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A Life Cycle Assessment and Life Cycle Cost Analysis of Colorado Department of Transportation Concrete Mixtures

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A LIFE CYCLE ASSESSMENT AND LIFE CYCLE COST ANALYSIS OF COLORADO DEPARTMENT OF TRANSPORTATION CONCRETE MIXTURES

by:

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This thesis entitled:
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written by Morgan Talmage

has been approved
for the Department of Civil, Environmental, and Architectural Engineering

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The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline

ABSTRACT

Talmage, Morgan (M.S., Department of Civil, Environmental, and Architectural
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A life cycle assessment and life cycle cost analysis of Colorado Department of
Transportation concrete mixtures

Thesis directed by Professor Wil V. Srubar III

This thesis presents a comprehensive life cycle assessment of all 1262 pre-approved Colorado Department of Transportation (CDOT) concrete mixture designs and compares the results with the published National Ready Mix Concrete Association (NRMCA) sustainability national and regional benchmarks. This thesis provides a cradle-to-gate comparative life cycle assessment (LCA), which accounts for impacts occurring during raw material supply, transportation, and manufacturing of the concrete mixtures. The environmental impacts compared in this LCA are global warming potential, ozone depletion potential, acidification potential, eutrophication potential, smog potential, total primary energy consumption, and non-renewable energy consumption. In addition, a life cycle cost analysis is performed on all 1262 CDOT mixture designs to estimate the economic cost associated with each mixture. Trade-offs between cost and environmental impacts are also presented, analyzed, and discussed herein.

CONTENTS

CHAPTER 1 INTRODUCTION 1

1.1. Scope of Work 3

CHAPTER 2 LITERATURE REVIEW 4

2.1. Life Cycle Assessment 4

2.1.1. LCA Framework 4

2.1.2. Impact Indicators 9

2.1.3. Limitations of LCA 19

2.1.4. Future of LCA 20

2.2. Life-Cycle Cost Analysis 21

2.3. Optimization and Trade-off of Impact Categories and Economic Cost 21

CHAPTER 3 METHODOLOGY 24

3.1. LCA Goal and Scope 24

3.1.1. Goal 24

3.1.2. Scope 24

3.2. Life Cycle Inventory 29

3.3. Comparative LCA 30

3.4. Life Cycle Cost Analysis 32

3.4.1. CDOT Life Cycle Cost Analysis Specification 32

3.4.2. LCCA of CDOT's Concrete Mixtures 33

3.5. Concrete Usage from CDOT 36
CHAPTER 4 RESULTS AND DISCUSSION 38
4.1. CDOT Mixture Design Analysis 38
4.1.1. Design and Field Compression Strength 38
4.2. CDOT Mixture Design LCA Analysis 40
4.2.1. Global Warming Potential (GWP) 41
4.2.2. Ozone Depletion Potential (ODP) 47
4.2.3. Acidification Potential (AP) 53
4.2.4. Eutrophication Potential (EP) 58
4.2.5. Smog Potential (POCP) 64
4.2.6. Total Primary Energy (PEC) 69
4.2.7. Non-Renewable Energy (NRE) 75
4.2.8. All impact categories 81
4.3. CDOT Mixture Design LCCA Analysis 84
4.4. LCA Analysis Trends 91
CHAPTER 5 CONCLUSION AND RECOMMENDATIONS 93
CHAPTER 6 REFERENCES 95

LIST OF FIGURES

Figure 1: Process-Based LCA Framework and Steps [7] 6

Figure 2: Life Cycle Assessment Full System Boundary [8] 7

Figure 3: LCA Midpoint and Endpoint Relationships 12

Figure 4: Energy Consumption Through a Product or Process Life Cycle 16

Figure 5: Total Primary Energy Consumption Boundary of a Product or Process Life Cycle 17

Figure 6: LCA and LCCA Decision Process 23

Figure 7: LCA System Boundary Included in this Study to be Parallel with NRMCA National and Regional Benchmark Reports 26

Figure 8: Map of NRMCA Regions from [4] 31

Figure 9: Field Compressive Strength and Design (Lab) Compressive Strength 39

Figure 10: Histogram of CDOT's Mixtures by Design (Laboratory) Compressive Strengths 40

Figure 11: NRMCA Rocky Mountain and National Benchmark Global Warming Potential (GWP) 42

Figure 12: Lab Design Compression Strength and GWP of CDOT Mixtures with Cement Only 43

Figure 13: Lab Design Compression Strength and GWP of CDOT Mixtures with Fly Ash 44

Figure 14: Field Compression Strength and GWP of CDOT Cement-Only Mixtures 45
Figure 15: Field Compression Strength and GWP of CDOT Mixtures with Fly Ash 45
Figure 16: Histogram of CDOT's Concrete Mixtures Global Warming Potential (GWP) 46
Figure 17: Cumulative Distribution Function of CDOT's Concrete Mixtures Global Warming Potential (GWP) 47
Figure 18: NRMCA Rocky Mountain and National Benchmark Ozone Depletion Potential (ODP) 48
Figure 19: Lab Design Compression Strength and ODP of CDOT Mixtures with Cement Only 49
Figure 20: Lab Design Compression Strength and ODP of CDOT Mixtures with Fly Ash 49
Figure 21: Field Compression Strength and ODP of CDOT Cement-Only Mixtures 50
Figure 22: Field Compression Strength and ODP of CDOT Mixtures with Fly Ash 51
Figure 23: Histogram of CDOT's Concrete Mixtures Ozone Depletion Potential (ODP) 52
Figure 24: Cumulative Distribution Function of CDOT's Concrete Mixtures Ozone Depletion Potential (ODP) 52

Figure 25: NRMCA Rocky Mountain and National Benchmark Acidification Potential (AP) 53

Figure 26: Lab Design Compression Strength and AP of CDOT Mixtures with Cement Only 54

Figure 27: Lab Design Compression Strength and AP of CDOT Mixtures with Fly Ash 55

Figure 28: Field Compression Strength and AP of CDOT Cement-Only Mixtures. 56

Figure 29: Field Compression Strength and AP of CDOT Mixtures with Fly Ash.. 56

Figure 30: Histogram of CDOT's Concrete Mixtures Acidification Potential (AP).. 57

Figure 31: Cumulative Distribution Function of CDOT's Concrete Mixtures Acidification Potential (AP) 58

Figure 32: NRMCA Rocky Mountain and National Benchmark Eutrophication Potential (EP) 59

Figure 33: Lab Design Compression Strength and EP of CDOT Mixtures with Cement Only 60

Figure 34: Lab Design Compression Strength and EP of CDOT Mixtures with Fly Ash 60

Figure 35: Field Compression Strength and EP of CDOT Cement Only Mixtures. 61

Figure 36: Field Compression Strength and EP of CDOT Mixtures with Fly Ash.. 62

Figure 37: Histogram of CDOT's Concrete Mixtures Eutrophication Potential (EP) 63

Figure 38: Cumulative Distribution Function of CDOT's Concrete Mixtures Eutrophication Potential (EP) 63

Figure 39: NRMCA Rocky Mountain and National Benchmark Smog Potential (POCP)........ 64

Figure 40: Lab Design Compression Strength and POCP of CDOT Mixtures with Cement Only 65

Figure 41: Lab Design Compression Strength and POCP of CDOT Mixtures with Fly Ash 66

Figure 42: Field Compression Strength and POCP of CDOT Cement Only Mixtures 67

Figure 43: Field Compression Strength and POCP of CDOT Mixtures with Fly Ash 67

Figure 44: Histogram of CDOT's Concrete Mixtures Smog Potential (POCP)........ 68

Figure 45: Cumulative Distribution Function of CDOT's Concrete Smog Potential (POCP)........ 69

Figure 46: NRMCA Rocky Mountain and National Benchmark Total Primary Energy Consumption (PEC) 70

Figure 47: Lab Design Compression Strength and PEC of CDOT Mixtures with Cement Only 71

Figure 48: Lab Design Compression Strength and PEC of CDOT Mixtures with Fly Ash 72

Figure 49: Field Compression Strength and PEC of CDOT Cement Only Mixtures 73

Figure 50: Field Compression Strength and PEC of CDOT Mixtures with Fly Ash73

Figure 51: Histogram of CDOT's Mixtures Total Primary Energy Consumption (PEC) 74

Figure 52: Cumulative Distribution Function of CDOT's Concrete Mixtures Primary Energy Consumption (PEC)........ 75

Figure 53: NRMCA Rocky Mountain and National Benchmark Non-Renewable Energy Consumption (NRE) 76

Figure 54: Lab Design Compression Strength and NRE of CDOT Mixtures with Cement Only........ 77

Figure 55: Lab Design Compression Strength and NRE of CDOT Mixtures with Fly Ash 77

Figure 56: Field Compression Strength and NRE of CDOT Cement Only Mixtures 78

Figure 57: Field Compression Strength and NRE of CDOT Mixtures with Fly Ash 79

Figure 58: Histogram of CDOT's Concrete Mixtures Non-Renewable Energy Consumption (NRE)........ 80

Figure 59: Cumulative Distribution Function of CDOT's Concrete Mixtures Non-Renewable Energy Consumption (NRE) 80

Figure 60: Normalized Environmental Performance of Rocky Mountain vs. National Concrete Mixtures........ 82

Figure 61: CDOT Concrete Usage in m^3 per year 85

Figure 62: Cost vs. Cementitious Content of mixtures with Cement Only........ 87

Figure 63: Cost vs. Cementitious Content of mixtures with Fraction Fly Ash Replacement.. 88

Figure 64: Cost vs. Compressive Strength of mixtures with Cement Only.............. 89

Figure 65: Cost vs. Compressive Strength of mixtures with Fraction Fly Ash Replacement.. 89

LIST OF TABLES

Table 1: Life Cycle Assessment Category Indicators 10

Table 2: Description of Life Cycle Stages Included in this Study 25

Table 3: Midpoint Indicators Included in this Study 27

Table 4: Completeness, Sensitivity, and Consistency Check 28

Table 5: Rocky Mountain Benchmark Data per Compressive Strength 32

Table 6: National Benchmark Data per Compressive Strength 32

Table 7: Life Cycle Cost Analysis Coefficients 35

Table 8: NRMCA Rocky Mountain Transportation Averages 36

Table 9: NRMCA National Transportation Averages 36

Table 10: CDOT Concrete Classes, Description and Average Usage [31] 37

Table 11: Number of CDOT Concrete Mixture Designs that meet Rocky Mountain Benchmark 82

Table 12: Percentage of CDOT Concrete Mixture Designs that meet Rocky Mountain Benchmark 83

Table 13: Percentage of Mixtures that do not meet standard that use cement only84

Table 14: CDOT Concrete Usage per Concrete class per Year [31] 86

Table 15: CDOT's Approximate Yearly Cost of Concrete with exclusion of Design-Build Projects 90

CHAPTER 1 INTRODUCTION

Emissions related to construction material manufacturing, transport, use, and disposal impact the environment, climate, and human health. The construction industry is one of the largest consumers of natural resources. Concrete, a composite material of aggregate, cementitious material, water, and additives, is the most widely used material in the construction industry [1], and its extensive use can impart harmful consequences on the environment.

Portland cement is responsible for most of the environmental emissions attributed to concrete production. The manufacture of portland cement is responsible for 5-7% of global anthropogenic CO_2 emissions [2]. During cement production, emissions are released by (1) the combustion of fossil fuel, (2) the calcination of calcium carbonate (i.e., limestone), and (3) the emissions from electricity for transportation and operating the manufacturing facilities [3].

In an effort to decrease the environmental impacts of concrete, supplementary cement materials (SCMs) are often used as a partial cement replacement. The most commonly used SCM is fly ash, a byproduct from the burning of coal, which has been shown in numerous studies to reduce the environmental impacts of ordinary portland cement concrete and improve its mechanical and durability properties [29, 30].

With the intention of lowering environmental impacts due to concrete manufacturing and providing awareness to the impacts of the cement and concrete industry, the National Ready Mixture Concrete Association (NRMCA) recently created a benchmarking report to identify the United States with baseline metrics for developing more sustainable (i.e., low environmental impact) concrete mixtures. The benchmark report was developed in accordance with the requirements of the Carbon Leadership Forum (CLF) Product Category Rules (PCR) for ISO 14025 TYPE III Environmental Product Declarations (EPDs) for Concrete v1.1 (December 2013) [4]. The NRMCA report developed “representative” statistical samples of NRMCA member plants with a 95% confidence level and a 5% margin of error, and includes both a national as well as regional benchmark reports. The reports provide cradle-to-gate environmental impact indicators for concrete production. The report consists of six benchmark ready-mix concretes (with varying compressive strengths) and their affiliated benchmark environmental impacts to help guide decision-making related to the design of concrete mixtures for both public and private construction projects.

The Colorado Department of Transportation (CDOT) has 1262 preapproved concrete mixtures that have been used in transportation-related construction projects over the past few decades. These mixtures all contain different quantities of cement, fly ash, aggregates, and water. To date, there have been no studies that analyze the environmental impacts of these mixtures [5]. CDOT, like many other US Departments of Transportation, released a Sustainability Program and Action Plan with a goal of developing and supporting sustainability initiatives while providing safe and effective transportation systems [6]. Thus, environmental impact assessments of high environmental impact construction materials, like concrete, fall within the scope of CDOT's sustainability program.

1.1. Scope of Work

This thesis presents a comprehensive life cycle assessment of all 1262 pre-approved CDOT concrete mixture designs and compares the results with the published NRMCA sustainability national and regional benchmarks. This thesis provides a cradle-to-gate comparative life cycle assessment, which accounts for impacts occurring during raw material supply, transportation, and manufacturing of the concrete mixtures. The environmental impacts compared in this LCA are global warming potential, ozone depletion potential, acidification potential, eutrophication potential, smog potential, total primary energy consumption, and non-renewable energy consumption. In addition, a life cycle cost analysis is performed on all 1262 CDOT mixture designs to estimate the economic cost associated with each mixture. Trade-offs between cost and environmental impacts are also presented, analyzed, and discussed herein.

CHAPTER 2 LITERATURE REVIEW

2.1. Life Cycle Assessment

Standardized accounting for embodied environmental impacts is a relatively new methodology. Recently, many organizations, such as the International Standards Organizations (ISO) and US Green Building Council (USGBC), have fully adopted a standardized method known as life cycle assessment (LCA). LCA quantifies the environmental impacts of a product or process throughout the full life cycle. The LCA technique uses an inventory of energy and material inputs and a set of assumptions to quantify the potential environmental impacts associated to a specific product or process [7]. The full life cycle can be evaluated from material extraction to end of life. Many different useful tools and programs can be used to conduct an LCA. In this research – and in the NRMCA report – Athena, an LCA tool, is used to model and conduct the LCA. The Athena LCA methodology is in alignment and compliance with ISO 14040/14044 and North American standards [8].

2.1.1. LCA Framework

LCA methodologies are generally classified into three main categories: (1) process-based LCA, (2) economic input-output LCA (EIO-LCA), and (3) hybrid LCA. Process-based LCA is the methodology is used in this study, because it directly measures the impacts of material and energy flows to and from the environment [9]. In calculating the total environmental impact of the impact indicators, a process-based LCA systematically models the known energy inputs (and potential outputs) by utilizing a process flow diagram in each phase of the life cycle. For the LCA tool used in this study, Athena, this includes emissions and impacts from the product stage, construction stage, use stage, and end-of-life stage, as well as emissions and impacts from transportation for all processes and material within the scope of the LCA [9].

Process-based LCAs are most commonly used because of their ability to be detailed and intimately connected to details of all aspects of the scope of the LCA. Process-based LCAs typically produce very specific analyses and the highest-precision results of all LCA methodologies. There are, however, limitations of this method. The lack of comprehensive data, non-uniform quality of data, subjective system boundary definitions, time required to complete a LCA make process-based LCAs difficult [10].

LCA methodology and standards adopted by ISO include four basic steps: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation. The entire process of a LCA is iterative and requires constant evaluation to make sure the results are as accurate and consistent as possible. All the steps in an LCA directly affect the consistency and transparency of the results. The basic framework and the iterations involved in LCA are depicted in **Figure 1**. As shown by arrows, constant evaluation and back-checking result in the most accurate results. Although ISO 14044 provides a standardized framework and steps for conducting a LCA, the actual methodology is based on the practitioner's best judgment [9,11].

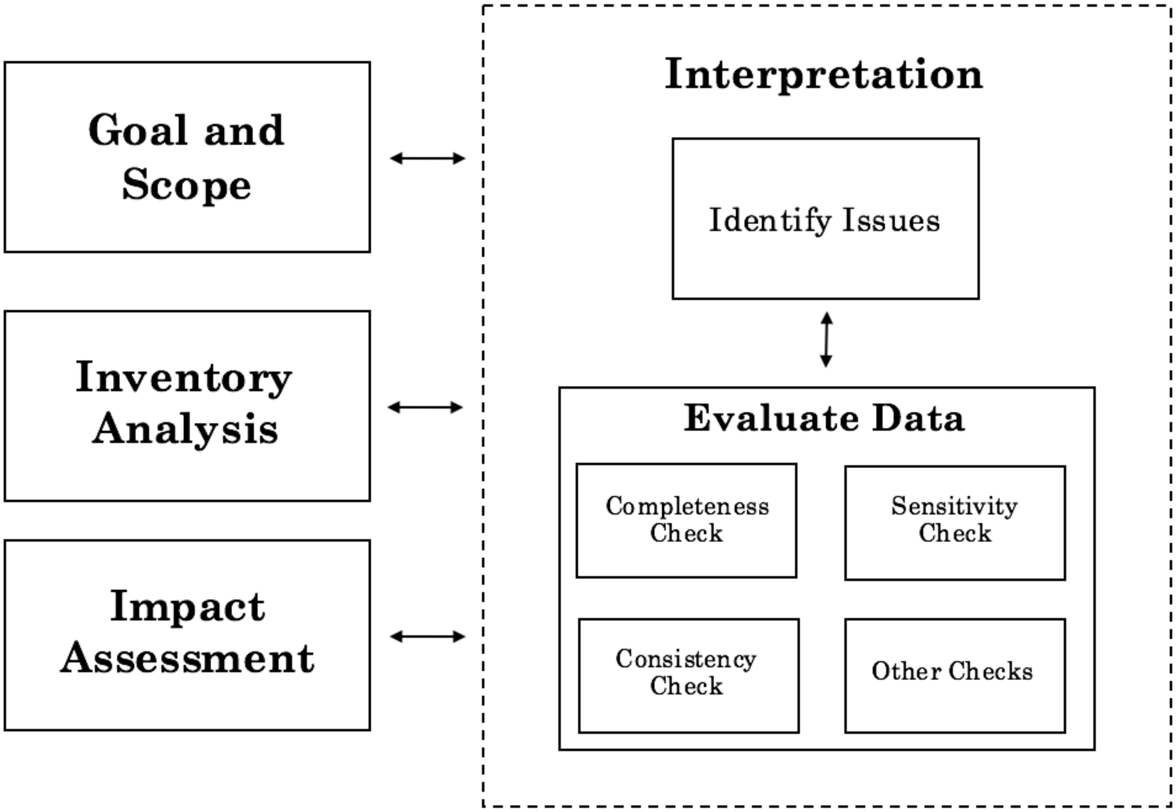

Figure 1: Process-Based LCA Framework and Steps [7]

The foundation for the entire assessment is based upon the goal and the scope phase of the framework. The LCA goal includes the definition of the problem and reason for the study and the objectives. The scope determines the product system and the setting and boundaries in which the study is evaluating. In specific, the scope includes the product being studied with a definitive functional unit, the system boundary, methodological choices, and details of analysis. The selection of the appropriate impact categories is guided by the goal of the study, and the number of categories analyzed is limited by practicality and depth of the study [12]. The system boundary presented in **Figure 2**, from product stage to construction to use to end of life, is the entire life cycle that can be evaluated. However, the scope can be altered to fit the goal of the study. The goal and scope are evaluated and analyzed throughout the entire LCA process to make sure that the data determined at the end of the study is transparent and precisely correlated to the goal and scope.

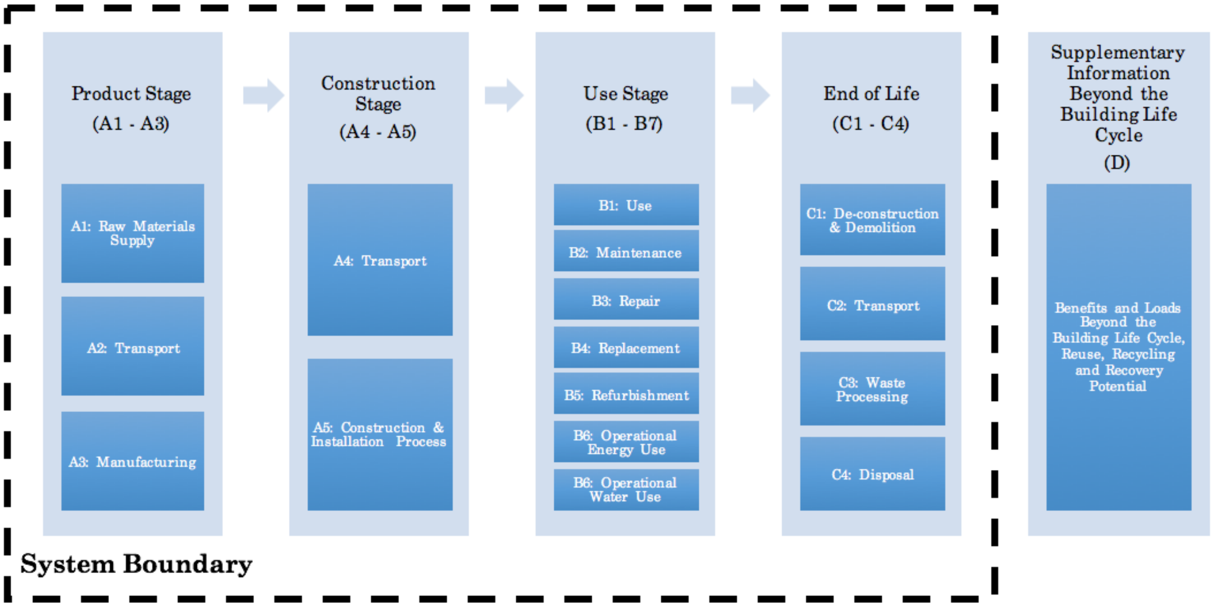

Figure 2: Life Cycle Assessment Full System Boundary [8]

The second step, inventory analysis, involves data collection and calculation procedures to quantify relevant inputs and outputs of the system being study. This step includes measuring, calculating or estimating material and energy inputs, wastes, and emissions data caused by a functional unit of the product that is established in the goal and scope. The data are specific to the system boundaries of the study and takes into consideration the system's surroundings [12]. After data collection, the calculation of the emissions relative to the considered functional unit is recorded.

The third step in LCA is the impact assessment, where the input and output data quantified in the inventory analysis are aggregated and evaluated. This step includes identifying the environmental impact categories that are to be studied, establishing which emissions influence which impacts, and then totaling the relative impacts in this order. This step is difficult because many of the same emissions may contribute to multiple impact categories, which needs to be translated into a single impact. Many different tools have been developed to automatically perform this calculation, including Athena, which is used in this study [13].

The fourth step is the interpretation phase in the evaluation of the whole LCA, which is characterized in **Figure 1** as identifying issues and evaluating data through a set of checks according to [14]. ISO requires these checks as a minimum to verify that (1) the assessment is transparent and aligned with the goal and scope, (2) the data used are accurate and complete, and (3) that all assumptions and allocations are noted. The additional checks are left up to the evaluator, which can enhance the precision of the LCA and solidify any concerns with the transparency of the LCA.

LCA can be used to quantify the environmental impacts of a single product or process or to conduct a comparative LCA. Comparative LCAs are used to compare products or processes and is often a guide in making an assertion that one option is environmentally preferable to another [2]. LCAs conducted for this purpose require thorough development to ensure that the systems being compared are functionally equivalent. Development includes verifying that the data used are similarly precise, comprehensive, and fully descriptive of the situations. The transparency in the LCAs being compared is crucial in making an accurate assertion of which option is environmentally preferable. ISO 14044: 2006b requires a critical review to determine if the LCA meets the requirements of a transparent LCA, which can be used to support a comparative assertion [7].

> “In order to decrease the likelihood of misunderstandings or negative effects on external interested parties, a panel of interested parties shall conduct critical reviews on LCA studies where the results are intended to be used to support a comparative assertion intended to be disclosed to the public. (ISO 14044: 2006b, section 6.1: 31) [15]”

2.1.2. Impact Indicators

A typical LCA addresses between five and nine impact categories. Most commonly, acidification potential, aquatic eutrophication potential, global warming potential (embodied carbon), human health particulate, ozone depletion, smog potential, total primary energy consumption, non-renewable energy consumption and fossil fuel consumption are included in assessments of building products. These impact categories are shown in **Table 1** with their units of measure. To fully understand the environmental impacts of a product or process, all impact categories should be addressed; however, the indicators studied are ultimately dependent on the goal and scope of the LCA.

Table 1: Life Cycle Assessment Category Indicators

Midpoint LCIA Indicators	Units
Global Warming Potential	kg-CO_2 - eq
Ozone Depletion (air) Potential	kg CFC-11 - eq
Acidification Potential	kg-SO_2 - eq
Eutrophication Potential	kg N- eq
Smog (air) Potential	kg O_3 - eq
Human Health Respiratory Effects Potential	kg $PM_{2.5}$ - eq
Total Primary Energy Consumption	MJ
Non-Renewable Energy Consumption	MJ
Fossil Fuel Consumption	MJ

The relationship between all impact indicators is complex, and there are many interconnections [7]. Because emissions can cause environmental impacts to multiple indicators, environmental indicators are classified as midpoint indicators, which translate impacts into environmental themes. The ISO methodology aggregates the midpoint indicators into three areas of endpoint damage: (1) human health damage, (2) natural resource consumption, and (3) ecosystem damage [12]. All midpoint indicators have a direct connection to an endpoint impact but can also have secondary impacts to others. The relationship flow chart, **Figure 3**, shows these connections.

