	607
$35\%_1$	4407	3208	3954	4031	4231	433	442	452
$35\%_2$	4415	5298	4032	4225	4555	433	442	452
40%	3708	5222	5063	5391	4952	558	496	439
45%	4874	4746	4408	4882	4942	556	501	416
50%	4667	4671	3652	4936	4630	444	515	529

APPENDIX A.2 PVA & RAP DESIGN MIX BREAKDOWN

PVA and RAP 2nd Design Mix Pocatello Ready Mix Used for ITD Overlay High Strength Mix 8000 psi 1% by Volume Fiber Added (Nycon Polyvinyl Fibers 6mm) Item # PV06-RMS702-33SP								
INITIAL DESIGN MIX								
	Ingredients for 0.35 cf 5 Qty Small 4x8 Cylinders				Ingredients for 0.71 cf 3 Qty Large 6x12 Cylinders			
Cement	8.28	lbs	3756	grams	16.81	lbs	7624	grams
Fly Ash	1.46	lbs	662	grams	2.96	lbs	1344	grams
Fine Agg	15.4	lbs	6985	grams	31.26	lbs	14180	grams
Coarse Agg	23.27	lbs	10555	grams	47.24	lbs	21427	grams
Super Plasticizer	1.28	oz	0.78	oz	2.60	oz	1.58	oz
Water	3.57	lbs	1619	grams	7.25	lbs	3287	grams
*RAP WAS CALCULATED FOR EACH RAP % REPLACEMENT BATCH USING INITIAL DESIGN MIX ** Water was increased by 10% for all mixes with fiber CONTROL MIX WITH FIBER								
	Ingredients for 0.35 cf				Ingredients for 0.71 cf			
	5 Qty Small 4x8 Cylinders				3 Qty Large 6x12 Cylinders			
Cement	8.28	lbs	3756	grams	16.81	lbs	7624	grams
Fly Ash	1.46	lbs	662	grams	2.96	lbs	1344	grams
Fine Agg	15.4	lbs	6985	grams	31.26	lbs	14180	grams
Coarse Agg	23.27	lbs	10555	grams	47.24	lbs	21427	grams
Super Plasticizer	1.28	oz	0.78	oz	2.60	oz	1.58	oz
Water	3.927	lbs	1781	grams	7.97	lbs	3616	grams
Fiber	0.28392	lbs	129	grams	0.58	lbs	261	grams
35% RAP REPLACEMENT W/ FIBER								
	Ingredients for 0.35 cf 5 Qty Small 4x8 Cylinders				Ingredients for 0.71 cf 3 Qty Large 6x12 Cylinders			
Cement	8.28	lbs	3756	grams	16.8084	lbs	7624	grams
Fly Ash	1.46	lbs	662	grams	2.9638	lbs	1344	grams

Fine Agg	15.4	lbs	6985	grams	31.262	lbs	14180	grams
Coarse Agg	15.1255	lbs	6861	grams	30.70477	lbs	13927	grams
Rap Total 35%	8.1445	lbs	3694	grams	16.53334	lbs	7499	grams
Super Plasticizer	1.28	oz	0.78	oz	2.5984	oz	1.58	oz
Water	3.927	lbs	1781	grams	7.97181	lbs	3616	grams
Fiber	0.28392	lbs	1066	grams	0.58	lbs	261	grams

35% RAP Break Down by Sieve:

	5 Qty Small 4x8 Cylinders		3 Qty Large 6x12 Cylinders	
3/4"	362	grams	667	grams
5/8"	813	grams	1650	grams
1/2"	805	grams	1635	grams
3/8"	1034	grams	2100	grams
Pan	695	grams	1410	grams

50% RAP REPLACEMENT W/ FIBER

	Ingredients for 0.35 cf 5 Qty Small 4x8 Cylinders				Ingredients for 0.71 cf 3 Qty Large 6x12 Cylinders			
Cement	8.28	lbs	3756	grams	16.8084	lbs	7624	grams
Fly Ash	1.46	lbs	662	grams	2.9638	lbs	1344	grams
Fine Agg	15.4	lbs	6985	grams	31.262	lbs	14180	grams
Coarse Agg	11.635	lbs	5278	grams	23.61905	lbs	10713	grams
Rap Total 50%	11.635	lbs	5278	grams	23.61905	lbs	10713	grams
Super Plasticizer	1.28	oz	0.78	oz	2.5984	oz	1.58	oz
Water	3.927	lbs	1781	grams	7.97181	lbs	3616	grams
Fiber	0.28392	lbs	1066	grams	0.58	lbs	261	grams

50% RAP Break Down by Sieve:

	5 Qty Small 4x8 Cylinders		3 Qty Large 6x12 Cylinders	
3/4"	517	grams	1050	grams
5/8"	1161	grams	2357	grams
1/2"	1151	grams	2336	grams
3/8"	1478	grams	3000	grams
Pan	992	grams	2014	grams

75% RAP REPLACEMENT W/ FIBER

	Ingredients for 0.35 cf 5 Qty Small 4x8 Cylinders				Ingredients for 0.71 cf 3 Qty Large 6x12 Cylinders			
Cement	8.28	lbs	3756	grams	16.8084	lbs	7624	grams

Fly Ash	**1.46**	**lbs**	**662**	**grams**	**2.9638**	**lbs**	**1344**	**grams**
Fine Agg	**15.4**	**lbs**	**6985**	**grams**	**31.262**	**lbs**	**14180**	**grams**
Coarse Agg	**5.8175**	**lbs**	**2639**	**grams**	**11.80953**	**lbs**	**5357**	**grams**
Rap Total 75%	**17.4525**	**lbs**	**7916**	**grams**	**35.42858**	**lbs**	**16070**	**grams**
Super Plasticizer	**1.28**	**oz**	**0.78**	**oz**	**2.5984**	**oz**	**1.58**	**oz**
Water	**3.927**	**lbs**	**1781**	**grams**	**7.97181**	**lbs**	**3616**	**grams**
Fiber	**0.28392**	**lbs**	**129**	**grams**	**0.58**	**lbs**	**261**	**grams**

75% RAP Break Down by Sieve:

	5 Qty Small 4x8 Cylinders		**3 Qty Large 6x12 Cylinders**	
3/4"	776	grams	1575	grams
5/8"	1742	grams	3535	grams
1/2"	1726	grams	3503	grams
3/8"	2217	grams	4500	grams
Pan	1488	grams	3021	grams