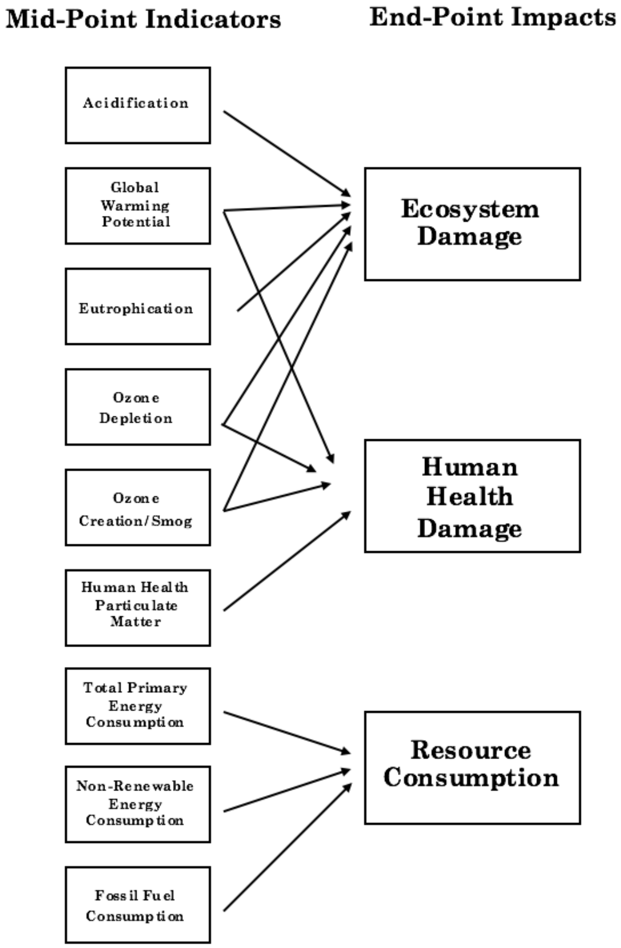

Figure 3: LCA Midpoint and Endpoint Relationships

2.1.2.1. Ecosystem and Human Health Damage Indicators

2.1.2.1.1. Global Warming Potential [Embodied Carbon] (GWP)

Global warming potential (GWP), also commonly known as "Embodied Carbon," is the measure of the quantity of greenhouse gas emissions that could become trapped in the atmosphere. GWP is calculated by the amount of energy the emissions of one ton of a gas will absorb over a given period of time relative to the emissions of one ton of carbon dioxide (CO_2) [16]. Greenhouse gasses impart many different impacts to the earth, including changes in precipitation, sea level rise, ocean currents, storms, hurricanes, and possible additional impacts on human health and biotic natural resources [17]. By combining these impacts, GWP provides a simple midpoint indicator representation of the relative radiative forcing resulting from a unit mass emission of a greenhouse gas [18].

2.1.2.1.2. Ozone Depletion (air) Potential (ODP)

The ozone high in earth's stratosphere protects its surface from the damage that can be caused by the sun's ultraviolet (UV) rays. Chlorofluorocarbons (CFCs) are released to the atmosphere through (1) the use of aerosols containing them, (2) refrigeration equipment, or (3) the industry producing and using refrigeration equipment. When CFCs are released into the atmosphere, the sunlight causes halocarbons to release chlorine atoms, which break down the ozone molecules [19]. When the ozone in earth's stratosphere is broken down, the ozone layer allows UVB radiation to reach the surface. Ozone depletion potential (ODP) is a measure of the expected impact on the ozone per unit mass emission of a gas as compared to that expected from the same mass emission of CFC-11 integrated over time [18]. ODP is commonly used as a comparison of relative impacts of different gases upon the ozone. When the sun's UV rays pass the depleted ozone layer, the UV rays can cause significant damage, including skin cancer, eye damage, reduction of plankton, and crop loss [7].

2.1.2.1.3. Acidification Potential (AP)

Acidification potential is a measure of the disposition of a unit of mass of a component to release hydrogen ions (H^+) to a receiving medium. The addition of hydrogen ions alters the pH of that medium and causes undesirable effects [17]. When the pH balance of water and soil is changed, there are many consequences that affect plants and animals that thrive on a specific pH level. Additionally, a change in pH can reduce the productivity of soil, which can cause supplementary decline in plant and animal health. The change in plant and animal health can also impact the liveliness of these species and reduce their potential as food sources for humans [7]. Acidification-causing substances are sulfur dioxide and nitrogen oxide that are transformed to either sulfuric acid or nitric acid through oxidization and photochemical reactions that eventually deposit on the surface of the earth [17].

2.1.2.1.4. Eutrophication Potential (EP)

Eutrophication is the surplus of biological activity in an aquatic system that stems from the addition of nutrients into the system. Eutrophication can inhibit the water system by depleting the available oxygen needed for species and threaten biodiversity. Eutrophication occurs when nitrogen and phosphorus are added to an aquatic system. Typically, this occurs from septic field seepage, storm and wastewater runoff, fossil fuel combustion and rainwater runoff after contact with fertilized agriculture and manure and aquaculture, which all contain nitrogen and phosphorus [17].

2.1.2.1.5. Smog (air) Potential (POCP)

Smog is the formation of ground-level ozone, which poses significant threats to air quality. The formation of smog is caused by the release of natural and man-made substances into the atmosphere, volatile organic substances (VOCs), and oxides of nitrogen, which reacts to sunlight. VOCs are emitted from building materials and building maintenance products, while oxides of nitrogen are emissions related to fossil fuel consumption. When the sunlight reacts with theses emissions, ground-level ozone and airborne particles are created. The formation of ground-level ozone is reported in weight of ozone (O_3). Ground level ozone poses significant threat to human health respiratory systems, including reduced lung function, aggravation asthma, and permanent lung damage [17].

2.1.2.2. Resource Consumption Indicators

Energy consumption throughout the life cycle of a product or process includes consumption of both renewable and non-renewable resources, shown in the process diagram (see **Figure 4**). Additionally, this consumption includes both primary and secondary energy. A primary energy source is a source that is extracted and can be used directly from nature; a secondary source is energy in the form of energy products used for different activities, such as electricity or fuel [20]. In LCAs, typically, the indicators analyzed are total primary energy consumption, non-renewable energy consumption, and fossil fuel consumption [8].

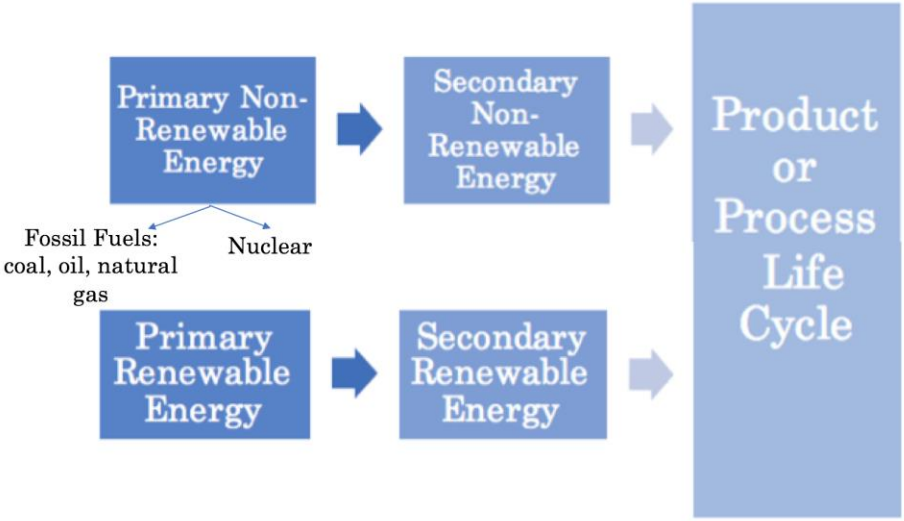

Figure 4: Energy Consumption Through a Product or Process Life Cycle

2.1.2.2.1. Total Primary Energy Consumption (PEC)

Total primary energy consumption is the umbrella term for "embodied" primary energy where the word "embodied" refers to all of the primary energy consumed throughout the life cycle of a product or process. The total primary energy consumption includes primary energy consumption of both renewable and non-renewable energy, as seen in the boundary in **Figure 5**. PEC is measured by the amount of primary renewable and non-renewable resources used or depleted that are converted into units of energy (MJ) [18]. Non-renewable energy includes fossil fuels and nuclear resources; renewable energy includes hydro, wood, sun, wind, and any other non-hydro renewable resource. The consumption of resources is an important impact indicator because of limited and declining resources, especially resources that are non-renewable [20,21].

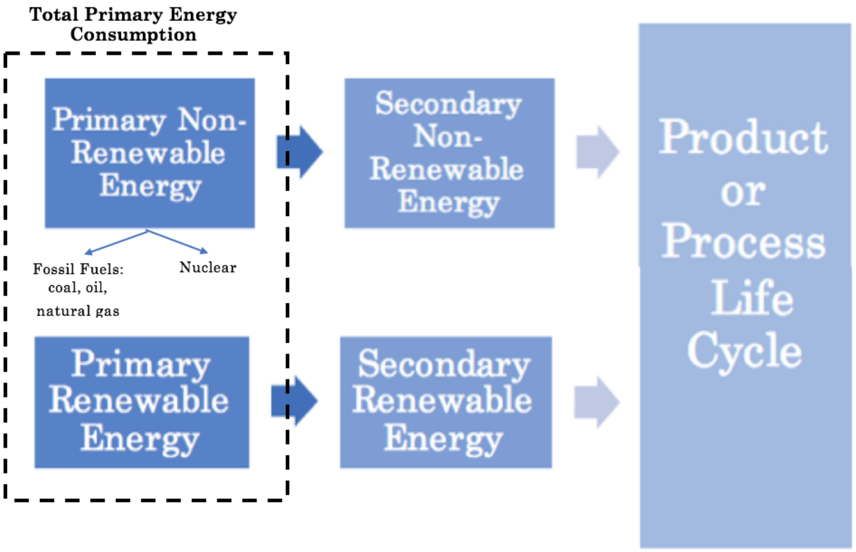

Figure 5: Total Primary Energy Consumption Boundary of a Product or Process Life Cycle

2.1.2.2.2. Non-Renewable Energy Consumption (NRE)

Within the category of primary energy consumption is non-renewable energy consumption (NRE). NRE includes all resources consumed that do not renew themselves within a human time scale, including fossil fuels and nuclear energy. The most common non-renewable energy source is fossil fuels [21]. Measured in MJ, the breakdown of these non-renewable energy sources can be seen in **Figure 5**.

2.1.2.2.3. Fossil Fuel Consumption

The indicator of fossil fuel consumption is an even more detailed piece of both non-renewable energy consumption and primary energy consumption. Fossil fuel consumption includes the consumption of coal, oil and natural gas, which have provided more than 80% of the total U.S. energy consumption for more than 100 years [20, 21].

2.1.2.3. Comparison of Impact Indicators

Though all impact indicators are significant, ISO 14042 includes a step of weighting. Weights can be assigned to the different impact categories and resources reflecting their relative importance in accordance with the goal of the study. This step is important because it gives a scaled basis for a comparison. Given that each study is different, weighting makes the importance of each study ultimately subjective, since few products are likely to out-perform alternatives across all impact categories. Weighting also provides a synthesis of performance score for all impact categories into a single score. Some LCA tools have an optional weighting set while others, like Athena, do not. Because this study is not intended to be subjective and is intended to be transparent, a weighting scale is not applied.

2.1.3. Limitations of LCA

The adoption of LCA has provided a way to quantify measures of environmental impacts, helped create a way to make comparative assertions, and made a method in which people can incorporate sustainability into design. LCA has many strengths, but there are also limitations. The data and assumptions that LCAs require add a significant amount of uncertainty, which can create gaps and errors in the outcome of the LCA results. Additionally, many LCA tools have incomplete data, which are not regionally specific in every detail. Lack of data and the use of proxy data can result in faulty precision which in turn causes miscalculations in the results [7]. LCA also does not provide an accurate way to predict future changes and future states, which adds an additional level of uncertainty [22]. Uncertainty and assumptions result in a relative expression of potential environmental impacts.

Comparative LCAs have similar weaknesses with the addition of more uncertainty due to the scaling of all flows to a comparable functional unit. Comparative LCAs can have goals to equate completely different materials, which must be scaled to be functionally equivalent systems. It is difficult to perfectly create a functional unit for two systems to have the same quantity, quality, and life span when the materials are inherently different [22]. The method is best defined as an estimation tool instead of an absolute measurement tool, although the results can falsely seem precise.

LCA also does not address occupational exposure limits, indoor air quality or other legal emission limits, resource management, or social equity. These other factors are important in decision making and for completely understanding and evaluating the sustainability of a system or process [22].

Studies have shown that users of the LCA method are frequently uninformed with the appropriate and acceptable environmental impact measures, the source of the data and how the data used in LCA relates to the ISO standards. This lack of understanding can undermine the potential of LCA and can create false arguments and inaccurate statements related to a product or process which adds additional risk that will lead to dependence on questionable data or studies [23].

2.1.4. Future of LCA

The characteristic uncertainty and difficulties associated with life cycle assessment provides room for growth. To facilitate the accuracy of the method, there is a future in standardization of uncertainty information. Studies show that the reporting of uncertainties in data sources and LCA results is not adequate and thus affects the outcome of LCAs [13]. To compensate, the future holds promise for more comprehensive databases for materials of construction and more standardized accounting of uncertainties. As the LCA field grows, develops, and becomes a required industry-wide method, manufacturers will add more comprehensive data and will minimize uncertainty and refine results for all products [22].

2.2. Life-Cycle Cost Analysis

The economic accounting of costs associated with a product or process throughout its full life cycle, known as life cycle cost analysis (LCCA), is the standardized method used by many organizations, including US Departments of Transportation. LCCA estimates the economic costs associated with all phases of a product or processes, including initial costs, operating costs, and refurbishment/replacement cost. LCCA includes the total discounted dollar cost of a product of process over a specified life cycle [24]. The goal of any LCCA is typically to reduce the economic cost of any product or process and to identify high-cost contributors and alternatives that can decrease the overall cost. This method is often used with LCA to establish and compare the economic and environmental cost of a product or process for enhanced decision making [25].

2.3. Optimization and Trade-off of Impact Categories and Economic Cost

LCA has the potential to be used in many ways. In its simplest form, LCA can be used to quantify and evaluate the environmental performance of a product or process. LCA also can act as part of a much broader decision process and can be used to understand general trade-offs of environmental impacts and select among alternative products or processes [14]. The method provides the ability to assess trade-offs between impacts and, by employing optimization techniques, elucidate and help designers make complex decisions. Additionally, LCA provides a basis for assessing potential improvements in the environmental performance of a product system [12].

Similarly, LCCA has the potential to be used to quantify and evaluate the economic performance of a product or process. LCCA can be used to make decisions on alternatives and understand the broad or general trade-offs of materials of processes involved in the system [26]. Economic optimization tools are often used for LCCA to make these decisions and address improvements on the overall economic cost [27].

The value of the information developed from both LCAs and LCCAs can be heightened in applicability in different contexts if they are both used not only on their own, but also simultaneously as part of a comprehensive decision-making process that weighs economic and environmental tradeoffs against each other. Although LCA and LCCA can provide data and results that are presented with options that have the lowest impacts or smallest economic costs, trade-offs between economic growth and environmental protection often occur. More specifically, establishing a functionally equivalent product or process that has lower impacts to the environment can have additional added economical costs and vice-versa [28].

In comparative LCAs, where functionally equivalent products are being directly compared, optimization techniques can be used to determine the tradeoffs between the use of different materials. Depending on the goal and scope of the study, the LCA and LCCA can be used together to select which product or process has the lowest desired costs (environmental and economic) [14], simplistically shown in **Figure 6**.

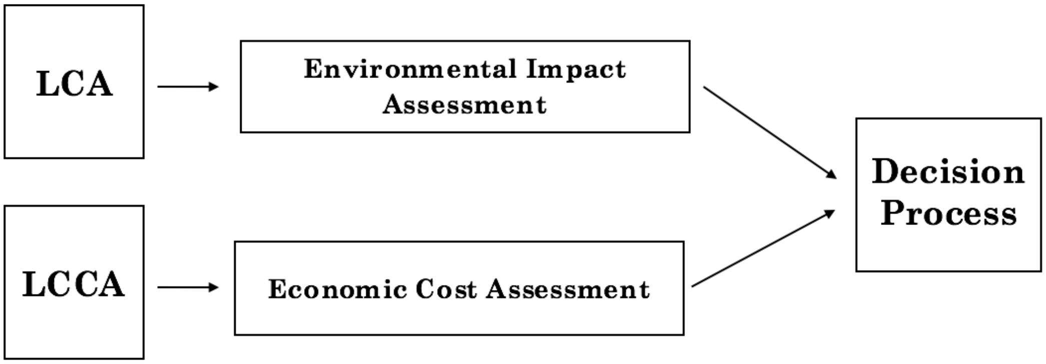

Figure 6: LCA and LCCA Decision Process

Currently, there is no adequate tool for fully integrating LCA and LCCA because of lack of information. However, optimization techniques are progressing to integrate these two in the selection of concrete mixture design [29]. With a sufficient data inventory, incorporation of optimization frameworks of environmental criteria with economic criteria would be a powerful decision-making tool [12].

Current approaches to this optimization tool look at both environmental and economical benefits through reduced wastes and treatment costs but neglect all other life cycle stages [12]. As discussed in **Section 2.1.1**, including the entire life cycle in analysis is the most ideal way to fully understand the trade-offs of a system or process [30].

CHAPTER 3 METHODOLOGY

3.1. LCA Goal and Scope

3.1.1. Goal

This LCA, conducted in accordance with ISO 14040/14044 standards, is a study of the environmental impacts of the Colorado Department of Transportation's (CDOT) approved concrete mixture designs. The results, of interest to structural engineers, ready-mixture concrete producers, and government agencies, will be used herein to compare the environmental impacts of each mixture design to the National Ready Mixed Concrete Association (NRMCA) national and regional life cycle assessment benchmark (i.e., industry average) standards.

3.1.2. Scope

Functional Unit: The scope of the LCA assumes a declared volumetric unit of 1 m^3 of each CDOT approved concrete mixture.

System Boundary: This LCA assumes cradle-to-gate system boundary with the life cycle stages A1-A3, as specified by EN 15804, as depicted in **Table 2.** This system boundary is parallel with the system boundary assumed in the NRMCA Benchmark LCA [4].

Table 2: Description of Life Cycle Stages Included in this Study

Life Cycle Stage	Processes
A1- Raw Material Supply	Extraction, handling and processing of raw materials and intermediate component products used in the production of concrete
A2- Transportation	Transportation of all input materials and fuels from the supplier to the gate of the concrete plant
A3- Manufacturing	Energy used to store, move, batch and mixture the concrete and operate the concrete plant as well as the transportation and processing of wastes from these core processes

From **Figure 2**, only the product stage (A1-A3) is included in this LCA. **Figure 7** shows the same figure with the appropriate system boundary for this study. As depicted, the construction stage, use stage, and end of life stage are excluded.

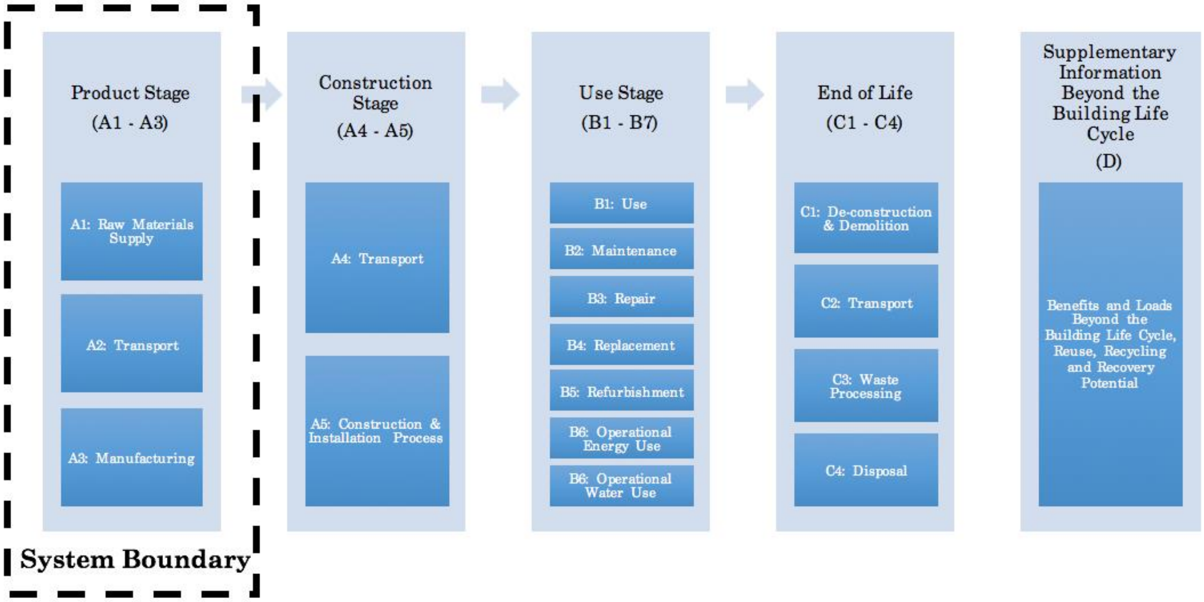

Figure 7: LCA System Boundary Included in this Study to be Parallel with NRMCA National and Regional Benchmark Reports

Methodological Choices:

- Allocation Assumptions: All concrete constituents used in this study are considered to be virgin materials. No constituents were considered to be byproducts, coproducts, or waste. The impact scenario was attributional rather than consequential (i.e., impacts are assessed only in regard to the current status quo at the time of the study).
- Impact Assessment: The impacts assessed in this study were chosen based off the impacts presented in the NRMCA report and the impact categories available in Athena. The LCA conducted in this study use the seven midpoint impact indicators shown in **Table 3**.

Table 3: Midpoint Indicators Included in this Study

Midpoint LCA Indicators	Abbreviation	Units
Global Warming Potential	GWP	Kg-CO_2 - eq
Ozone Depletion (air) Potential	ODP	kg CFC-11 - eq
Acidification Potential	AP	kg-SO_2 - eq
Eutrophication Potential	EP	kg N- eq
Smog (air) Potential	POCP	kg O_3 - eq
Total Primary Energy Consumption	PEC	MJ
Non-Renewable Energy Consumption	NRE	MJ

- Interpretation methods: All interpretation methods used in this study align with ISO 104044 interpretation methods shown in **Figure 1**. Interpretation included constant evaluation with the goal and scope of the study to maintain consistency throughout the impact assessment. The interpretation stage also includes a completeness, sensitivity, and consistency check shown in **Table 4**. Throughout these evaluations of the data, the same iterative steps were taken to ensure transparency throughout.

Table 4: Completeness, Sensitivity, and Consistency Check

Interpretation Check	Description
Completeness	The LCA in this study uses Athena as a life cycle assessment tool. Athena has been third-party verified. Assessments conducted using Athena are in accordance with the ISO 14040 and ISO 14044 standards and other standards as appropriate, and has been internally reviewed and, when warranted, externally peer reviewed. All constituents in the CDOT concrete mixtures have complete and up-to-date data in Athena, which aligns with these standards.
Sensitivity	The data used in this LCA is strictly from CDOT's approved concrete mixtures. No mixtures were estimated and no assumptions to the choices of mixture designs were made, eliminating sensitivity to the reliability of the final results. All data used is sensitive to the region. Regionality is incorporated into the LCA to avoid any sensitivity concerns.
Consistency	The LCA completed in the NRMCA Benchmark and the LCA completed in this study both use the exact system boundary. Even though some of the assumptions are not elucidated, both LCAs use Athena as a life cycle assessment tool. Thus, all assumptions within the boundary regarding all processes will have no discrepancies.

Analysis Details:

- Sources of data: All data used in this study come from Athena's life cycle inventory (LCI) database. Athena's assumptions for portland cement are not disclosed to the public, but are up-to-date for North America and the United States, in particular. Assumptions for both coarse and fine aggregate are used from Ecoinvent profiles in Simapro as proxies for aggregates. Water and fly ash are considered to be burden free except for the transportation stage. The concrete manufacturing process is based on the NRMCA Ready Mixture

LCA as well as all the mixtures that are available in Athena [8]. The NRMCA updated its Industry Wide cradle-to-gate LCA and EPDs for ready-mixed concrete in 2016, which included additional data from additional ready mixture plants [8].

- Data methods: All concrete mixtures in this study were inputted into Athena's custom concrete mixture module which uses region-appropriate electricity grids, transportation modes and distances, and product manufacturing technologies applicable to the product mixture for the selected region [8].
- Data quality requirements: Because this LCA is being used in a comparative LCA, the data quality of both studies is equivalent. The NRMCA benchmark study and this study were carried out using Athena as the tool to develop the LCA.
- Critical review: This study is yet to be third-party reviewed; however, the NRMCA Benchmark was internally reviewed for compliance.

3.2. Life Cycle Inventory

Data collection for inventory analysis came directly from the coefficients used in Athena's LCI database. Athena utilizes regionally specific industry data, including published LCAs and third-party verified environmental product declarations (EPDs). The data related to basic materials, building products and components, fuel use, and transportation are regionally sensitive and consider manufacturing technology, transportation, and an electricity grid. The LCI database is regularly updated. All data is generally less than 10 years old and all data is comprised of ISO 14040/14044-compliant unit processes [8].

3.3. Comparative LCA

A comparative LCA is employed to compare the environmental impacts of CDOT's 1262 concrete mixtures with the NRMCA national and regional benchmarks (see **Figure 8**). The NRMCA Rocky Mountain region benchmark has lower environmental impacts in all 7 categories than the national benchmark. The NRMCA LCA was formed using statistical analysis of 517 surveys distributed to NRMCA members and, subsequently, using Athena to carry-out a life cycle assessment.

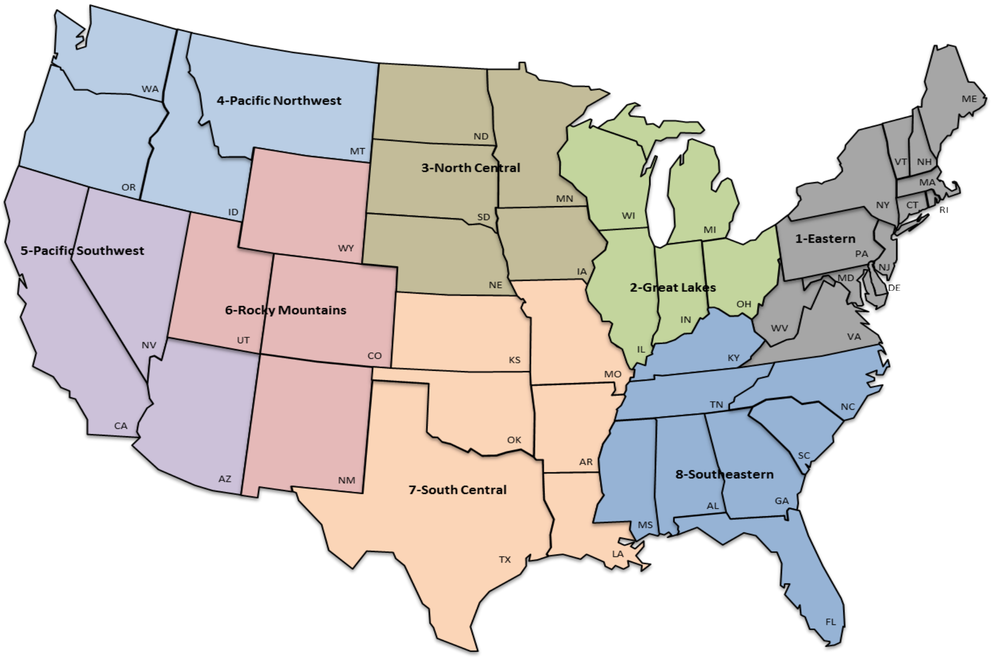

Figure 8: Map of NRMCA Regions from [4]

This study's LCA and the NRMCA LCA are designed to be identical and completely transparent, utilizing the same declared unit of 1 m^3 of a concrete mixture. Both LCAs have the same cradle-to-gate system boundary and use the same life cycle inventory and LCA tool.

The results from this study's life cycle assessment were compared directly to the benchmark data presented in **Table 5** and **Table 6**. The impacts excluded from this comparison were Human Health Respiratory Effects Potential and Fossil Fuel consumption because they were excluded from the NRMCA Benchmark report.

Table 5: Rocky Mountain Benchmark Data per Compressive Strength

Compressive Strength	GWP (per m^3)	ODP (per m^3)	AP (per m^3)	EP (per m^3)	POCP (per m^3)	PEC (per m^3)	NRE (per m^3)
2500	283.73	4.30E-06	1.26	0.12	17.05	2323.3	2283.5
3000	315.01	4.87E-06	1.38	0.13	18.24	2536.5	2492.5
4000	383.48	5.83E-06	1.64	0.15	20.86	3007.7	2954.6
5000	471.53	7.05E-06	2.7	0.22	32.18	3613.6	3548.8
6000	496.66	7.41E-06	2.8	0.23	33.28	3795.7	3727.6
8000	603.49	8.90E-06	3.21	0.27	37.39	4536.3	4545.2

Table 6: National Benchmark Data per Compressive Strength

Compressive Strength	GWP (per m^3)	ODP (per m^3)	AP (per m^3)	EP (per m^3)	POCP (per m^3)	PEC (per m^3)	NRE (per m^3)
2500	288.76	4.94E-06	1.32	0.15	17.54	2344.8	2325.4
3000	320.99	5.45E-06	1.45	0.16	18.85	2567.3	2546
4000	391.53	6.57E-06	1.73	0.19	21.72	3058.7	3033.5
5000	482.27	8.00E-06	2.83	0.27	33.36	3690.9	3660.6
6000	508.09	8.42E-06	2.94	0.28	34.54	3880.1	3848.3
8000	618.02	1.02E-05	3.38	0.32	38.99	4649.7	4611.7

3.4. Life Cycle Cost Analysis

3.4.1. CDOT Life Cycle Cost Analysis Specification

For CDOT, the goal of using LCCA is to evaluate the overall long-term economic efficiency between competing alternative investment options. The Federal Highway Administration (FHWA) defines LCCA as an analysis technique that incorporates initial and discounted future agency, user, and other relevant economic costs over the life of alternative investments. LCCA attempts to identify the best value for investment expenditures [19]. With the FHWA's definition and push for LCCA, CDOT uses the technique to compare alternatives for asphalt and concrete pavements.

3.4.2. LCCA of CDOT's Concrete Mixtures

Accounting for economic cost considers boundary stages of manufacturing (A1) of mixture constituents and transportation (A2) of mixture constituents to the batch plant. The manufacturing stage is excluded because it is considered equal for all mixtures. Transportation beyond the batch plant is not included because it is considered to be independent of mixture proportioning. No other life cycle stages are considered in this analysis.

The economic impact metric, cost (\$), is calculated according to the following equations:

$$Cost = Cost_{A1} + Cost_{A2} \tag*{Eq. 1}$$

$$Cost_{A1} = \sum_c m_c * CostC_c \tag*{Eq. 2}$$

$$Cost_{A2} = \sum_c m_{c,train}{,}* CostC_{train} * d_{c,train} + \sum_c m_{c,truck} * CostC_{truck} * d_{c,truck} \tag*{Eq. 3}$$

Cost is the total economical cost of both life cycle stages A1 and A2, as calculated by Eq. 1. $Cost_{A1}$ is the cost of stage A1 where m_c is each constituent's mass, $CostC_c$ is the cost coefficients for each constituent. The cost of life cycle stage

A2, $Cost_{A2}$, is the cost of transportation of all input materials and fuels from the supplier to the gate of the concrete plant, where $m_{c,train}$ and $m_{c,truck}$ is the constituent mass transported by train and truck respectively, $CostC_{train}$ and $CostC_{truck}$ are the cost coefficients for transportation by train and truck and $d_{c,train}$ and $d_{c,truck}$ are the distances the constituent traveled by train and truck, respectively. The cost coefficients are stated in **Table 7**.

Table 7: Life Cycle Cost Analysis Coefficients

Constituent	Cost ($/kg)	Reference
Coarse Aggregate	0.012	[29]
Fine Aggregate	0.02	[29]
Cement	0.0985	[29]
Water	0.005	[29]
Fly Ash	0.03	[29]
Transportation	($/kg-mi)	Reference
Truck	0.005	[29]
Train	0.0009	[29]

To stay consistent with the NRMCA benchmark, the distance of transportation is taken from the NRMCA benchmark document [4]. The LCCA is only performed for the Rocky Mountain region, since the mixtures are from the Colorado Department of Transportation. The computation of the economic cost for the national benchmark would not be an equal comparison. Modes of transportation for the Rocky Mountain region include truck and rail, shown in **Table 8**, with the associated distances of transportation. The national benchmark includes transportation from truck, rail, ocean, and barge, as seen in **Table 9.**

Table 8: NRMCA Rocky Mountain Transportation Averages

Transportation Mode	Units	Cement	Fly Ash	Crushed Coarse Aggregate	Natural Coarse Aggregate	Crushed Fine Aggregate	Natural Fine Aggregate
Truck	mi	109	161.9	14.9	7.2	0.2	29.2
Rail	mi	0.4	0	0	0	0	0
Ocean	mi	0	0	0	0	0	0
Barge	mi	0	0	0	0	0	0

Table 9: NRMCA National Transportation Averages

Transportation Mode	Units	Cement	Fly Ash	Crushed Coarse Aggregate	Natural Coarse Aggregate	Crushed Fine Aggregate	Natural Fine Aggregate
Truck	mi	76.8	66.3	19	17.8	4.5	31.8
Rail	mi	48.4	60.9	20	6.2	0.6	0.7
Ocean	mi	72.2	13.7	7.2	8.3	0	7.4
Barge	mi	33.8	33.8	1.9	1.9	0	5.4

LCCA is adopted in this study because of CDOT's use of LCCA as a selection of alternatives. This study produced a good depiction of life cycle economic costs and tradeoffs of alternatives in comparison with the National Ready Mixture Concrete Association's average cost data of \$75/m^3 [29, 31].

3.5. Concrete Usage from CDOT

CDOT has 11 different classes of concrete that are included in their specifications [5]. **Table 10** shows the list of concrete classes. Each specific concrete class has many different mixtures that meet the class requirements. All data acquired for CDOT excludes the use of concrete in Design-Build Projects.

Table 10: CDOT Concrete Classes, Description and Average Usage [31]

Concrete Class	Required Field Compressive Strength (psi)	Description	Average % Used
B	4500 at 28 days	Air Entrained concrete for general Use	0.402%
D	4500 at 28 days	Dense medium strength structural concrete	8.312%
DT	4500 at 28 days	Used for deck resurfacing and repairs	0.123%
P	4200 at 28 days	Used for pavements	90.264%
E	4200 at 28 days	Used for fast track pavements needing early strength	0.336%
H	4500 at 28 days	Used for bare concrete bridge decks that will not receive a waterproofing membrane	0.169%
HT	4500 at 28 days	Used as top layer for bare concrete bridge decks that will not receive a waterproofing membrane	0.043%
S35	5000 at 28 days	Dense high strength structural concrete.	0.002%
S40	5800 at 28 days	Dense high strength structural concrete	0.319%
S50	7250 at 28 days	Dense high strength structural concrete	0.029%
SSC	4500 at 28 days	Shot-crete	0.002%

CHAPTER 4 RESULTS AND DISCUSSION

4.1. CDOT Mixture Design Analysis

Results in this chapter are divided into three different sections. The first section presents an analysis of the documented compressive strengths of CDOT's concrete mixtures. The following section presents results of the comparative LCA and compares the results to the national and regional NRMCA. Finally, results of the LCCA are presented in the last section.

4.1.1. Design and Field Compression Strength

Colorado Department of Transportation reports both concrete design (lab) strength as well as their concrete field compression strength for all 1262 mixtures. In this study, "concrete design strength" was assumed the strength to which the concrete mixture was designed and tested in the laboratory, and the "concrete field strength" was assumed the strength of the concrete determined from field testing.

To compare CDOT's design compressive strength with the field compressive strength, an R^2 was calculated for the condition in which the strengths were plotted against each other. A model line with a slope of 1 is also plotted as an indicator of how well the design compressive strength perfectly coincides with the field compressive strength. With a R^2 of 0.11, the perfect line in **Figure 9** indicates that the lab design compression strength, as expected, is higher than the achieved field strength. This difference is likely attributable to the controlled environmental conditions of design specimens versus field-cured specimens.

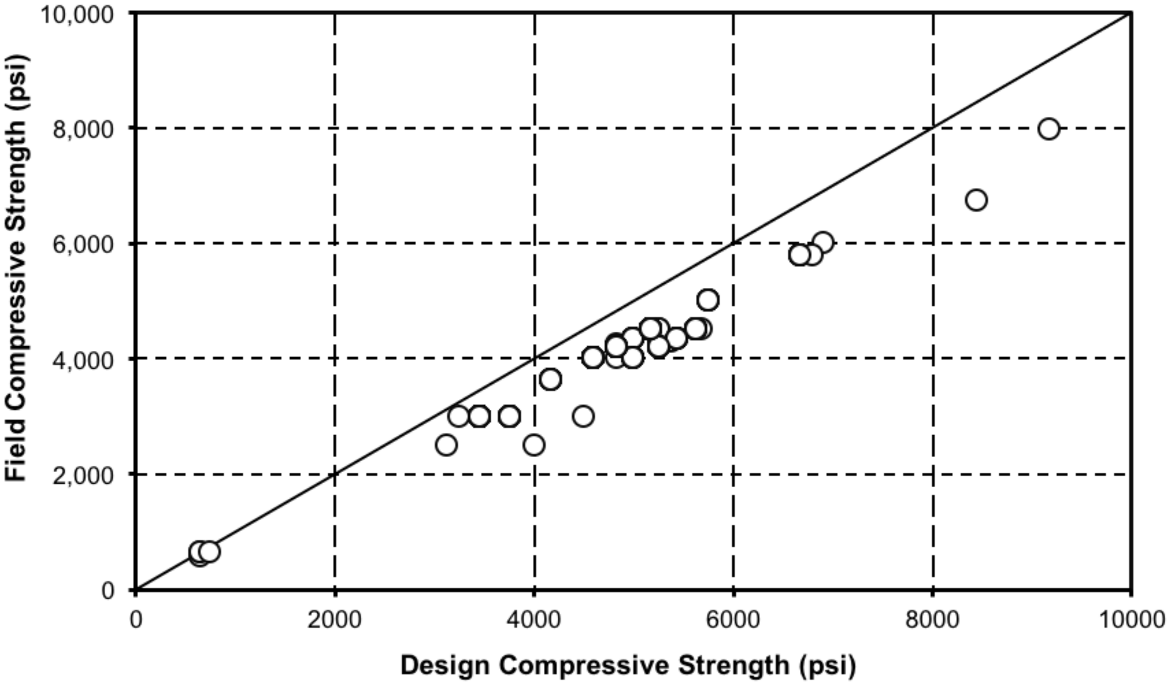

Figure 9: Field Compressive Strength and Design (Lab) Compressive Strength

A histogram of all 1262 concrete mixtures lab design strength is shown in **Figure 10**. As illustrated by the histogram, concrete mixtures with design (laboratory) compressive strengths of 4500 psi, 3000 psi, 4200 psi, and 4000 psi are the most frequently utilized. It can be assumed that the concrete designs from 4000 psi and above are used for structural (high load-bearing) purposes, while the lower strength concrete mixtures are used for lower-performance applications.

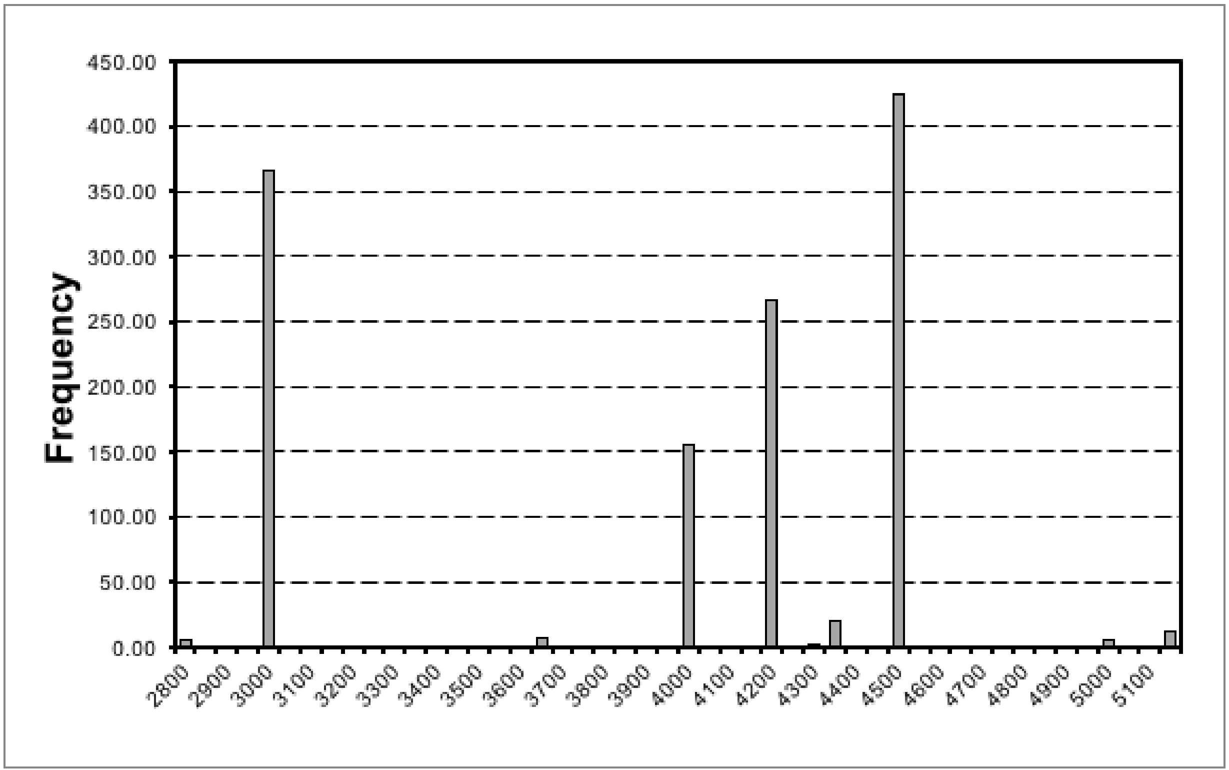

Figure 10: Histogram of CDOT's Mixtures by Design (Laboratory) Compressive Strengths

4.2. CDOT Mixture Design LCA Analysis

For use in this research, both the field compression strength and the design compression strength were used in comparison with the published environmental indicator benchmark. As discussed, both the Rocky Mountain region and national benchmarks are plotted to compare the performance of the 1262 CDOT approved mixtures. The national benchmark is consistently higher in environmental impacts than that of the Rocky Mountain region in all categories. Therefore, mixtures below the Rocky Mountain benchmark for an impact indicator are also below the national benchmark.

Additionally, separate plots are shown in this study for cement-only mixtures and mixtures with supplementary cementitious materials (i.e., fly ash). This distinction depicts how the use of fly ash affects the environmental impacts of concrete mixtures. 20% of CDOT's 1262 concrete mixtures use cement only. The other 80% of the mixtures incorporate fly ash as a fraction of the cement replacement to improve performance, as discussed in **Chapter 1**.

For each impact indicator, a histogram and a cumulative distribution function are plotted to highlight the variability of impacts of CDOT's concrete mixture designs and the probability level associated with the impacts of CDOT's concrete mixtures impacts.

4.2.1. Global Warming Potential (GWP)

The midpoint indicator, global warming potential (GWP), affects both the ecosystem and human health, as discussed in **Section 2.1.2.** The NRMCA benchmark for GWP is expressed in units of kg CO_2 eq. The results presented in **Figure 11**, confirms that the Rocky Mountain benchmark is below the national benchmark for global warming potential. The Rocky Mountain benchmark for GWP is on average 2.08% lower than the national benchmark for GWP.

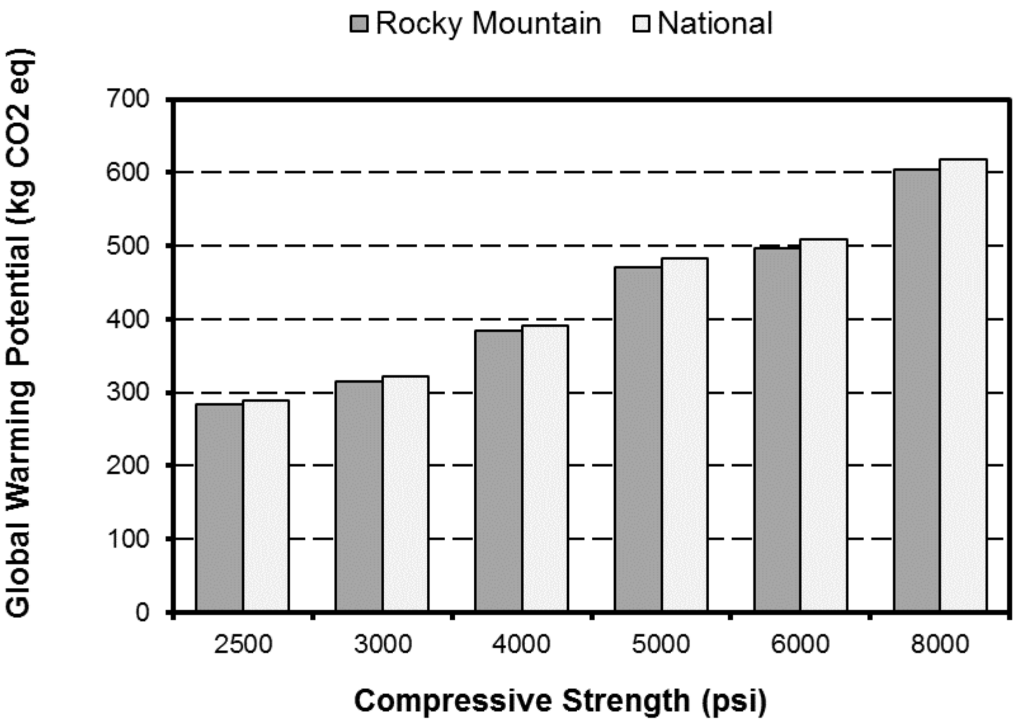

Figure 11: NRMCA Rocky Mountain and National Benchmark Global Warming Potential (GWP)

The results presented in **Figure 12** and **Figure 13** show the GWP of CDOT concrete mixtures in reference to their lab design compression strengths. **Figure 12** shows the GWP for mixtures designed with cement only and **Figure 13** shows the GWP for mixtures designed with a fraction of fly ash replacement. Both the Rocky Mountain and national benchmarks are plotted on the graphs for comparison. Approximately 82.1% of lab design strength mixtures have a lower GWP than the Rocky Mountain benchmark. Of the mixtures that do not meet the benchmark, approximately 75.2% are cement-only mixtures and 24.8% use a fraction of fly ash replacement.

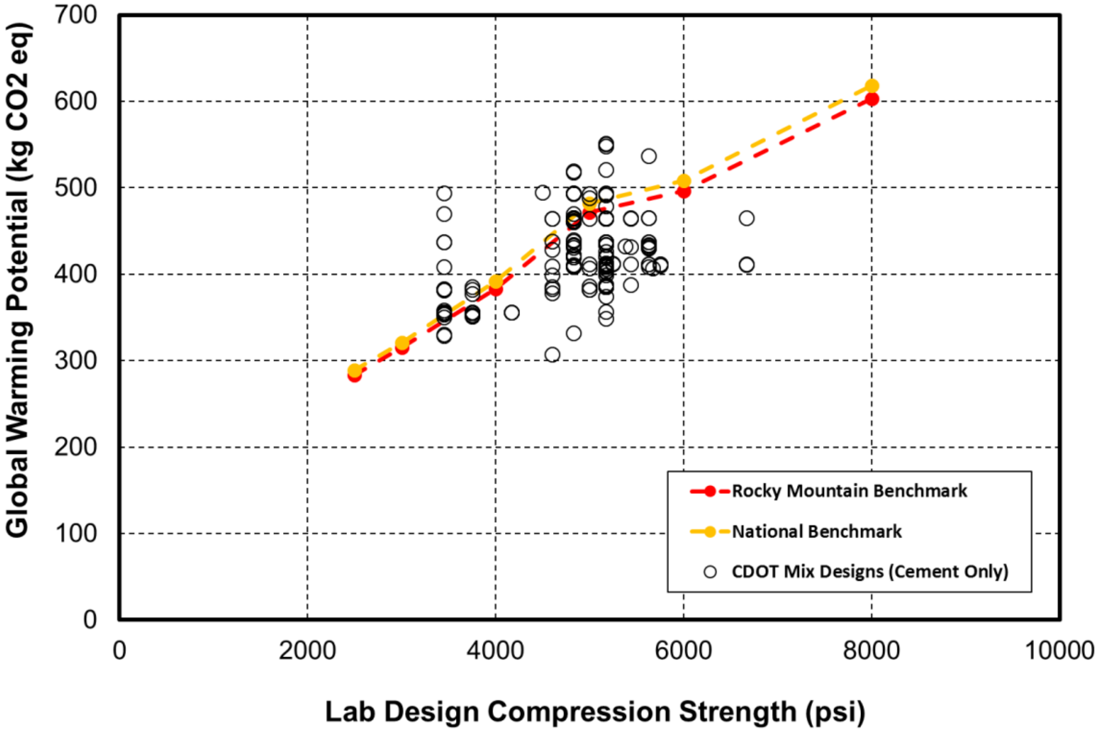

Figure 12: Lab Design Compression Strength and GWP of CDOT Mixtures with Cement Only

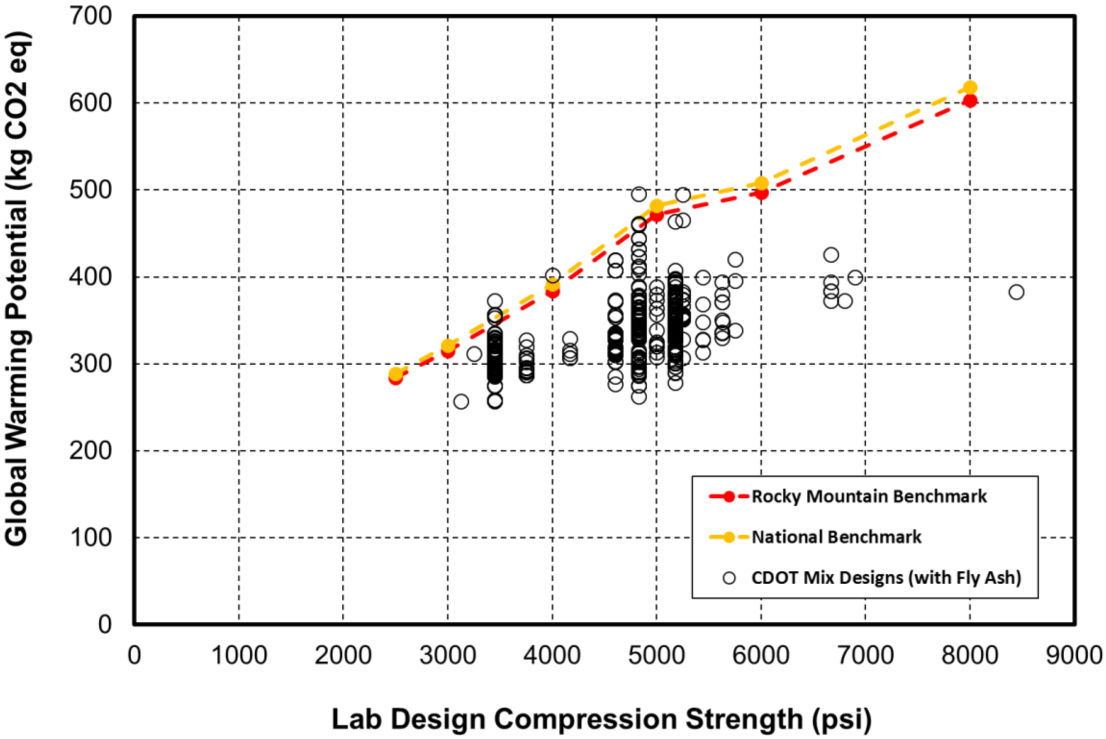

Figure 13: Lab Design Compression Strength and GWP of CDOT Mixtures with Fly Ash

Figure 14 and **Figure 15** show the global warming potential of the CDOT concrete mixtures using their field compression strengths. **Figure 14** shows the GWP for mixtures designed with cement only and **Figure 15** shows the GWP for mixtures designed with a fraction of fly ash replacement. Approximately 89.6% mixtures meet the GWP Rocky Mountain benchmark. Of the mixtures that do not meet the benchmark, 84% are mixtures that used cement only.

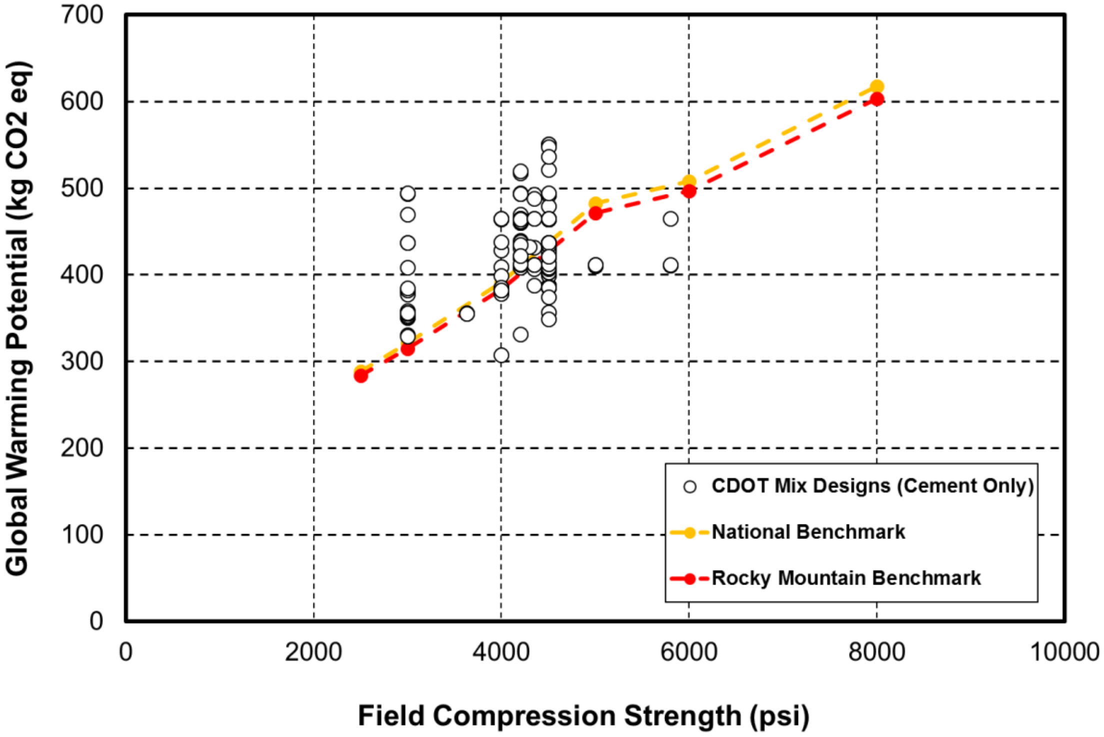

Figure 14: Field Compression Strength and GWP of CDOT Cement-Only Mixtures

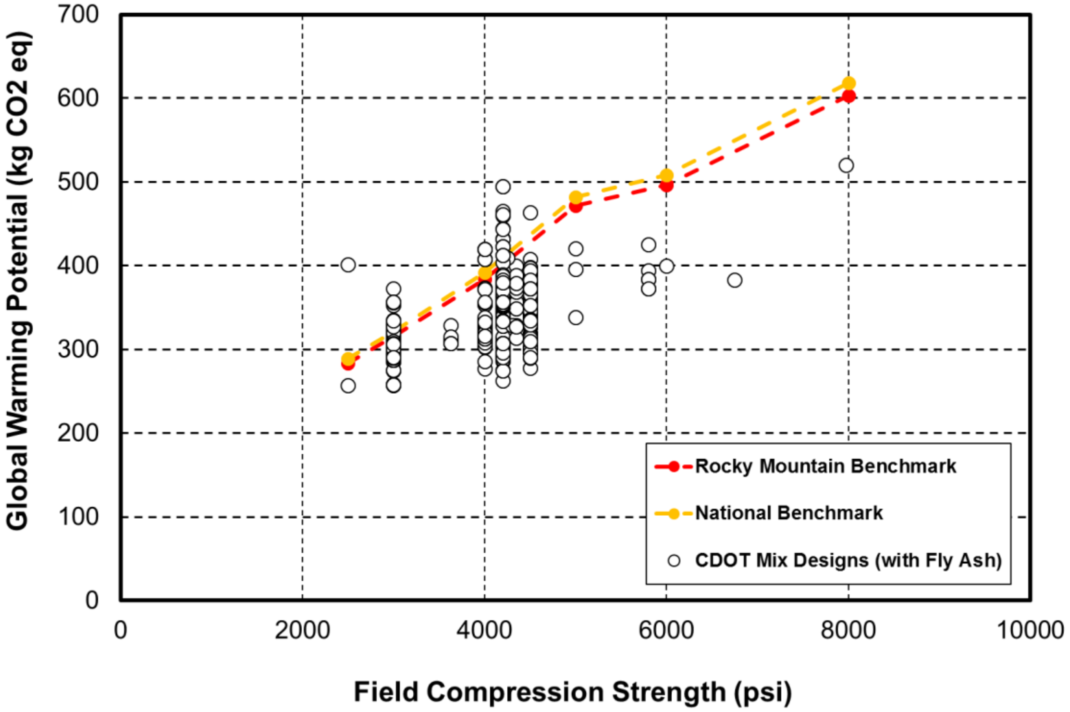

Figure 15: Field Compression Strength and GWP of CDOT Mixtures with Fly Ash

Figure 12, **Figure 13, Figure 14** and **Figure 15** show that higher-strength mixture designs tend to have higher GWP, largely due to the increased quantity of cement in the mixtures. On average 96% of the GWP of concrete is from cement [34]. Since the majority of the mixtures that do not meet the benchmark use cement only, it is evident that the addition of a fraction of fly ash replacement helps lower the impacts to global warming potential.

The results shown in **Figure 16** and **Figure 17** display the range of impacts from CDOT's 1262 concrete mixtures. The range of global warming potential for this set of concrete mixtures is approximately 290.46 to 411.81 kg CO_2 eq.

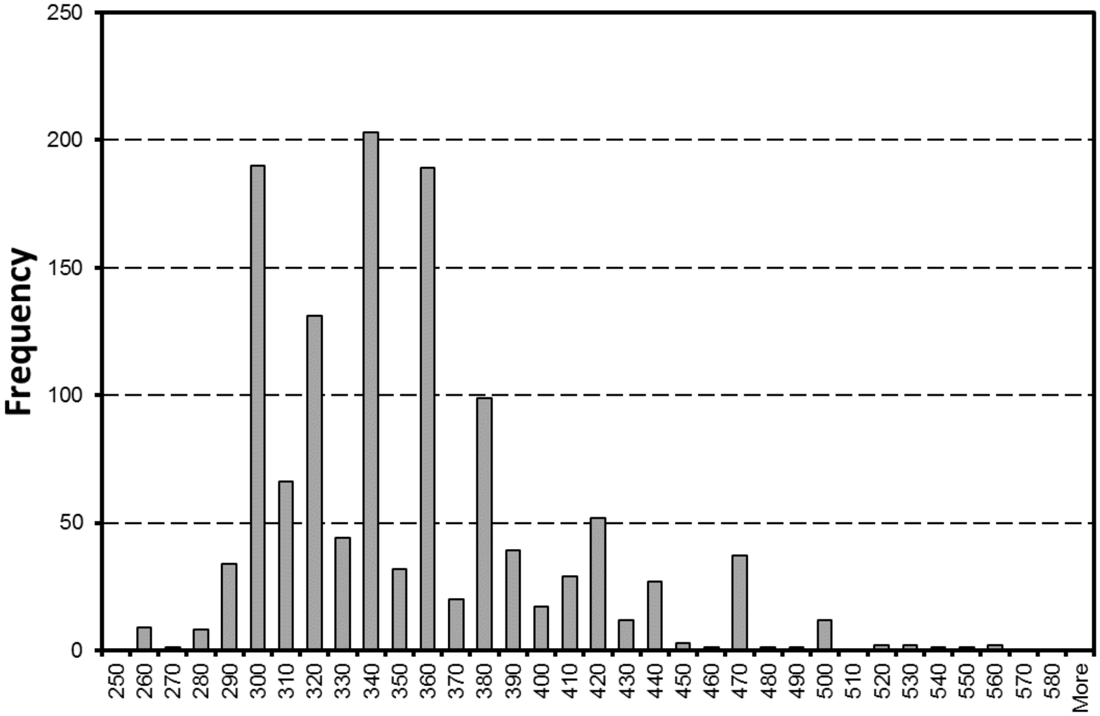

Figure 16: Histogram of CDOT's Concrete Mixtures Global Warming Potential (GWP)

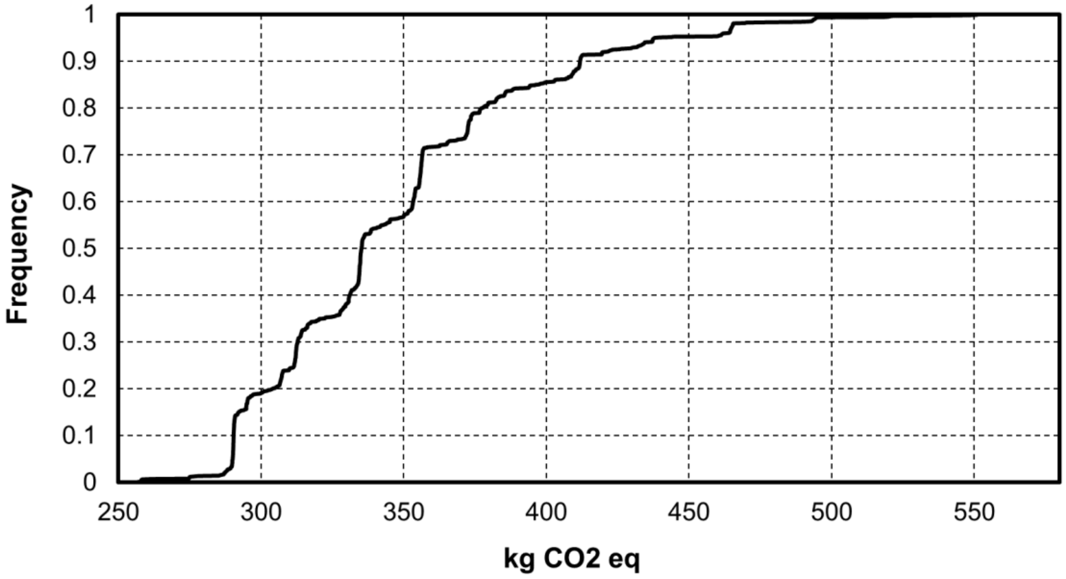

Figure 17: Cumulative Distribution Function of CDOT's Concrete Mixtures Global Warming Potential (GWP)

4.2.2. Ozone Depletion Potential (ODP)

The midpoint indicator, ozone depletion potential (ODP), affects both ecosystem damage and human health damage as discussed in **Section 2.1.2.** The NRMCA benchmark for ODP is expressed in units of kg CFC-11 eq. The comparison shown in **Figure 18** reiterates that the Rocky Mountain benchmark is below the national benchmark. The Rocky Mountain benchmark for ODP is on average 11.91% lower than the national benchmark for ODP.

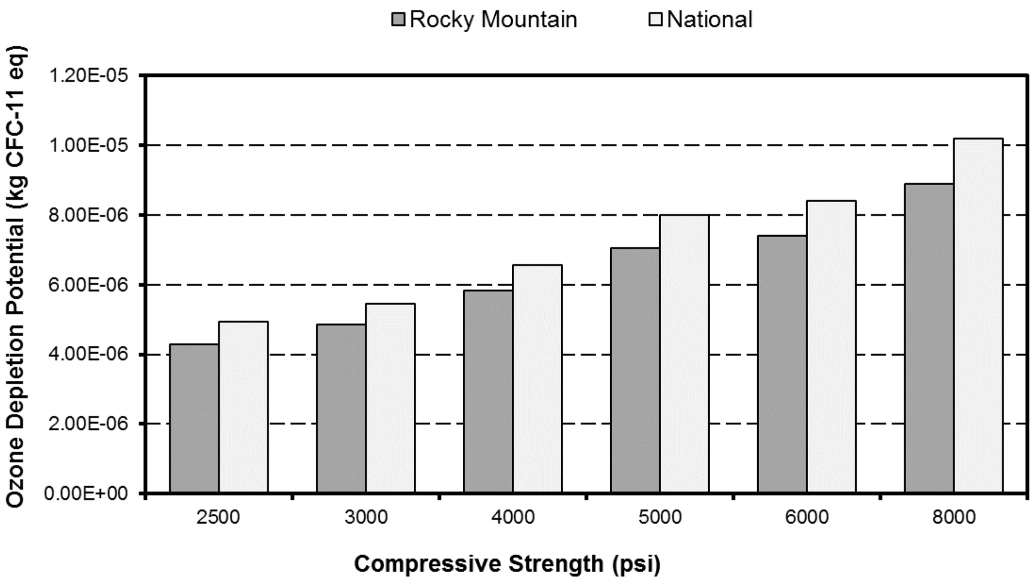

Figure 18: NRMCA Rocky Mountain and National Benchmark Ozone Depletion Potential (ODP)

The results presented in **Figure 19** and **Figure 20** show the CDOT concrete mixtures ozone depletion potential in reference to their lab design compression strengths. **Figure 19** shows the ODP for mixtures designed with cement only and **Figure 20** shows the ODP for mixtures designed with a fraction of fly ash replacement. Both the Rocky Mountain and national benchmarks are plotted on the graphs for comparison. Approximately 0.4% of the mixtures have a lower ODP than the Rocky Mountain benchmark. The few mixtures that do exceed the benchmark are mixtures that use a fraction of fly ash replacement.

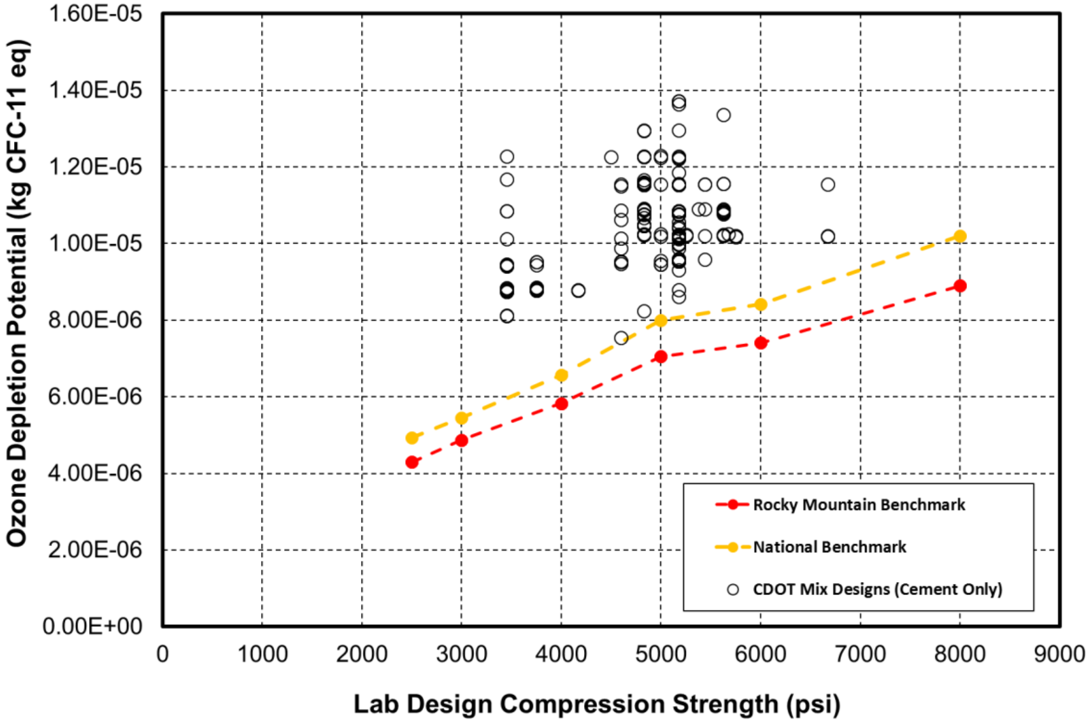

Figure 19: Lab Design Compression Strength and ODP of CDOT Mixtures with Cement Only

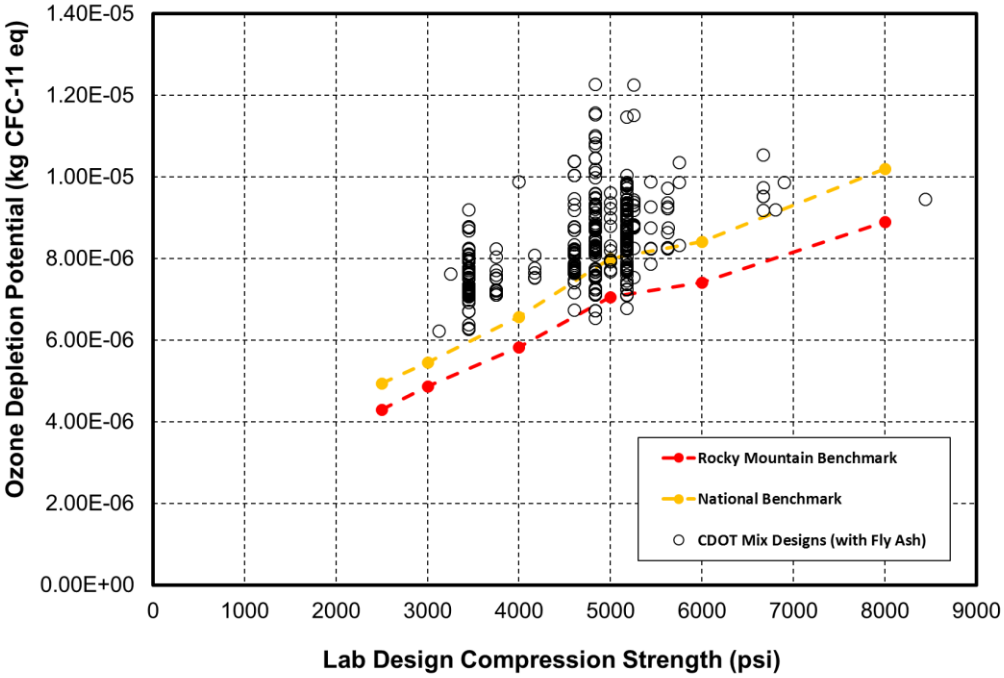

Figure 20: Lab Design Compression Strength and ODP of CDOT Mixtures with Fly Ash

Figure 21 and **Figure 22** show the ozone depletion potential of the CDOT concrete mixtures using their field compression strengths. **Figure 21** shows the ODP for mixtures designed with cement only and **Figure 22** shows the ODP for mixtures designed with a fraction of fly ash replacement. Approximately 0% of mixtures meet the Rocky Mountain benchmark.

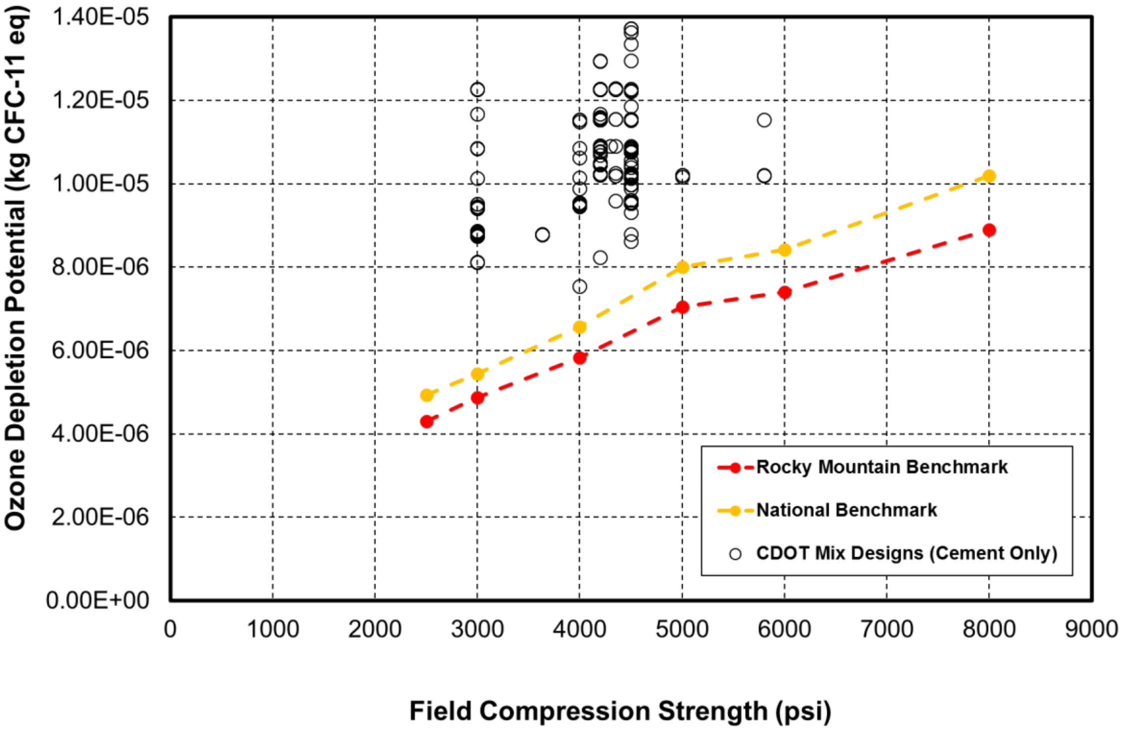

Figure 21: Field Compression Strength and ODP of CDOT Cement-Only Mixtures

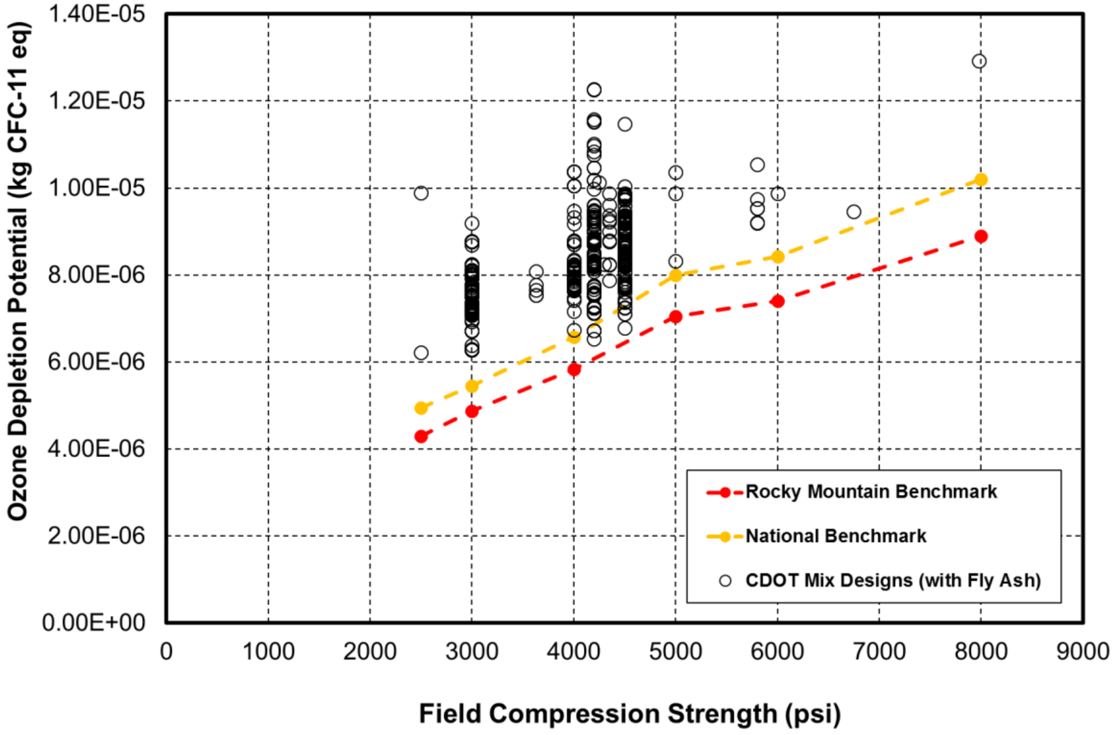

Figure 22: Field Compression Strength and ODP of CDOT Mixtures with Fly Ash

Figure 21 and **Figure 22** show that higher-strength mixtures tend to have higher ODP. However, the largest contributor to ozone depletion potential in this LCA is due to the manufacturing phase. A negligible amount of concrete mixtures meet the Rocky Mountain Rocky Mountain benchmark for ODP.

The results shown in **Figure 23** and **Figure 24** display the range of impacts from CDOT's 1262 concrete mixtures. The range of ozone depletion potential for this set of concrete mixtures are approximately 0.0000071 to 0.000010 CFC-11.

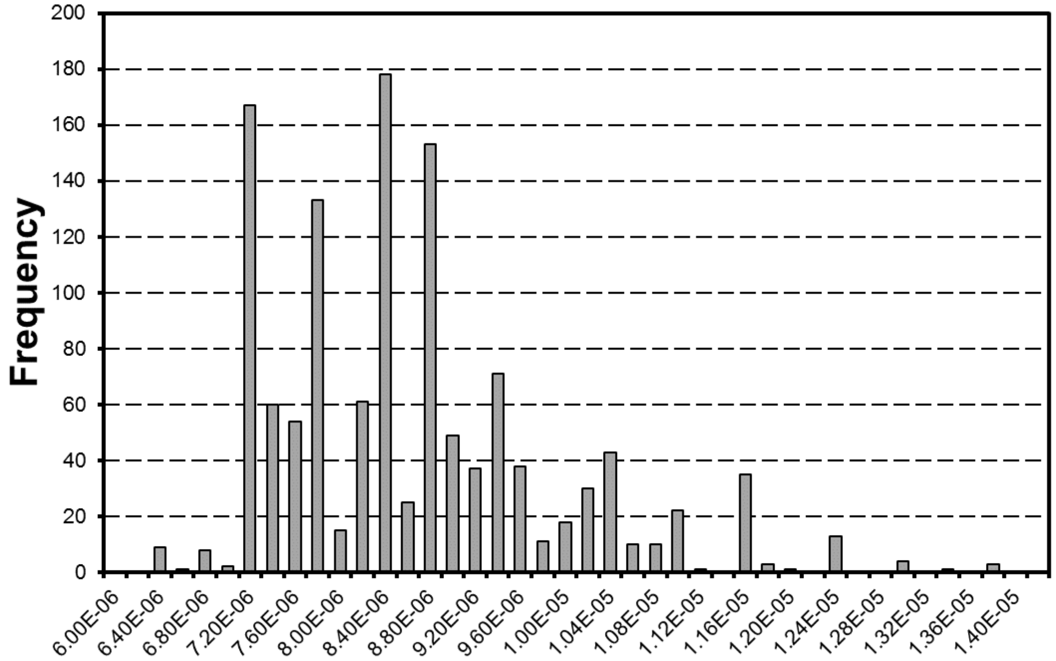

Figure 23: Histogram of CDOT's Concrete Mixtures Ozone Depletion Potential (ODP)

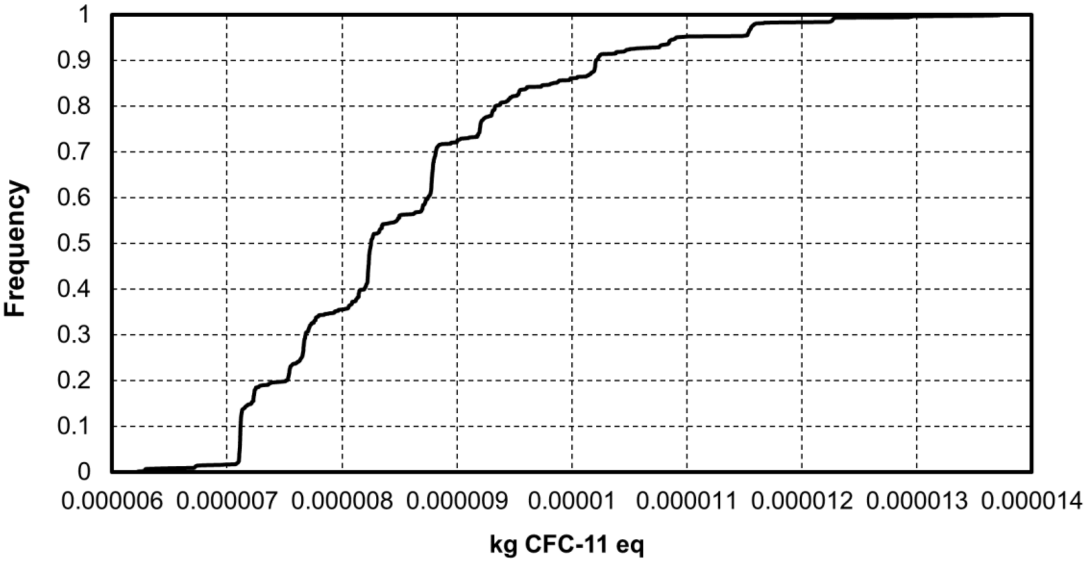

Figure 24: Cumulative Distribution Function of CDOT's Concrete Mixtures Ozone Depletion Potential (ODP)

4.2.3. Acidification Potential (AP)

The midpoint indicator, acidification potential, affects only ecosystem damage, as discussed in **Section 2.1.2.** The NRMCA benchmark metric for AP is expressed in units of kg SO_2 eq. **Figure 25** shows the NRMCA Rocky Mountain and national benchmark for acidification potential for each mixture strength. The Rocky Mountain region's benchmark for acidification potential is on average 4.8% lower than the national benchmark.

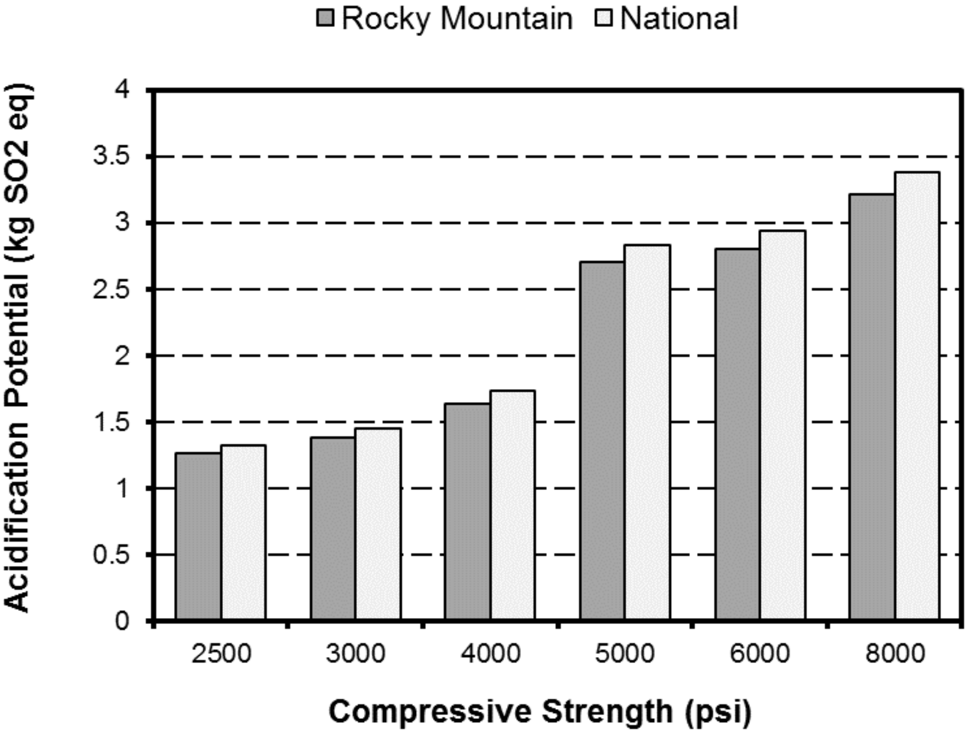

Figure 25: NRMCA Rocky Mountain and National Benchmark Acidification Potential (AP)

The results presented in **Figure 26** and **Figure 27** show the CDOT concrete mixtures acidification potential in reference to their lab design compressive strengths. **Figure 26** shows the AP for mixtures designed with cement only and **Figure 27** shows the AP for mixtures designed with a fraction of fly ash replacement. Both the Rocky Mountain and national benchmarks are plotted on the graphs for comparison. Approximately all 1262 CDOT mixtures meet the AP Rocky Mountain benchmark.

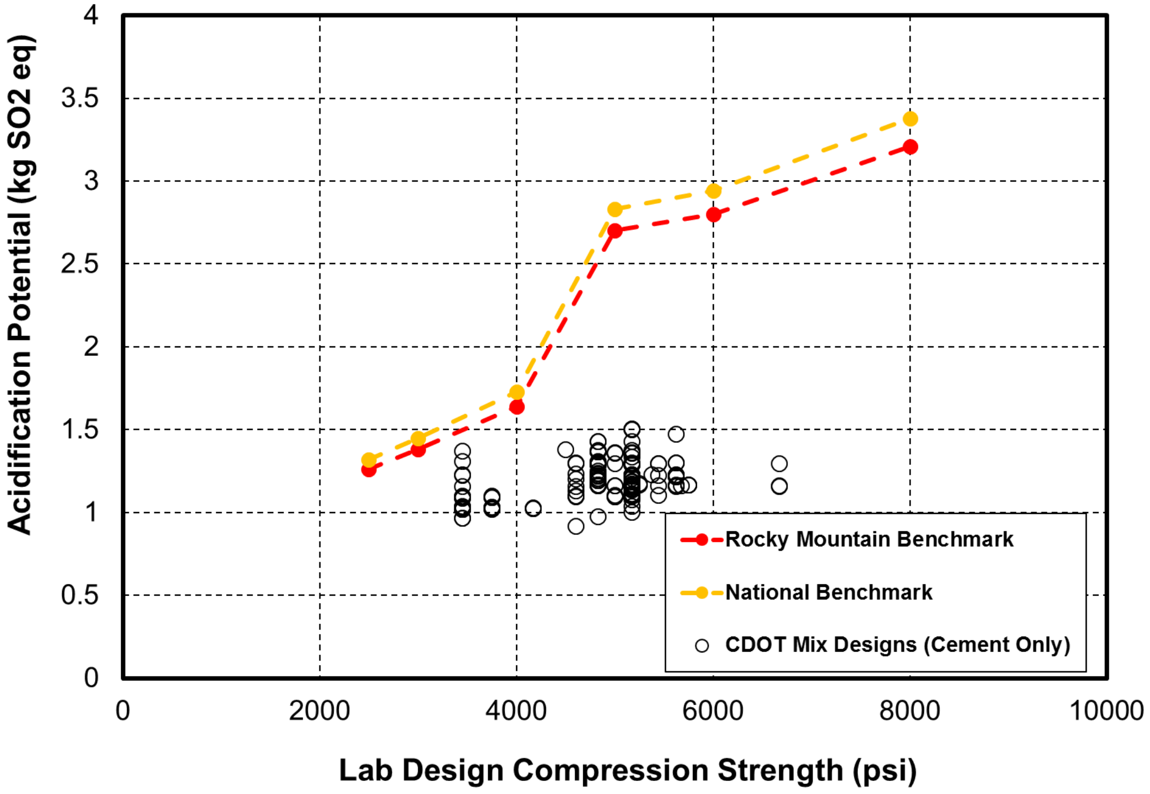

Figure 26: Lab Design Compression Strength and AP of CDOT Mixtures with Cement Only

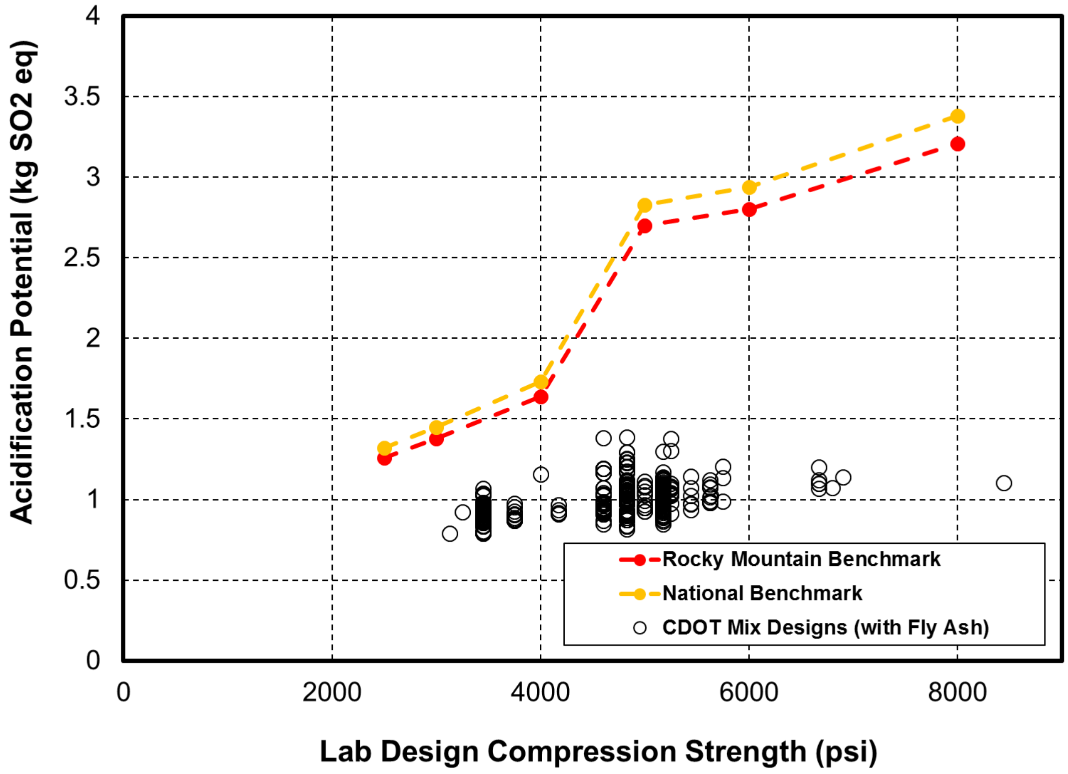

Figure 27: Lab Design Compression Strength and AP of CDOT Mixtures with Fly Ash

Figure 28 and **Figure 29** show the acidification potential of the CDOT concrete mixtures using their field compression strengths. **Figure 28** shows the AP for mixtures designed with cement only, and **Figure 29** shows the AP for mixtures designed with a fraction of fly ash replacement. The comparative LCA shows that approximately 100% of the mixtures are under the Rocky Mountain benchmark.

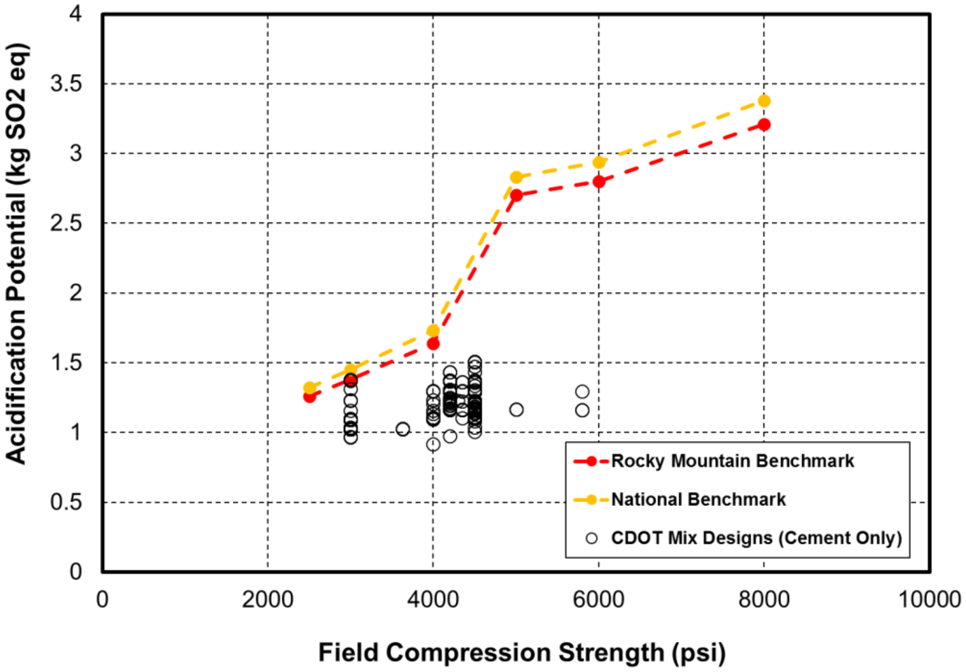

Figure 28: Field Compression Strength and AP of CDOT Cement-Only Mixtures

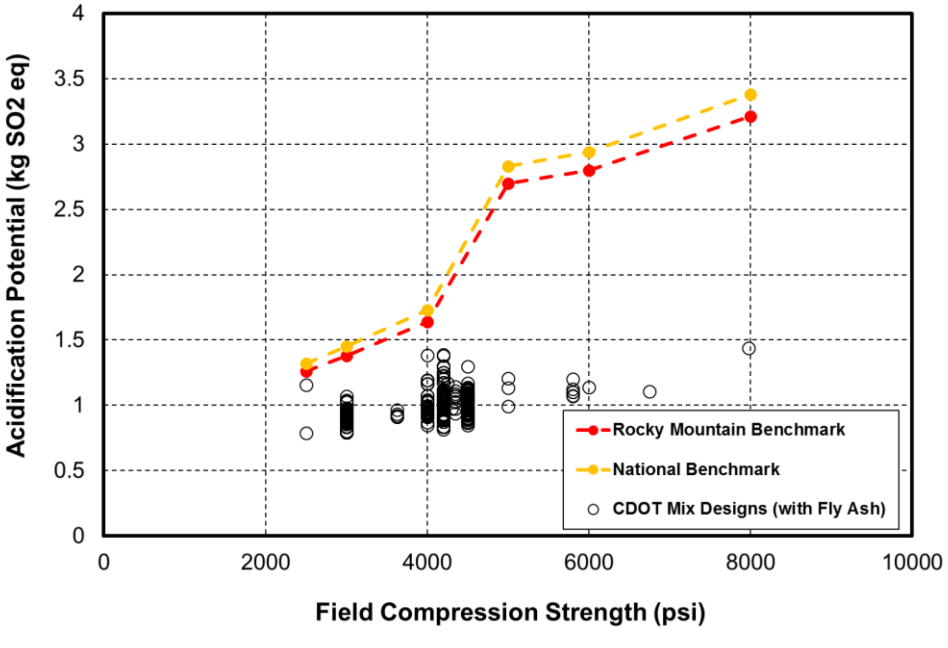

Figure 29: Field Compression Strength and AP of CDOT Mixtures with Fly Ash

Figure 26, **Figure 27**, **Figure 28** and **Figure 29**, show that in the benchmark data, higher-strength mixture designs tend to have higher AP. This result is largely due to the increased quantity of cement, since cement plants are typically a source of sulfur dioxide [35]. However, CDOT's concrete mixtures do not have the same influence on AP. Since the majority of the mixtures meet the benchmark by a significant margin, AP could be used as a tradeoff for another optimization criteria in a decision-making situation.

The results shown in **Figure 30** and **Figure 31** display the range of impacts from CDOT's 1262 concrete mixtures. The range of acidification potential for this set of concrete mixtures is approximately 0.872 to 1.168 kg SO_2 eq for 90% of the mixtures.

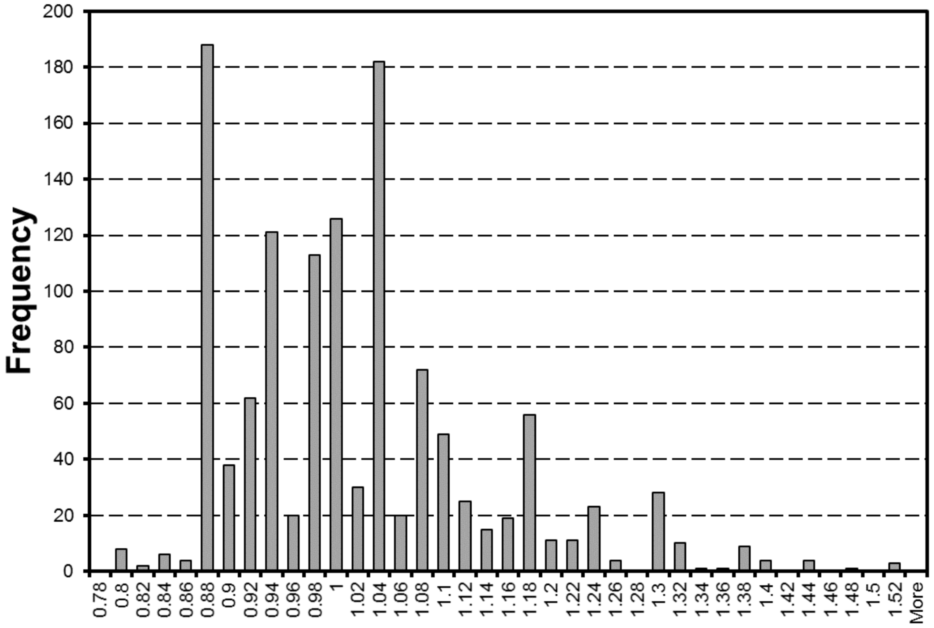

Figure 30: Histogram of CDOT's Concrete Mixtures Acidification Potential (AP)

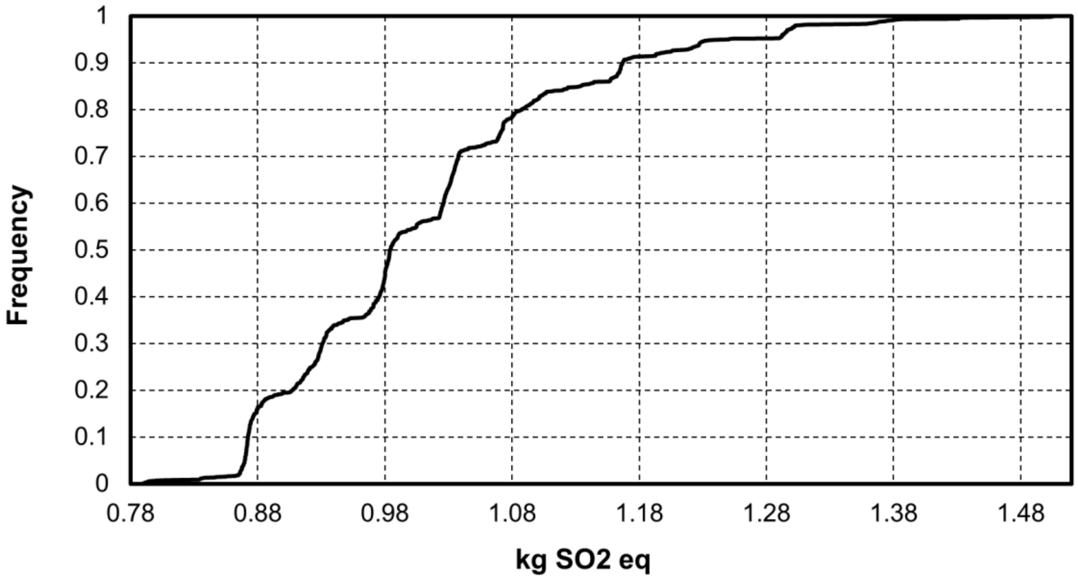

Figure 31: Cumulative Distribution Function of CDOT's Concrete Mixtures Acidification Potential (AP)

4.2.4. Eutrophication Potential (EP)

Eutrophication affects only ecosystem damage discussed in **Section 2.1.2.** The NRMCA benchmark metric for EP is expressed in units of kg N eq. The results, seen in **Figure 32**, show the differences in the Rocky Mountain and national benchmarks. The Rocky Mountain benchmark for EP is on average 18.63% lower than the national benchmark, the largest average difference in benchmarks of all impact indicators.

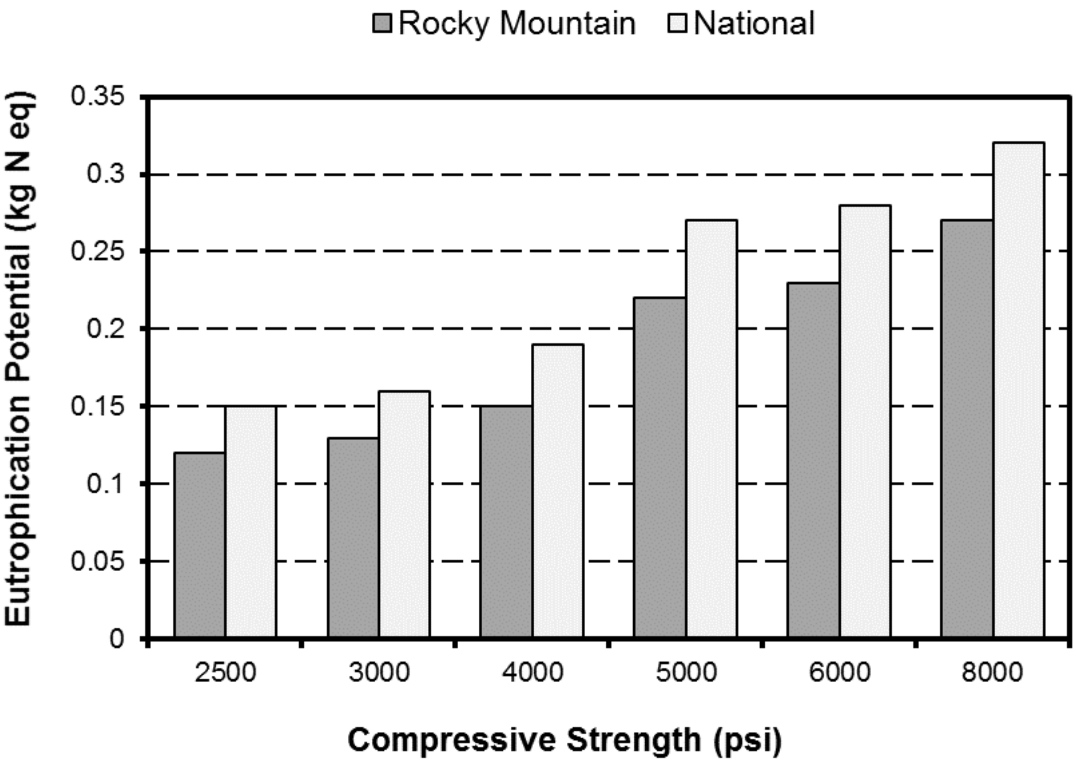

Figure 32: NRMCA Rocky Mountain and National Benchmark Eutrophication Potential (EP)

The results presented in **Figure 33** and **Figure 34** show the CDOT concrete mixtures eutrophication potential in reference to their lab design compression strengths. **Figure 33** shows the EP for mixtures designed with cement only and **Figure 34** shows the EP for mixtures designed with a fraction of fly ash replacement. Both the Rocky Mountain and national benchmarks are plotted on the graphs for comparison. 0% of the mixtures meet EP Rocky Mountain benchmark.

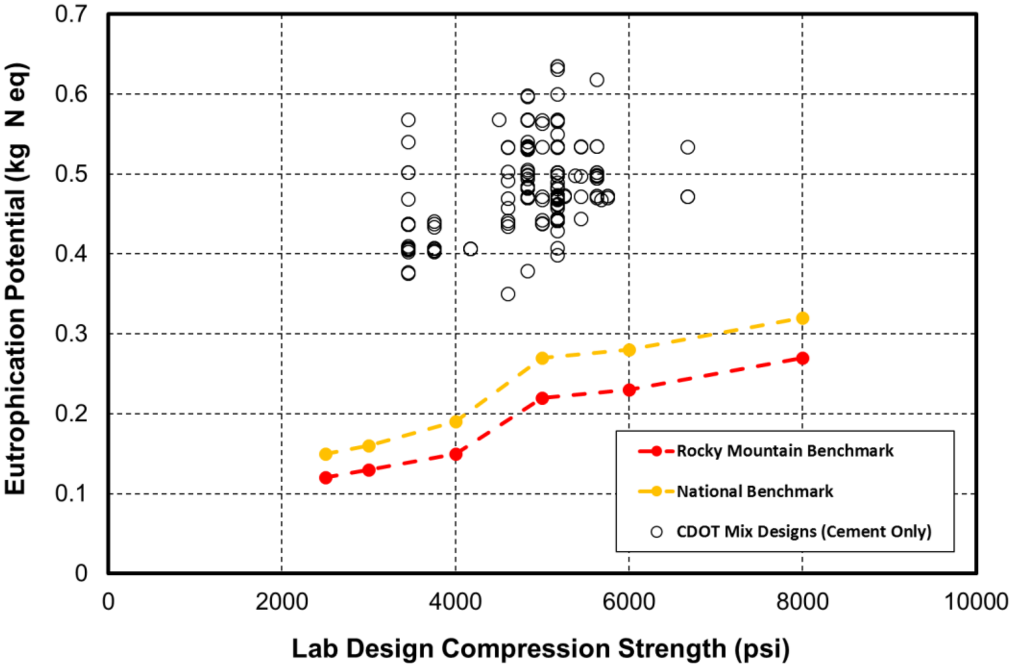

Figure 33: Lab Design Compression Strength and EP of CDOT Mixtures with Cement Only

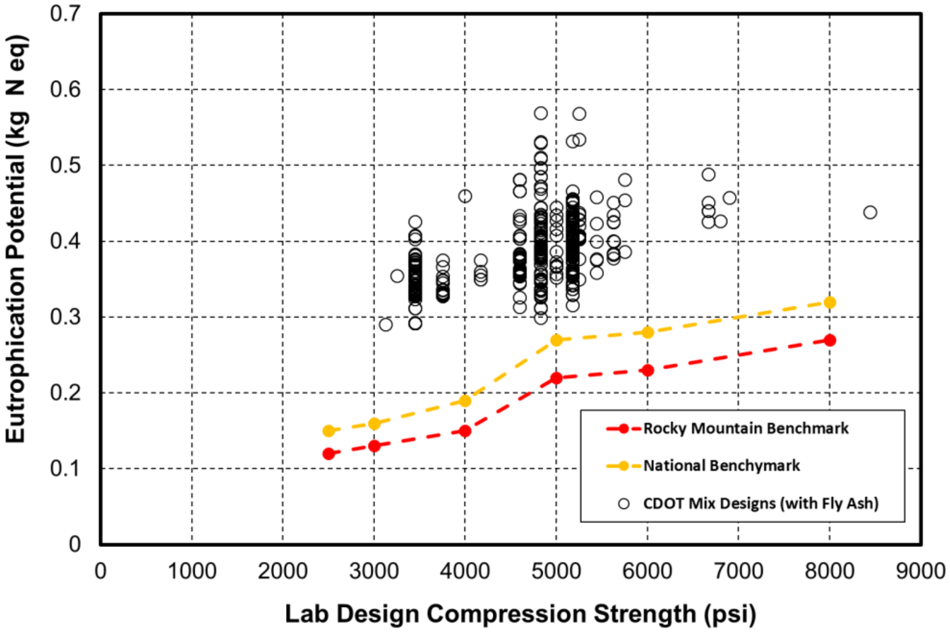

Figure 34: Lab Design Compression Strength and EP of CDOT Mixtures with Fly Ash

Figure 35 and **Figure 36**, show the eutrophication potential of the CDOT concrete mixtures using their field compression strengths. **Figure 35** shows the EP for mixtures designed with cement only and **Figure 36** shows the EP for mixtures designed with a fraction of fly ash replacement. This comparative LCA shows that approximately 0% of the mixtures meet EP Rocky Mountain benchmark.

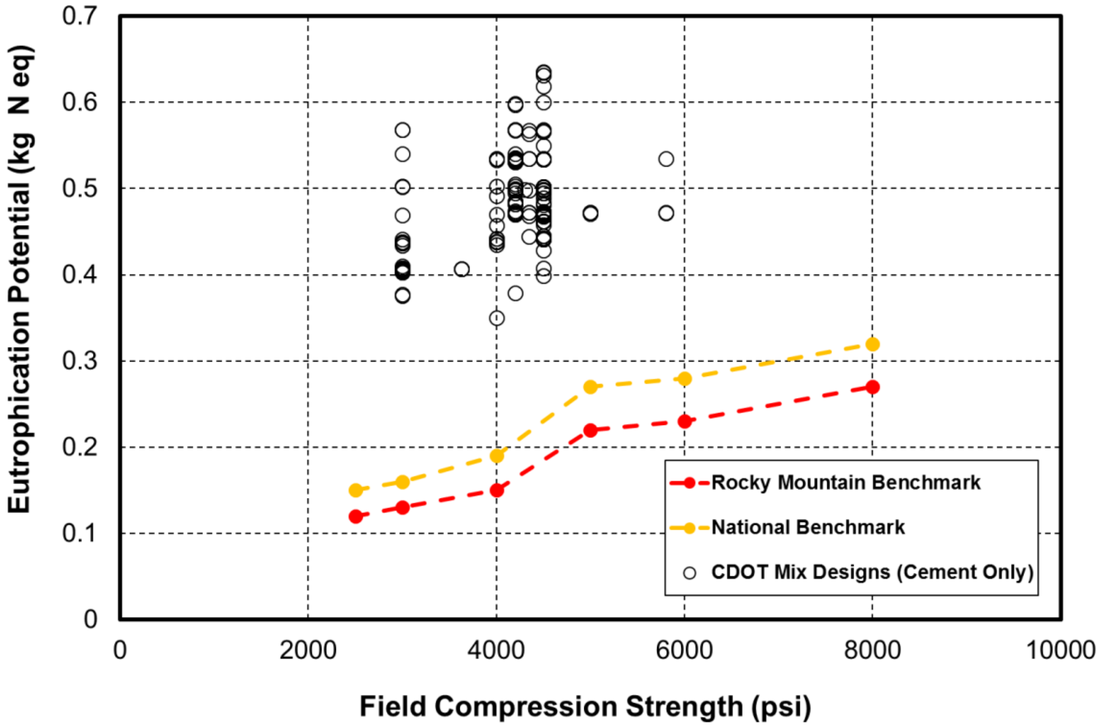

Figure 35: Field Compression Strength and EP of CDOT Cement Only Mixtures

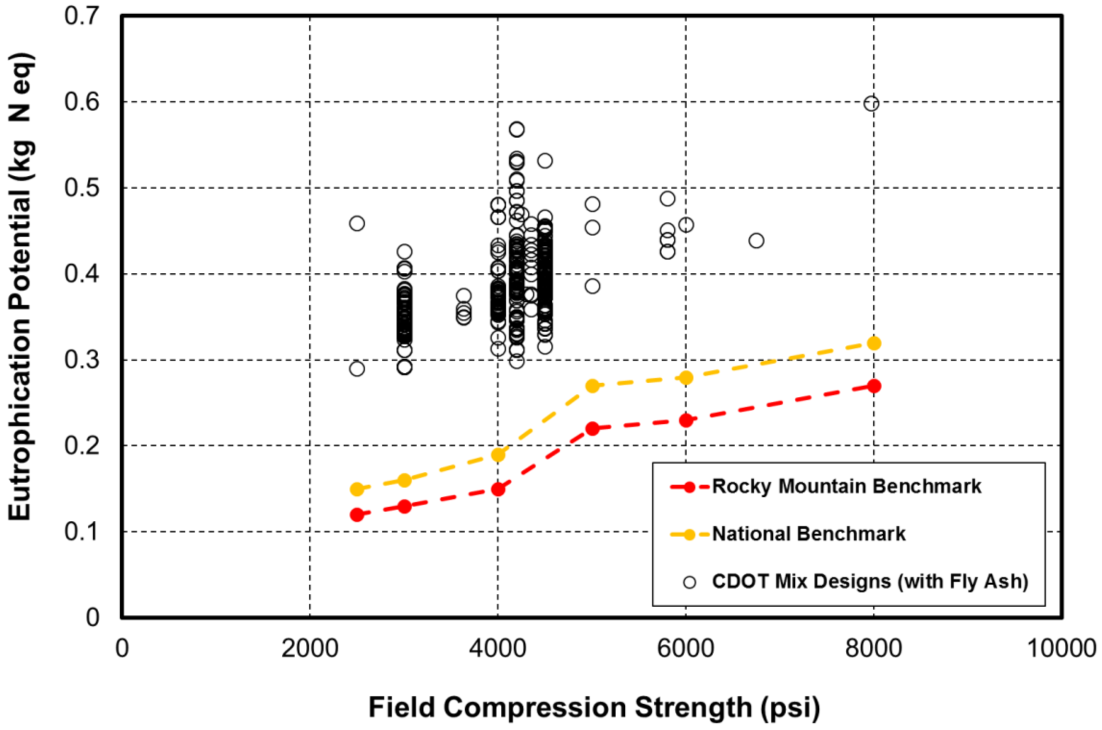

Figure 36: Field Compression Strength and EP of CDOT Mixtures with Fly Ash

Studies have shown that the largest contributor to eutrophication potential are coarse aggregate (accounting for 70%) and fine aggregate (accounting for approximately 30%) [35]. However, there is no visual trend of aggregate in CDOT's mixtures impacting EP. The overlying result from **Figure 33, Figure 34**, **Figure 35** and **Figure 36** shows that CDOT's concrete mixtures are significantly above the benchmark. In a mixture design optimization or decision-making process, eutrophication potential can be a tradeoff environmental indicator to focus on getting closer to the benchmark in exchange for another objective.

The results shown in **Figure 37** and **Figure 38** display the range of impacts from CDOT's 1262 concrete mixtures. The range of eutrophication potential for this set of concrete mixtures is approximately 0.330 kg N eq to 0.473 kg N eq when looking at a 90%.

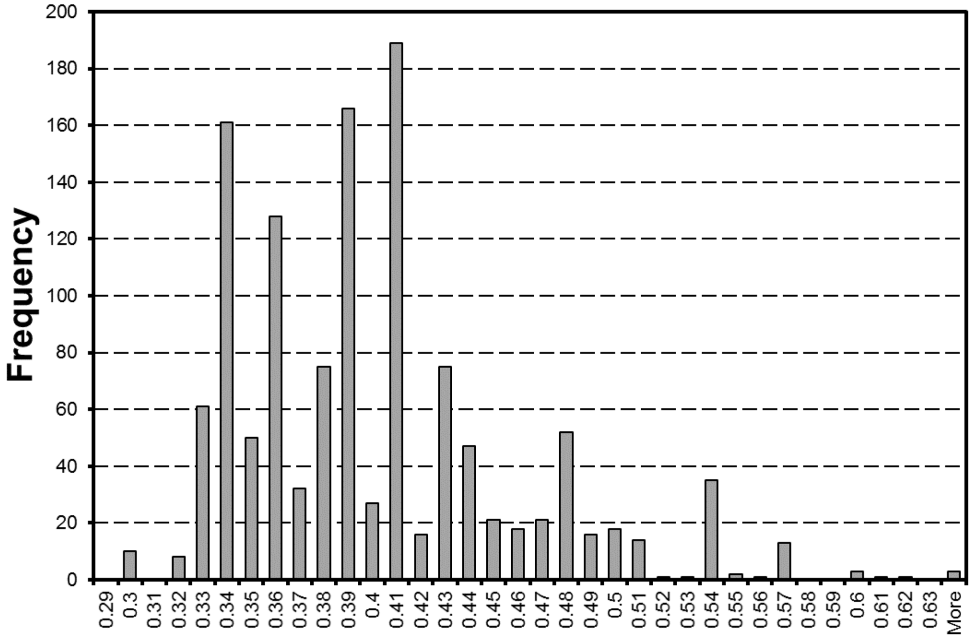

Figure 37: Histogram of CDOT's Concrete Mixtures Eutrophication Potential (EP)

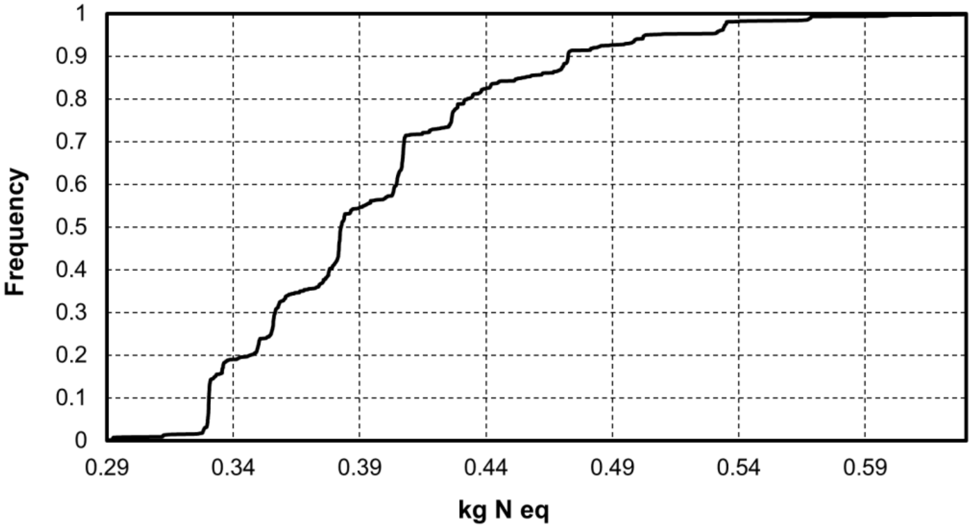

Figure 38: Cumulative Distribution Function of CDOT's Concrete Mixtures Eutrophication Potential (EP)

4.2.5. Smog Potential (POCP)

Smog potential effects ecosystem damage and human health discussed in **Section 2.1.2.** The NRMCA benchmark metric for POCP is expressed in units of kg O_3 eq. The results seen in **Figure 39**, show the significant difference in the Rocky Mountain and national benchmarks. The Rocky Mountain benchmark for POCP is on average 3.55% lower than the national benchmark.

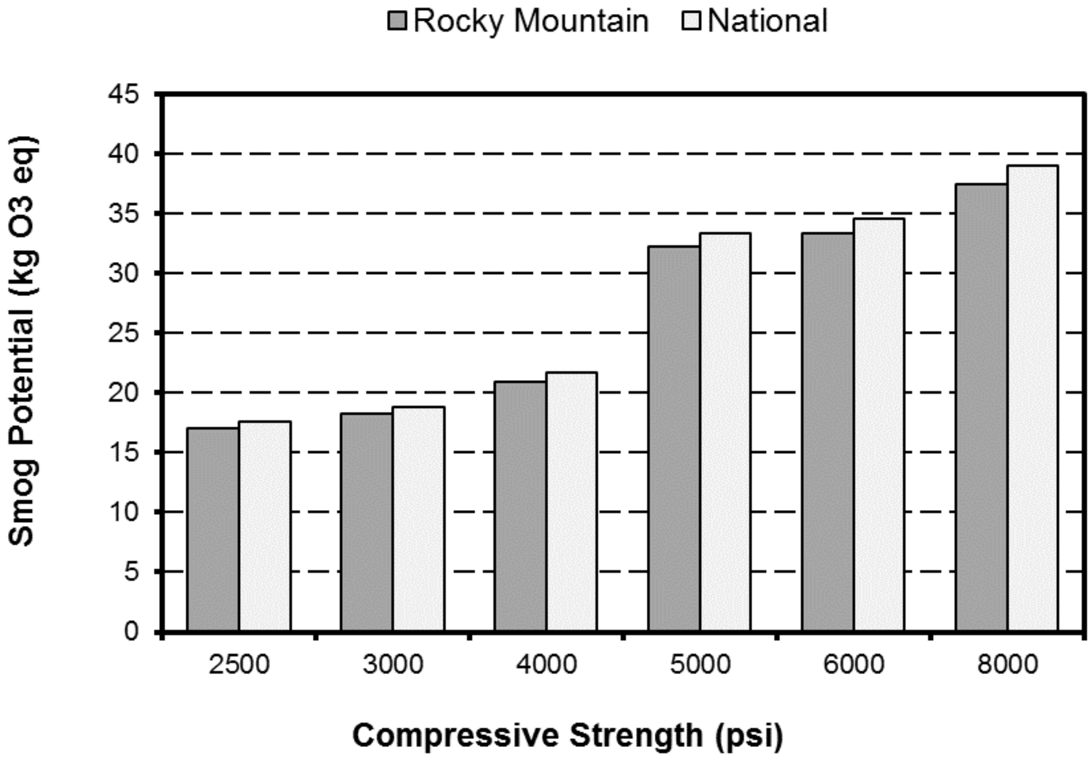

Figure 39: NRMCA Rocky Mountain and National Benchmark Smog Potential (POCP)

The results presented in **Figure 40** and **Figure 41** show the CDOT concrete mixtures smog potential in reference to their lab design compression strengths.

Figure 40 shows the POCP for mixtures designed with cement only and **Figure 41** shows the POCP for mixtures designed with a fraction of fly ash replacement. Both the Rocky Mountain and national benchmarks are plotted on the graphs to show how the CDOT mixtures compare. Approximately 99.2% of the mixtures meet POCP Rocky Mountain benchmark when analyzing the mixtures with their design strengths. The negligible number of mixtures that do not meet standard are approximately 80% cement only mixtures.

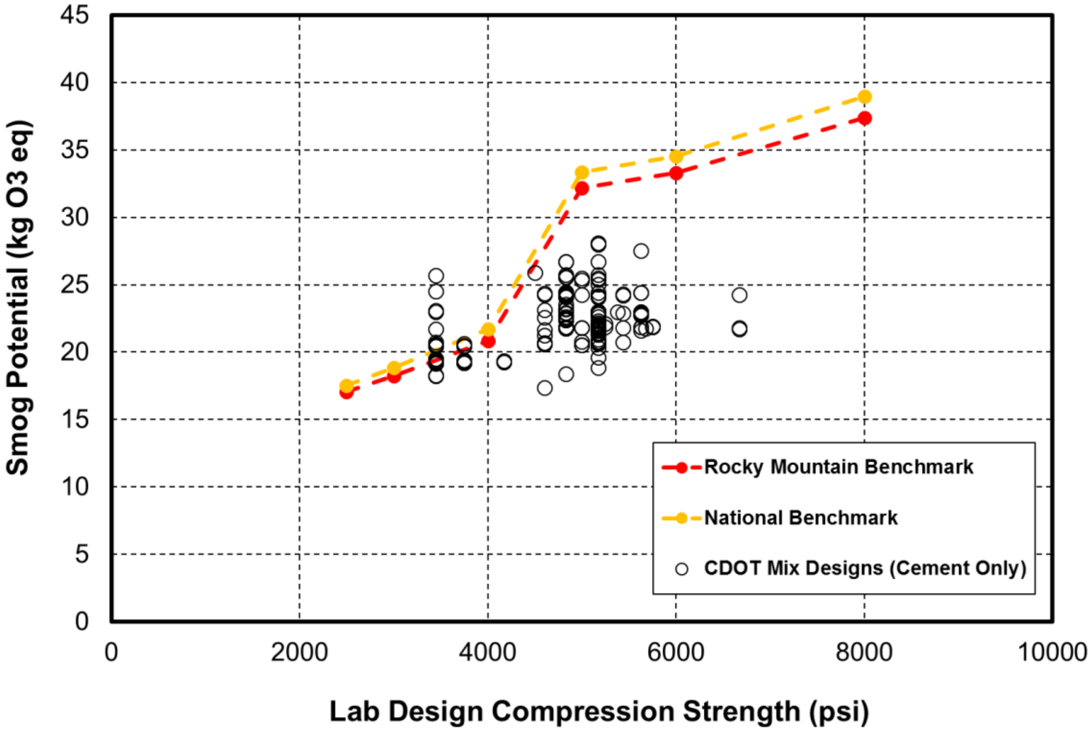

Figure 40: Lab Design Compression Strength and POCP of CDOT Mixtures with Cement Only

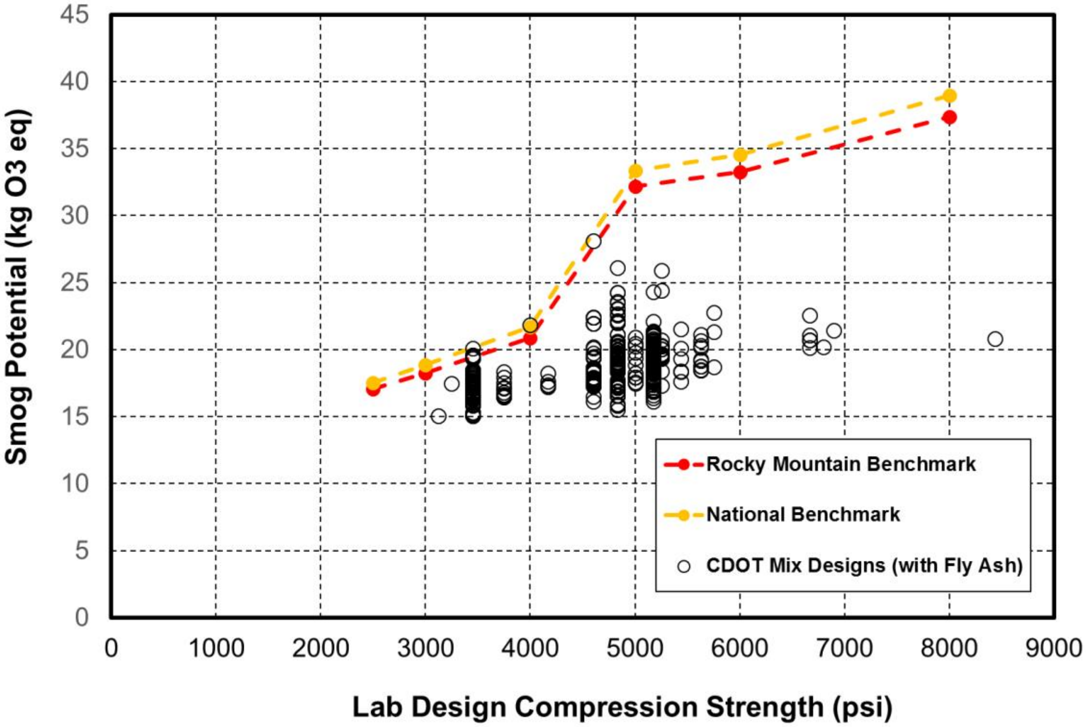

Figure 41: Lab Design Compression Strength and POCP of CDOT Mixtures with Fly Ash

Figure 42 and **Figure 43**, show the smog potential of the CDOT concrete mixtures using their field compression strengths. **Figure 42** shows the POCP for mixtures designed with cement only and **Figure 43** shows the POCP for mixtures designed with a fraction of fly ash replacement. This comparative LCA shows that approximately 94.1% mixtures meet POCP Rocky Mountain benchmark. The mixtures that do not meet the standard benchmark are roughly 79.7% mixtures that use cement only.

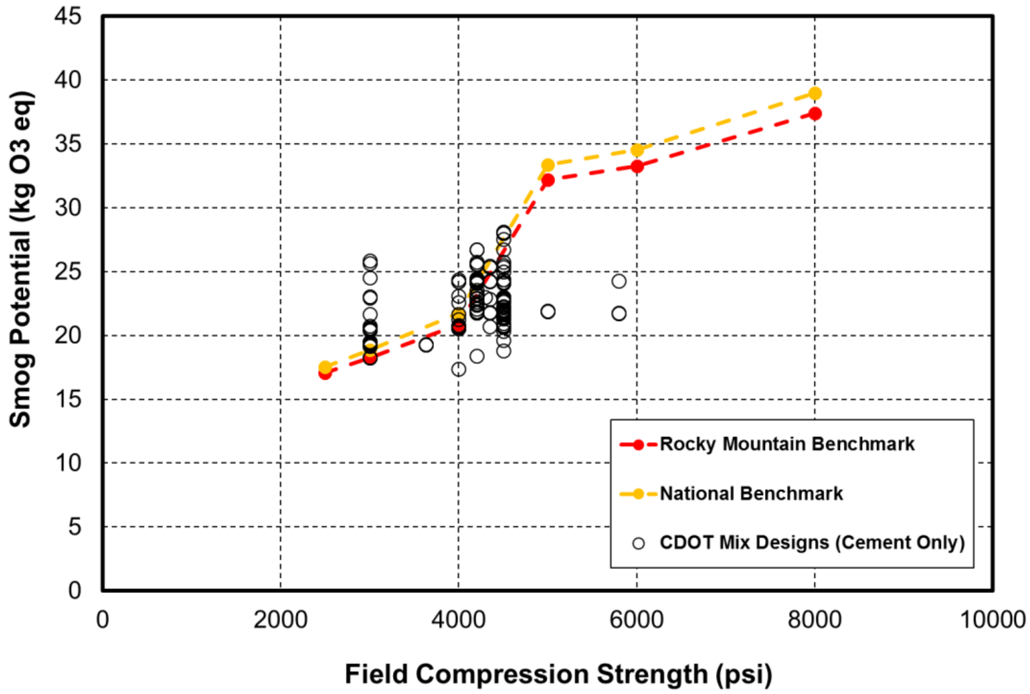

Figure 42: Field Compression Strength and POCP of CDOT Cement Only Mixtures

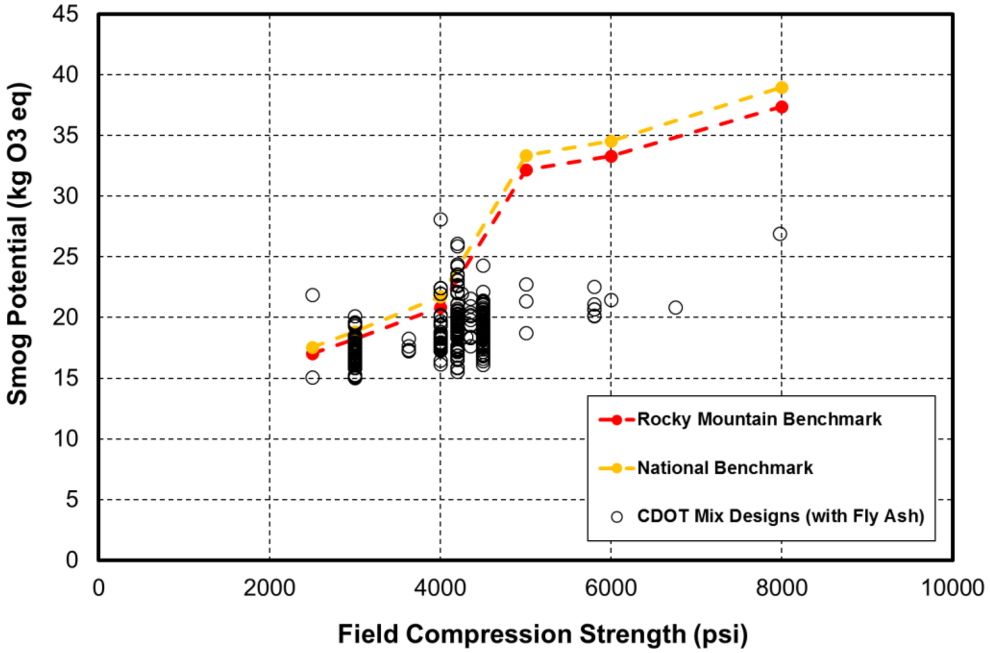

Figure 43: Field Compression Strength and POCP of CDOT Mixtures with Fly Ash

Figure 40 and **Figure 41, Figure 42** and **Figure 43** show that higher-strength mixture designs tend to have a slightly higher POCP, largely due to the increased quantity of cement. This reiterates the research that has shown cement plants are a significant source of sulfur dioxide since POCP increases as strength increases and cement content increases [35]. The majority of the mixtures meet the benchmark particularly in the lab design comparison.

The results shown in **Figure 44** and **Figure 45** display the range of impacts from CDOT's 1262 concrete mixtures. The range of smog potential for this set of concrete mixtures is approximately 16.53 kg O_3 eq to 21.90 kg O_3 eq.

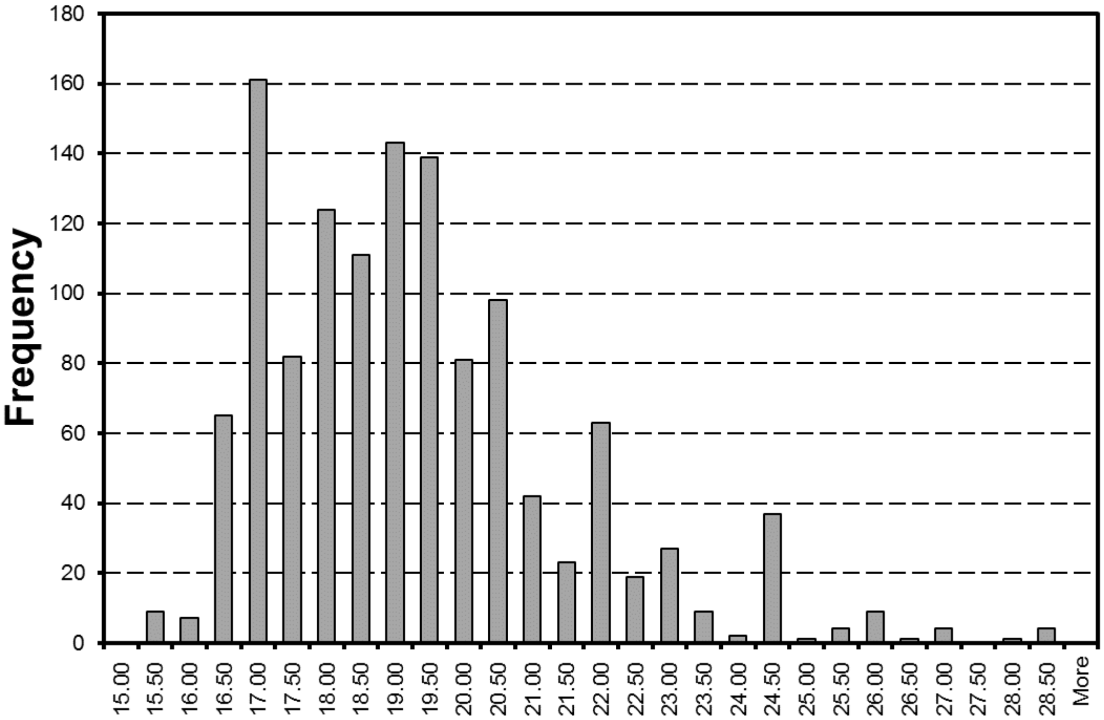

Figure 44: Histogram of CDOT's Concrete Mixtures Smog Potential (POCP)

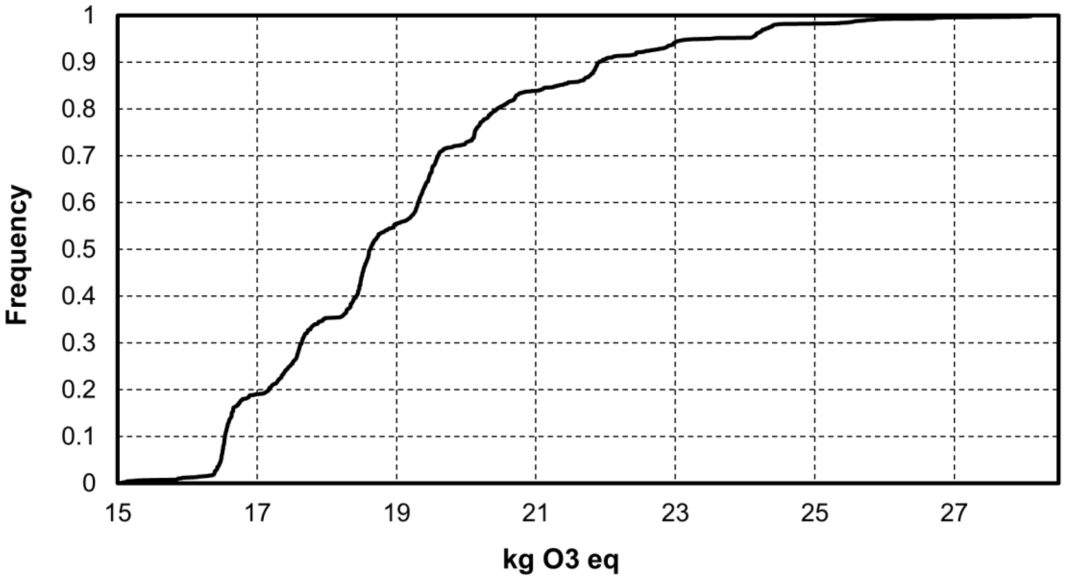

Figure 45: Cumulative Distribution Function of CDOT's Concrete Smog Potential (POCP)

4.2.6. Total Primary Energy (PEC)

Total primary energy consumption affects resource consumption as discussed in **Section 2.1.2.** The NRMCA benchmark metric for PEC is expressed in units of MJ. The results seen in **Figure 46**, show the significant difference in the Rocky Mountain and national benchmark. The Rocky Mountain benchmark for PEC is on average 1.75% lower than the national benchmark.

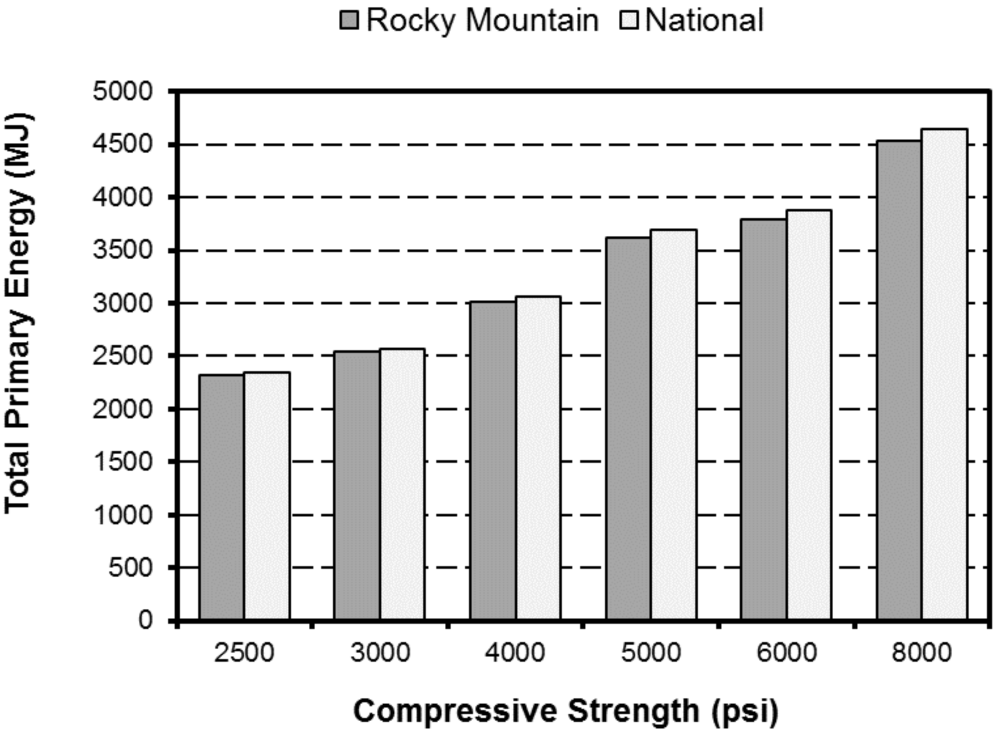

Figure 46: NRMCA Rocky Mountain and National Benchmark Total Primary Energy Consumption (PEC)

The results presented in **Figure 47** and **Figure 48** show the CDOT concrete mixtures total primary energy consumption in reference to their lab design compression strengths. **Figure 47** shows the PEC for mixtures designed with cement only and **Figure 48** shows the PEC for mixtures designed with a fraction of fly ash replacement. Both the Rocky Mountain and national benchmark are plotted on the graphs for comparison. Approximately 99.5% mixtures meet PEC Rocky Mountain benchmark. The few mixtures that don’t meet benchmark are mixtures that used cement only.

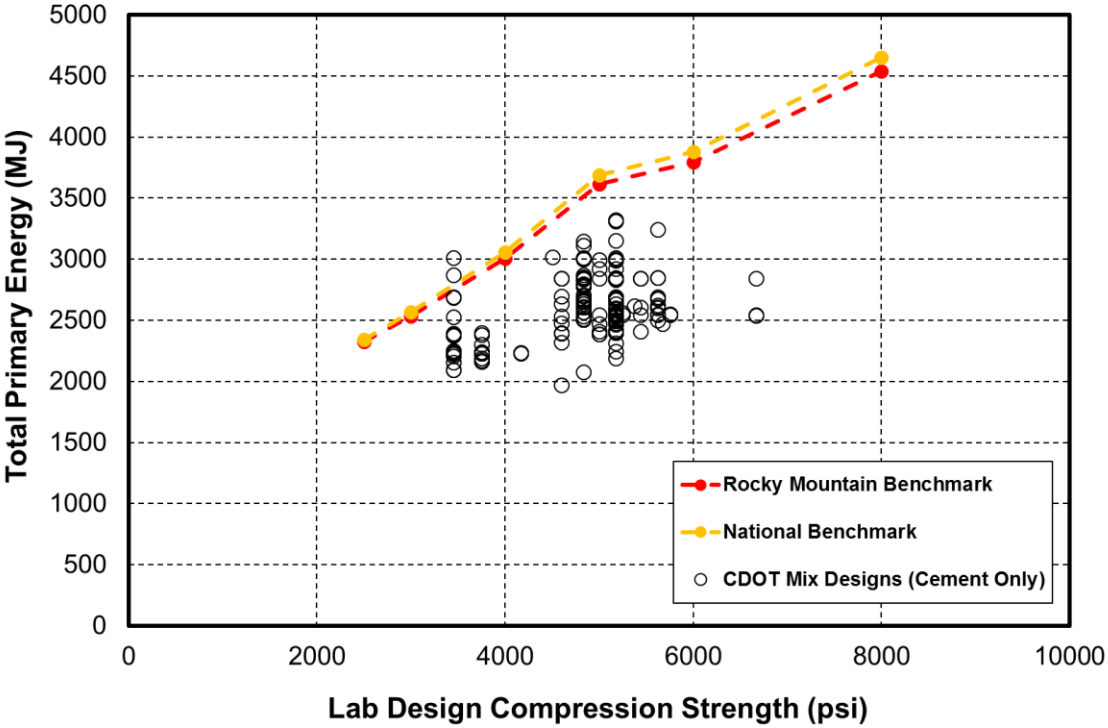

Figure 47: Lab Design Compression Strength and PEC of CDOT Mixtures with Cement Only

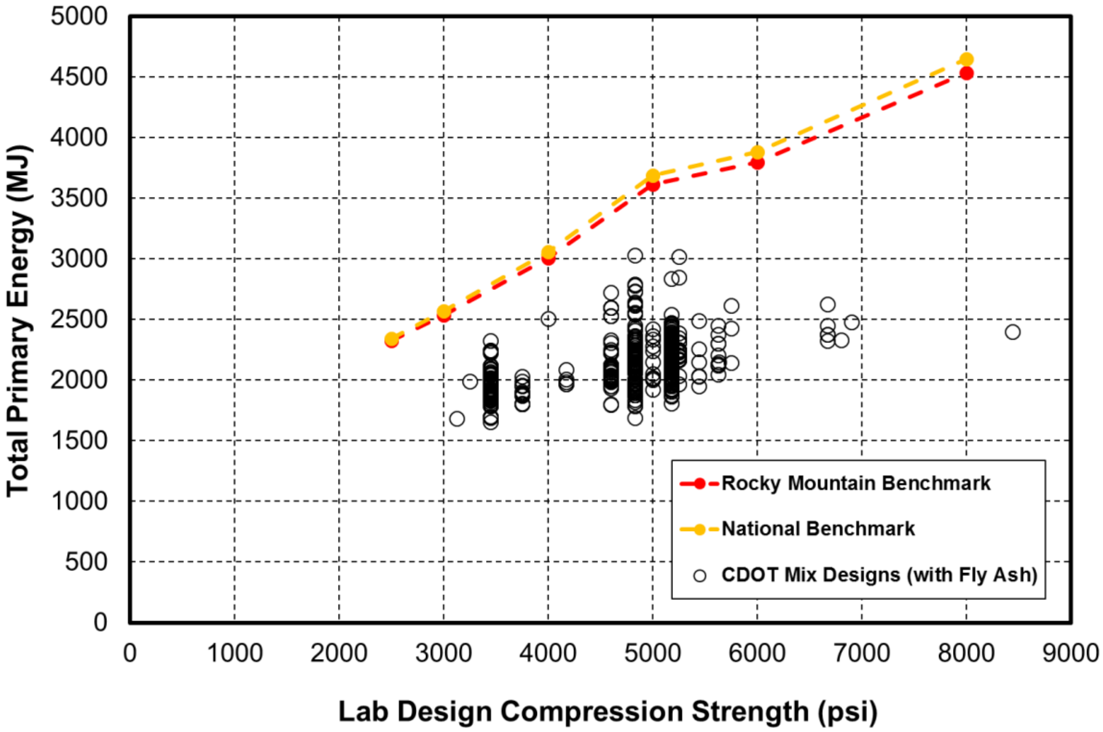

Figure 48: Lab Design Compression Strength and PEC of CDOT Mixtures with Fly Ash

Figure 49 and **Figure 50**, show the total primary energy consumption of the CDOT concrete mixtures using their field compression strengths. **Figure 49** shows the PEC for mixtures designed with cement only and **Figure 50** shows the PEC for mixtures designed with a fraction of fly ash replacement. This comparative LCA shows that approximately 99.3% of the mixtures meet PEC Rocky Mountain benchmark. The mixtures that do not meet standard are roughly 88.9% mixtures that use cement only.

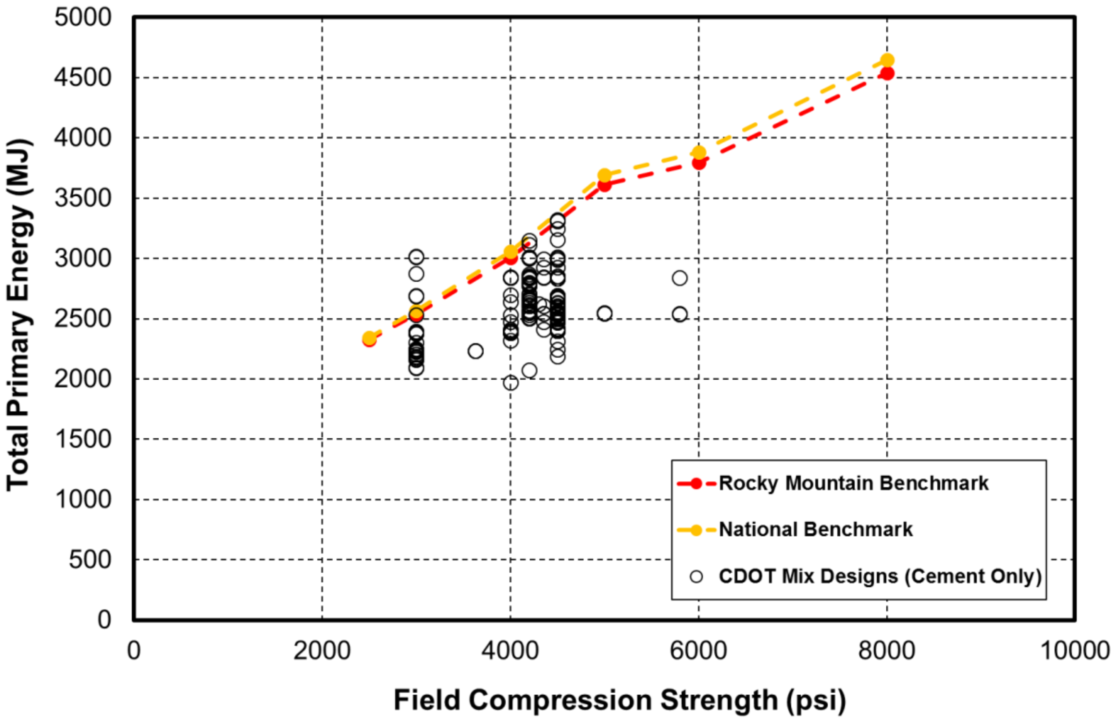

Figure 49: Field Compression Strength and PEC of CDOT Cement Only Mixtures

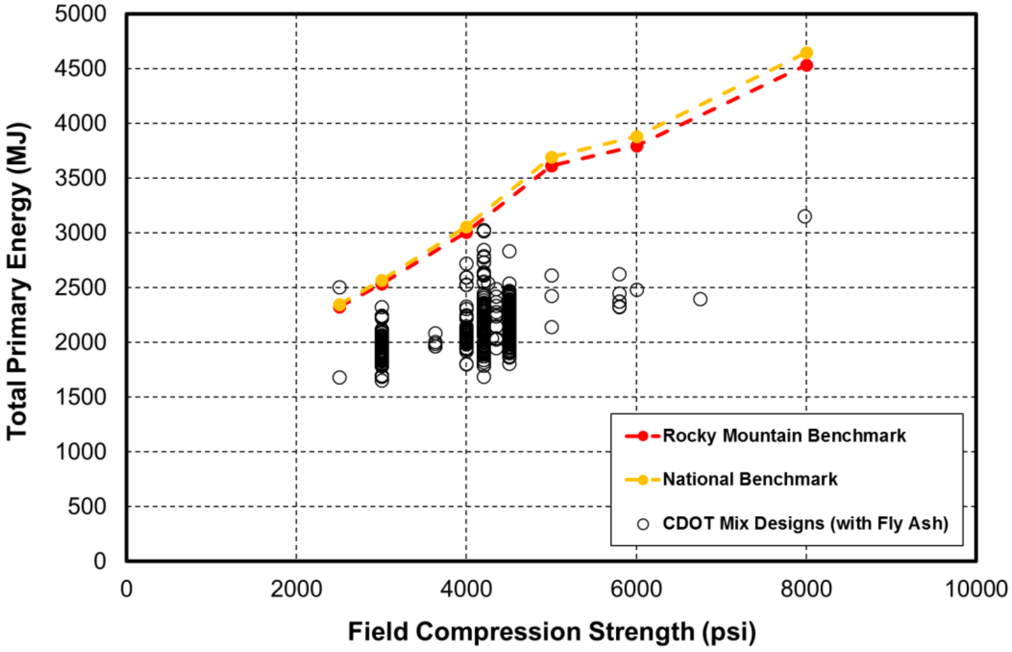

Figure 50: Field Compression Strength and PEC of CDOT Mixtures with Fly Ash

Figure 47, Figure 48, Figure 49 and **Figure 50** show that higher-strength mixture designs tend to have higher PEC, largely due to the increased quantity of cement. Since the majority of the mixtures that do not meet the benchmark use cement only, it is evident that the addition of a fraction of fly ash replacement helps lower the impacts to total primary energy consumption. This reiterates studies showing that cement manufacturing is the most energy-intensive of all manufacturing industries in the United States [34].

The results shown in **Figure 51** and **Figure 52** display the range of impacts from CDOT's 1262 concrete mixtures. The range of total primary energy consumption for this set of concrete mixtures is approximately 1874.2 MJ to 2547.0 MJ.

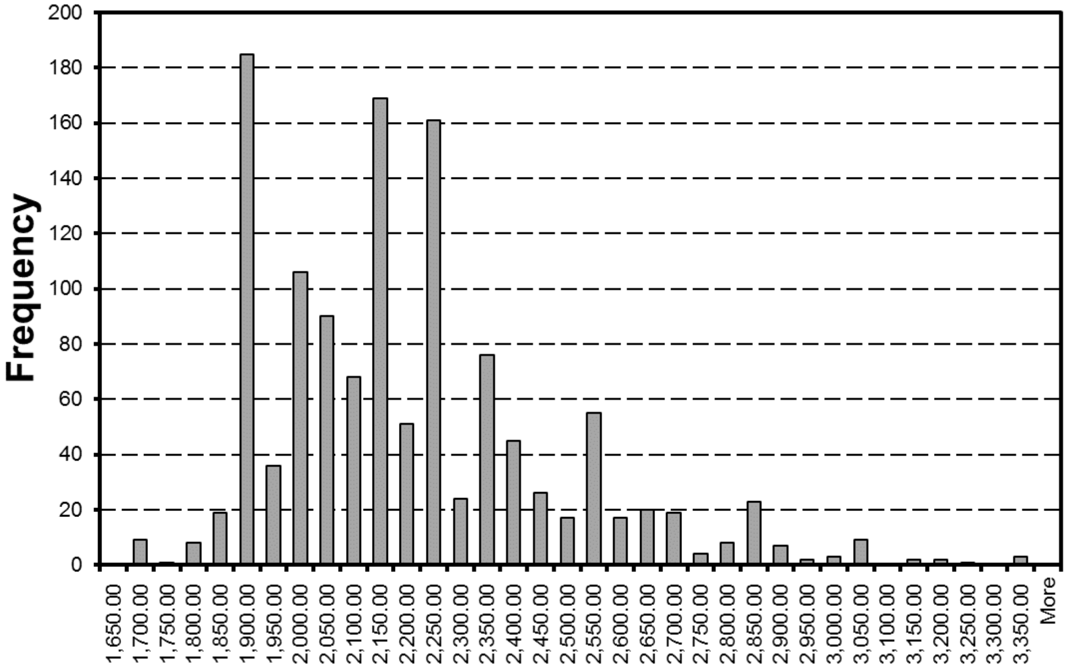

Figure 51: Histogram of CDOT's Mixtures Total Primary Energy Consumption (PEC)

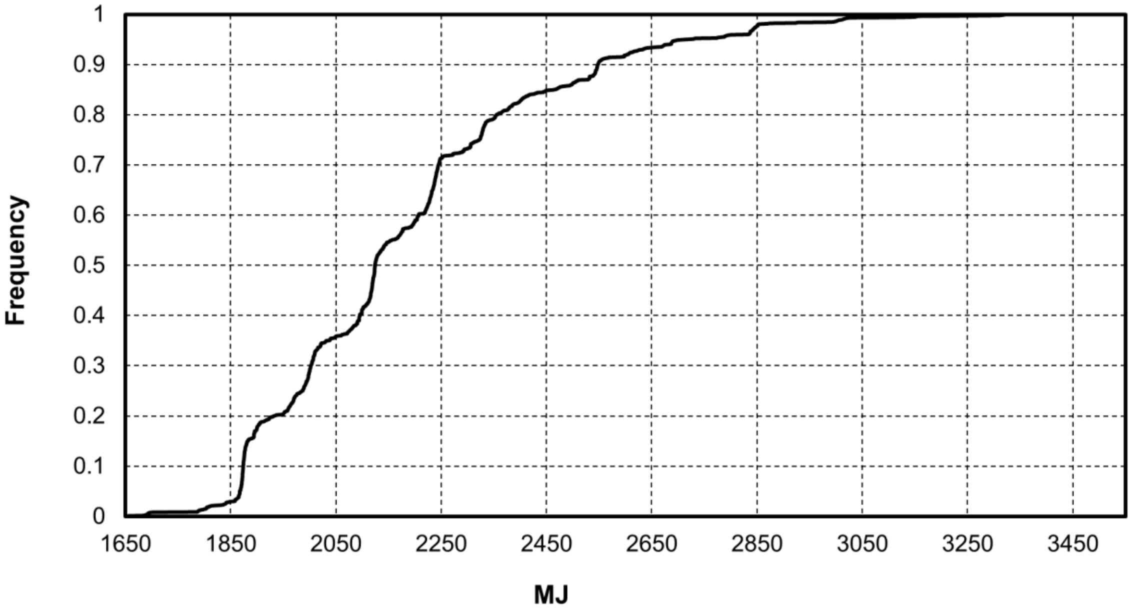

Figure 52: Cumulative Distribution Function of CDOT's Concrete Mixtures Primary Energy Consumption (PEC)

4.2.7. Non-Renewable Energy (NRE)

Non-renewable energy consumption affects resource consumption as discussed in **Section 2.1.2.** The NRMCA benchmark metric for NRE is expressed in units of MJ. The results seen in **Figure 53**, show the significant difference in the Rocky Mountain and national benchmark. The Rocky Mountain benchmark for NRE is on average 2.36% lower than the national benchmark.

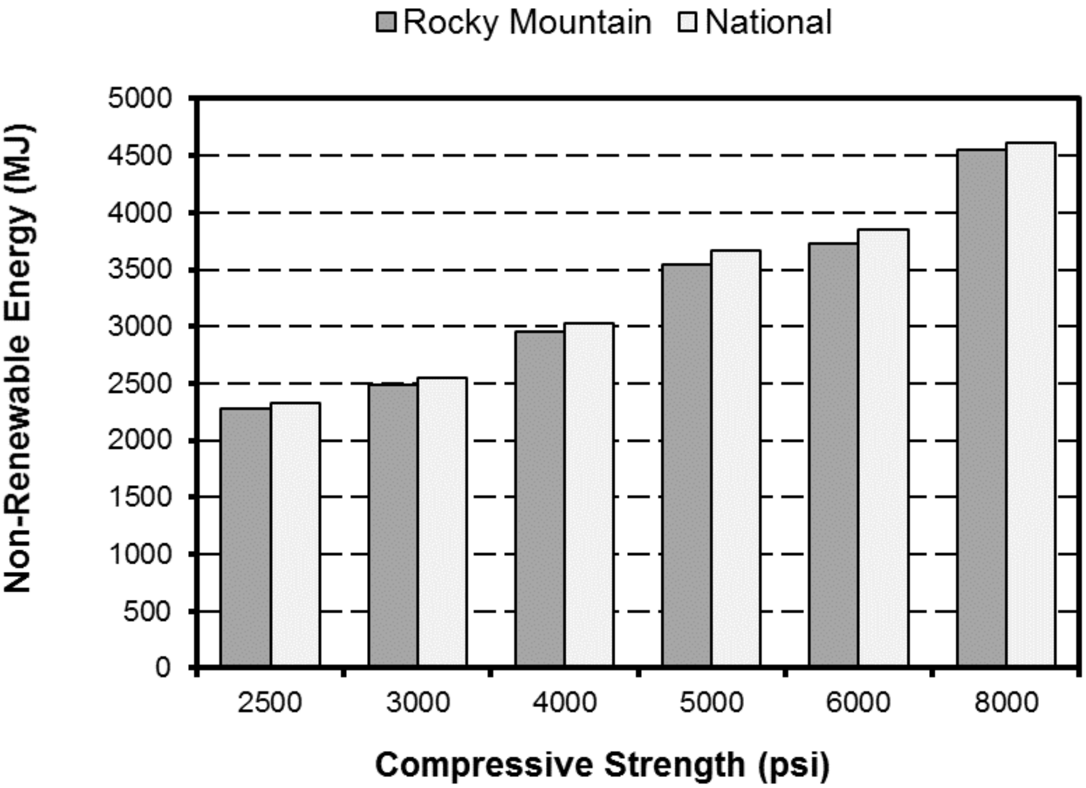

Figure 53: NRMCA Rocky Mountain and National Benchmark Non-Renewable Energy Consumption (NRE)

The results presented in **Figure 54** and **Figure 55** show the CDOT concrete mixtures non-renewable energy consumption in reference to their lab design compression strengths. **Figure 54** shows the NRE for mixtures designed with cement only and **Figure 55** shows the NRE for mixtures designed with a fraction of fly ash replacement. Both the Rocky Mountain and national benchmark are plotted on the graphs for comparison. Approximately 99.3% mixtures meet NRE Rocky Mountain benchmark. The few mixtures that don't meet benchmark are mixtures that used cement only.

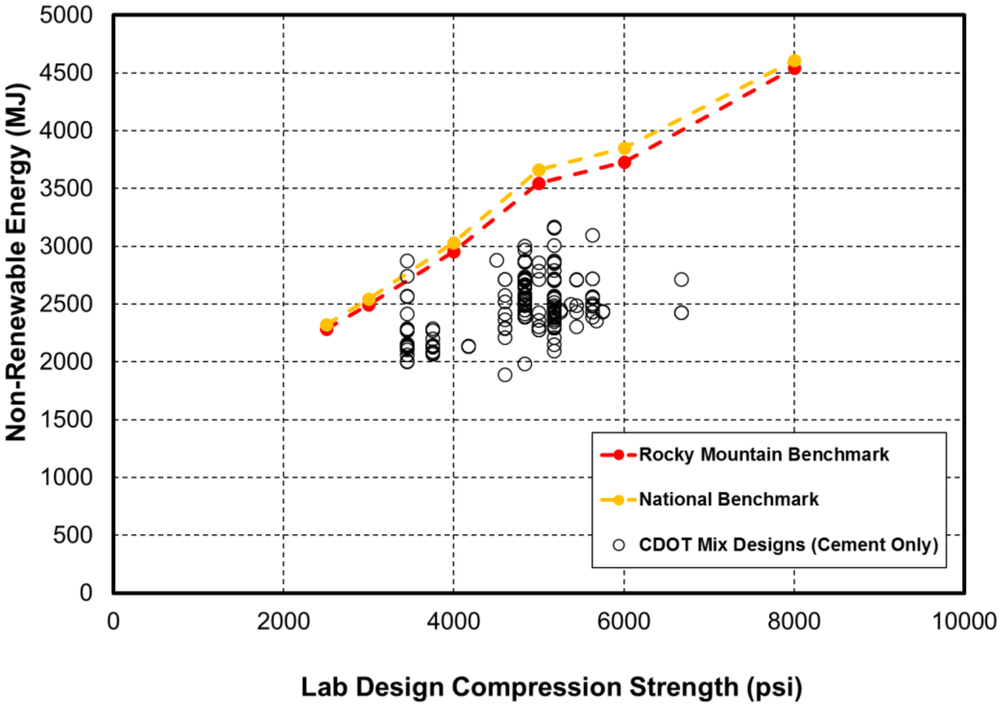

Figure 54: Lab Design Compression Strength and NRE of CDOT Mixtures with Cement Only

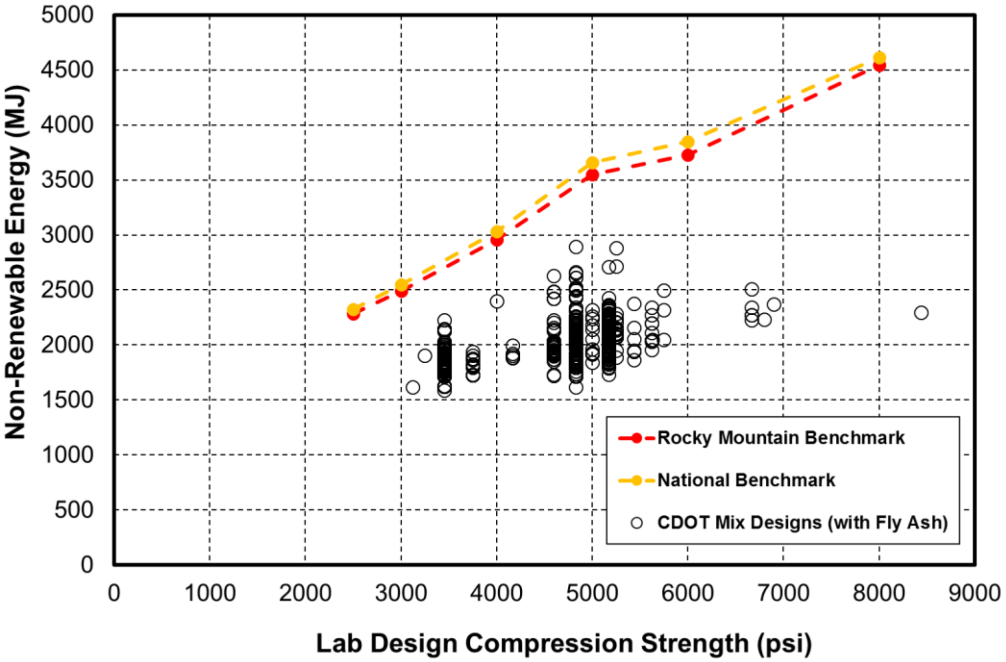

Figure 55: Lab Design Compression Strength and NRE of CDOT Mixtures with Fly Ash

Figure 56 and **Figure 57**, show the non-renewable energy consumption of the CDOT concrete mixtures using their field compression strengths. **Figure 56** shows the NRE for mixtures designed with cement only and **Figure 57** shows the NRE for mixtures designed with a fraction of fly ash replacement. This comparative LCA shows that approximately 99.8% of the mixtures meet NRE Rocky Mountain benchmark. The mixtures that do not meet standard are roughly all mixtures that use cement only.

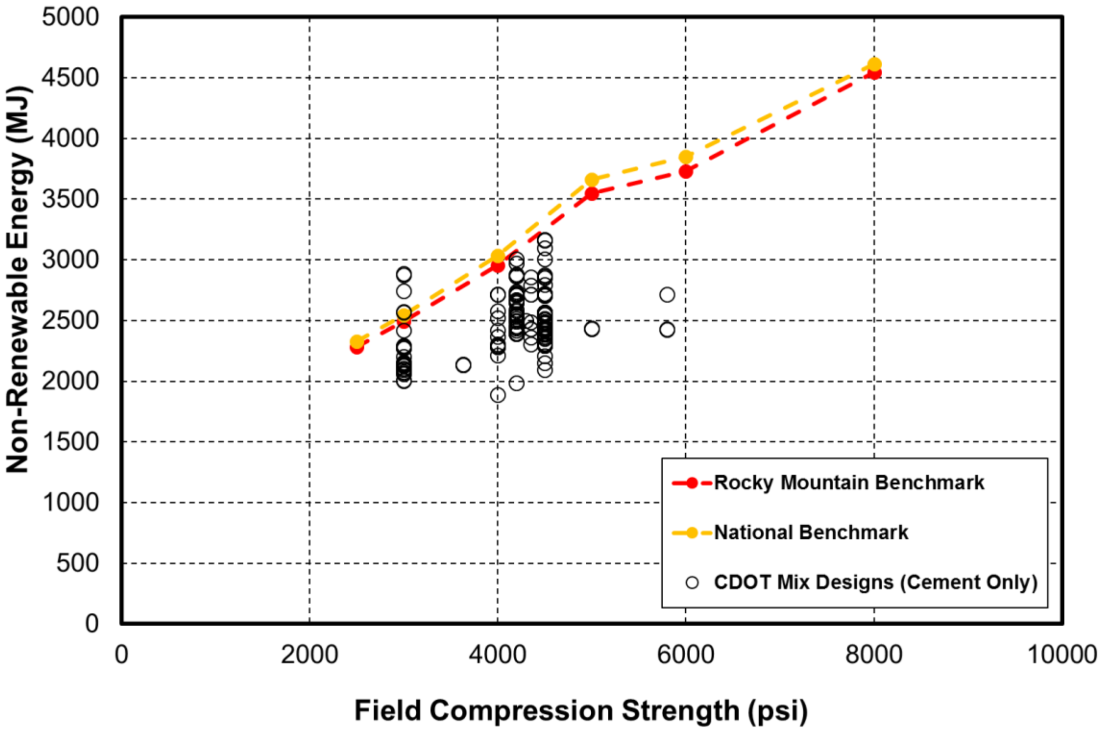

Figure 56: Field Compression Strength and NRE of CDOT Cement Only Mixtures

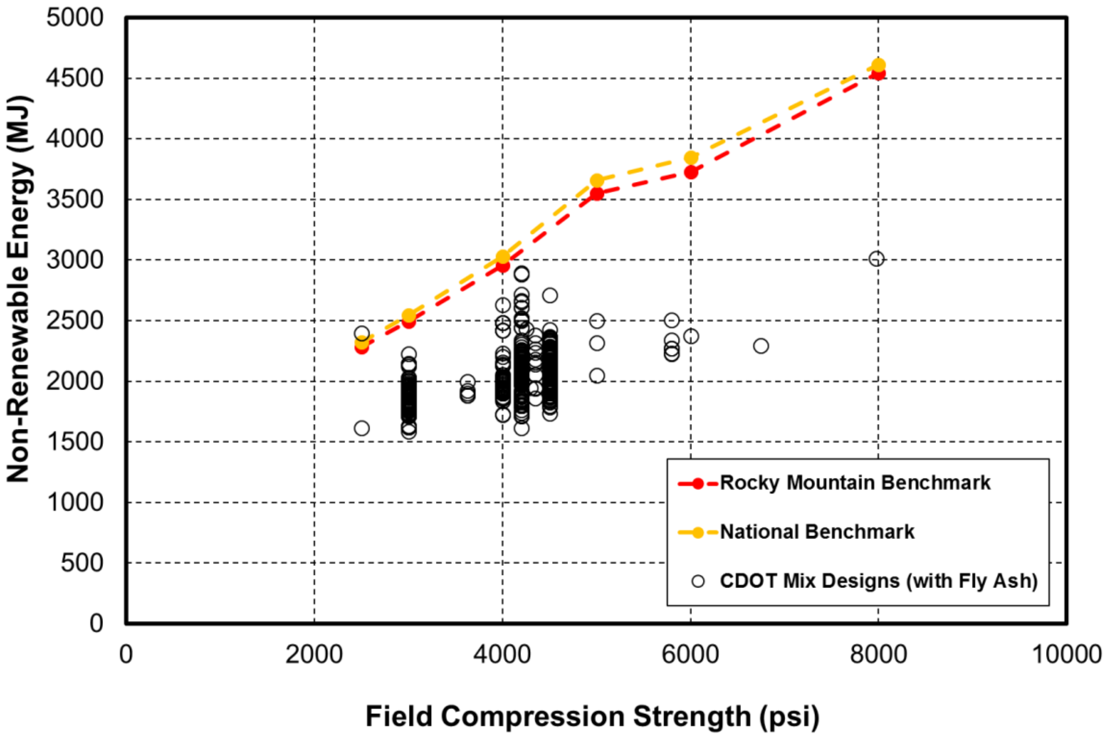

Figure 57: Field Compression Strength and NRE of CDOT Mixtures with Fly Ash

Figure 54, **Figure 55**, **Figure 56** and **Figure 57** show that higher-strength mixture designs tend to have higher NRE, largely due to the increased quantity of cement. Since the mixtures that do not meet the benchmark use cement only, it is evident that the addition of a fraction of fly ash replacement helps lower the impacts to total primary energy consumption. This reiterates studies showing that cement manufacturing is the most energy-intensive of all manufacturing industries in the United States [34].

The results shown in **Figure 58** and **Figure 59** display the range of impacts from CDOT's 1262 concrete mixtures. The range of non-renewable energy consumption for this set of concrete mixtures is approximately 1796.0 MJ eq to 2435.1 MJ.

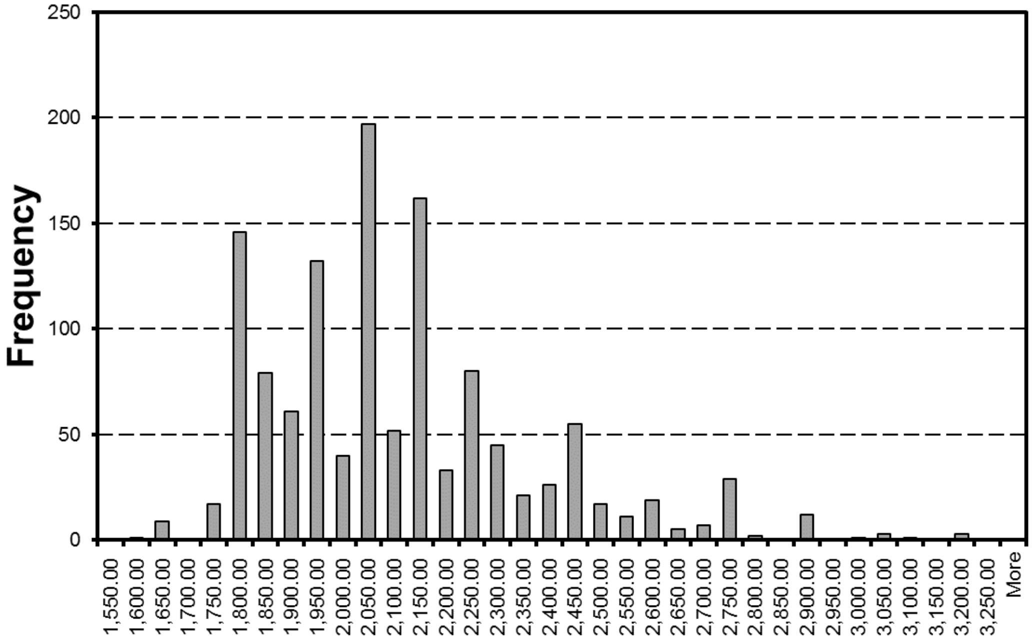

Figure 58: Histogram of CDOT's Concrete Mixtures Non-Renewable Energy Consumption (NRE)

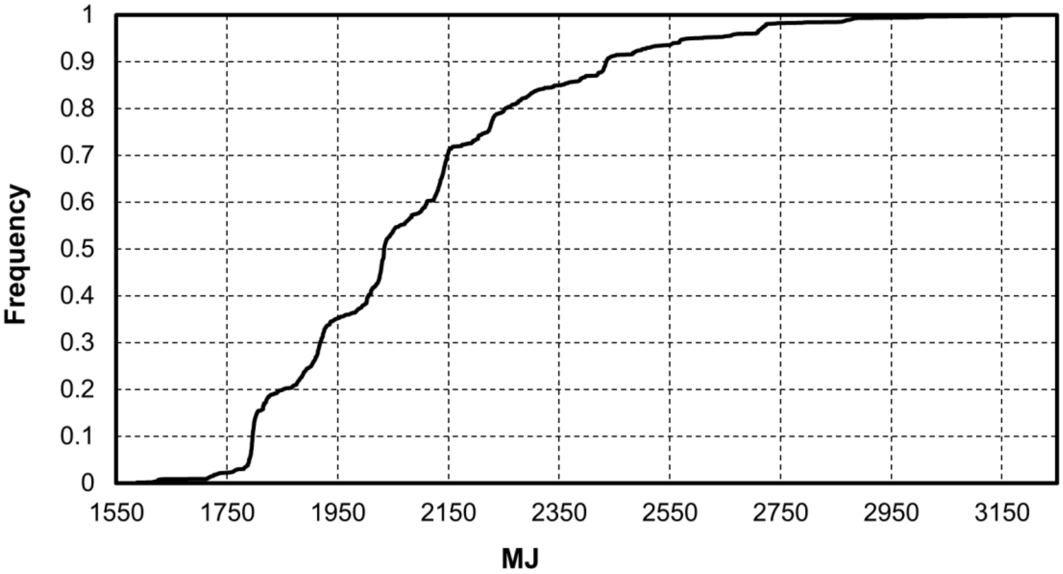

Figure 59: Cumulative Distribution Function of CDOT's Concrete Mixtures Non-Renewable Energy Consumption (NRE)

4.2.8. All impact categories

Figure 60 presents the average impact for each impact category normalized with the both the Rocky Mountain and national benchmark. The visual representation of all seven impact categories on a notionally common scale shows the opportunities for optimization, trade-off and an understanding of the performance of CDOT's concrete mixtures. All impact categories above 1.0 (global warming potential, acidification potential, smog potential, total primary energy consumption and non-renewable energy consumption) are performing environmentally better than the benchmarks. All impact categories below 1.0 (ozone depletion potential and eutrophication potential) are performing environmentally worse than the benchmarks. Targeted areas for tradeoffs in an optimization or decision-making process are the impact categories that are significantly under or over-performing.

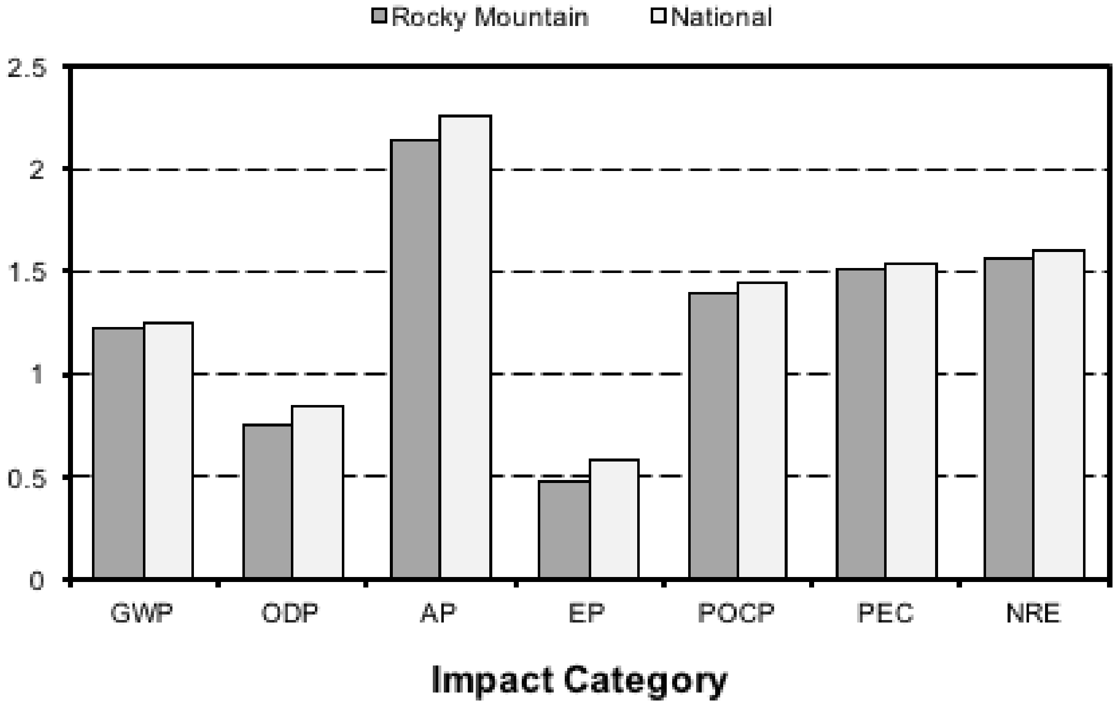

Figure 60: Normalized Environmental Performance of Rocky Mountain vs. National Concrete Mixtures

Table 11 shows an approximate number of CDOT concrete mixture designs that meet the Rocky Mountain benchmark as reported individually in **Sections 4.2.1-4.2.7.**

Table 11: Number of CDOT Concrete Mixture Designs that meet Rocky Mountain Benchmark

	GWP	ODP	AP	EP	POCP	PEC	NRE
Design Strength	1036	5	1262	0	1252	1256	1253
Field Strength	1131	0	1262	0	1188	1253	1260

Table 12 shows the approximate percentage of the 1262 mixtures that are below the Rocky Mountain benchmark. **Table 11** and **Table 12** are more accurate approximations of CDOT's environmental performance. This analysis considers each concrete mixture in comparison to the benchmarks while the result in **Figure 60** takes the average impact in comparison to the benchmarks.

Table 12: Percentage of CDOT Concrete Mixture Designs that meet Rocky Mountain Benchmark

	GWP	ODP	AP	EP	POCP	PEC	NRE
Design Strength	82.1%	0.4%	100.0%	0.0%	99.2%	99.5%	99.3%
Field Strength	89.6%	0.0%	100.0%	0.0%	94.1%	99.3%	99.8%

As discussed in the LCA analysis of the individual impact categories, cement manufacturing is the most energy-intensive of all manufacturing industries in the United States and accounts for 96% of the GWP of concrete is from cement [34]. These high impacts of cement are reflected directly in **Table 13** where mixtures that did not meet the benchmark were evaluated by use of cementitious materials. This table shows the result of the percentage of those "failing" mixtures that are cement only and mixtures that use any SCM. This result shows how the addition of SCMs have the potential to reduce the environmental costs.

Table 13: Percentage of Mixtures that do not meet standard that use cement only

	GWP	ODP	AP	EP	POCP	PEC	NRE
Design Strength	75.2%	0.0%	-	-	80.0%	100.0%	100.0%
Field Strength	84.0%	-	-	-	79.7%	88.9%	100.0%

4.3. CDOT Mixture Design LCCA Analysis

From 2006 to 2016, CDOT has used approximately 2,629,317 m^3 of concrete with the exception of Design-Build projects, shown in **Table 14.** Research has shown that majority of projects (83%) are typically delivered by Design-Bid-Build leaving only 10% of projects are delivered by Design-Build [32]. Therefore, this data shows a good estimation of the concrete used in for the transportation industry in Colorado. **Table 14** shows the specific quantities of concrete used per concrete class per year.

Overall, **Figure 61** depicts no constant trend in CDOT's concrete usage per year. Research shows that US Department of transportation concrete usage has no specific trends [33]. Concrete usage per year depends on the individual State's need for new and re-construction projects.

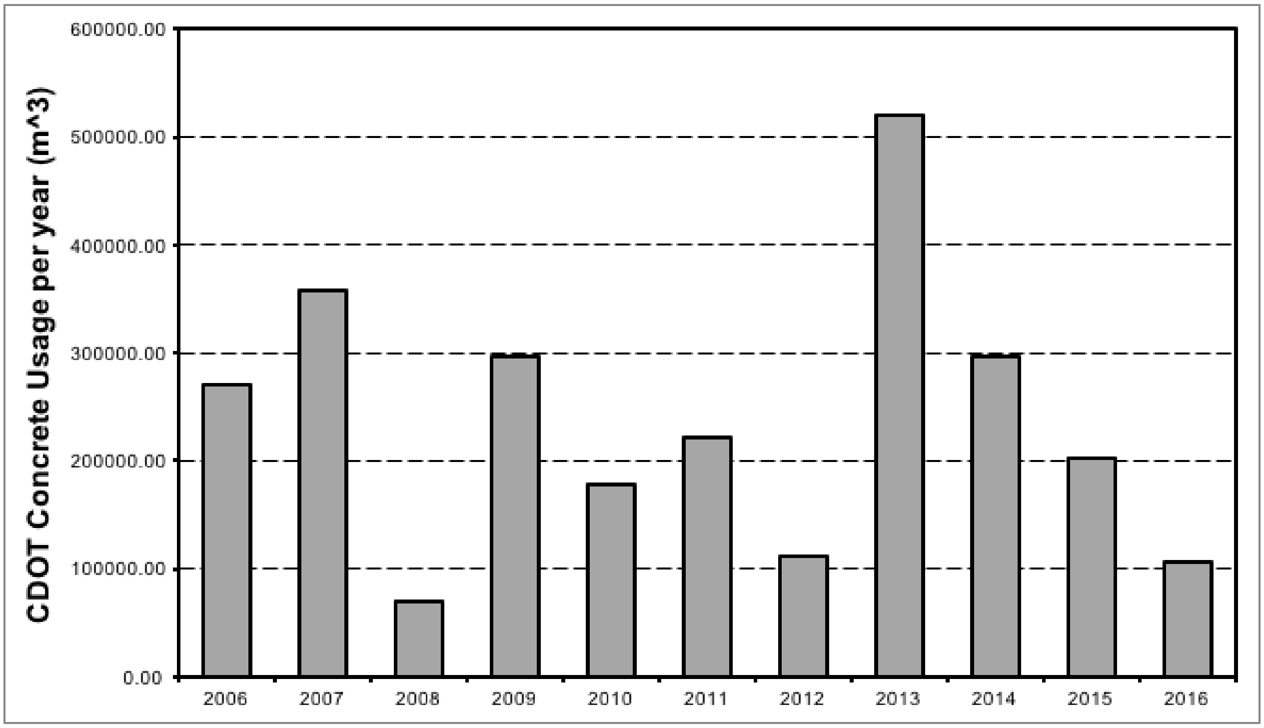

Figure 61: CDOT Concrete Usage in m^3 per year

Table 14: CDOT Concrete Usage per Concrete class per Year [31]

Concrete Class	2006 (in m^3)	2007 (in m^3)	2008 (in m^3)	2009 (in m^3)	2010 (in m^3)	2011 (in m^3)	2012 (in m^3)	2013 (in m^3)	2014 (in m^3)	2015 (in m^3)	2016 (in m^3)	Total (in m$^{3)}$
B*	1,555	781	1,562	1,020	1,089	622	687	639	1,363	605	634	**10,557**
D*	21,391	13,988	14,139	20,709	18,347	28,908	19,279	22,953	30,493	16,576	11,770	**218,551**
DT*	6	204	108	24	558	379	496	681	258	472	57	**3,243**
P	245,715	335,185	50,136	274,665	156,843	189,246	88,059	494,887	263,632	181,706	93,176	**2,373,251**
E*	682	491	641	18	643	1,277	1,206	852	336	2,754	20	**8,918**
H*	0	0	2,708	0	0	460	459	746	0	0	60	**4,433**
HT*	126	560	0	92	0	0	0	0	0	0	359	**1,137**
S35*	40	0	0	0	0	0	0	0	0	0	0	**40**
S40*	408	7,157	0	0	0	0	812	0	0	0	0	**8,376**
S50*	106	96	0	0	0	115	400	0	42	0	0	**759**
SSC*	**0**	0	0	0	0	17	34	0	0	0	0	**51**
Total	**270,029**	**358,461**	**69,294**	**296,527**	**177,481**	**221,024**	**111,432**	**520,758**	**296,125**	**202,112**	**106,075**	**2,629,317**

Additionally, a full LCCA of all CDOT's concrete mixtures is completed for life cycle stages A1-A2. **Figure 62** and **Figure 63** compare the cementitious content of CDOT's concrete mixtures to the economic cost of the mixtures in comparison to NRMCA's average cost data of \$75/m^3. **Figure 62** shows the tradeoff for mixtures designed with cement only and **Figure 63** shows the tradeoff for mixtures designed with a fraction of fly ash replacement.

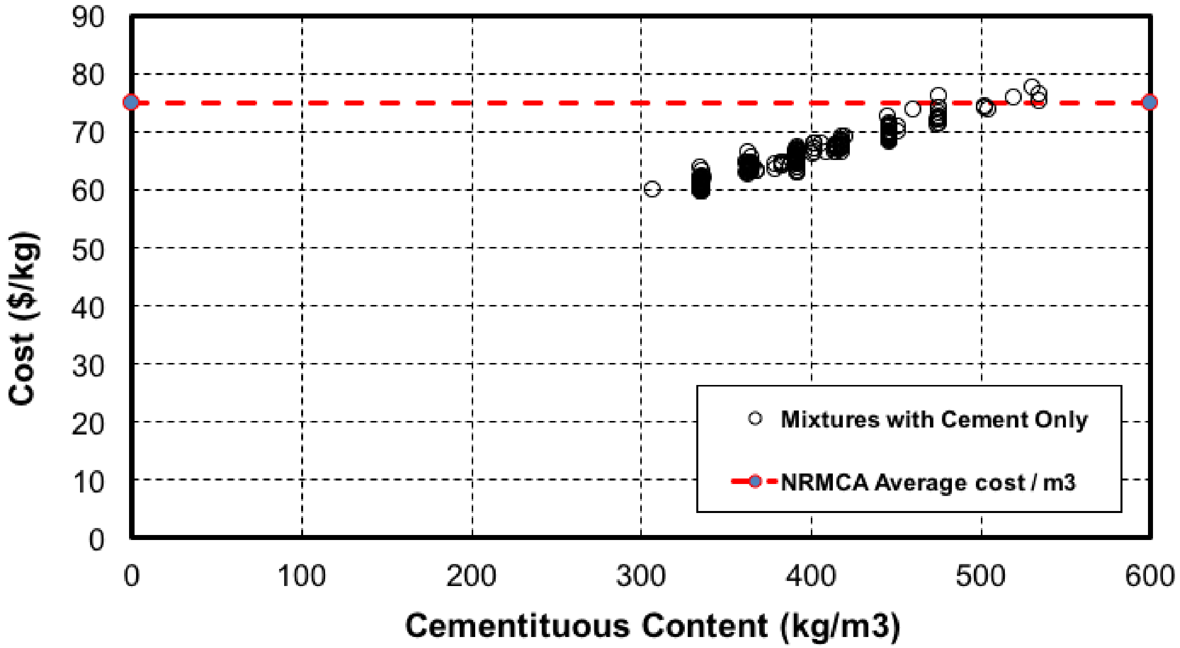

Figure 62: Cost vs. Cementitious Content of mixtures with Cement Only

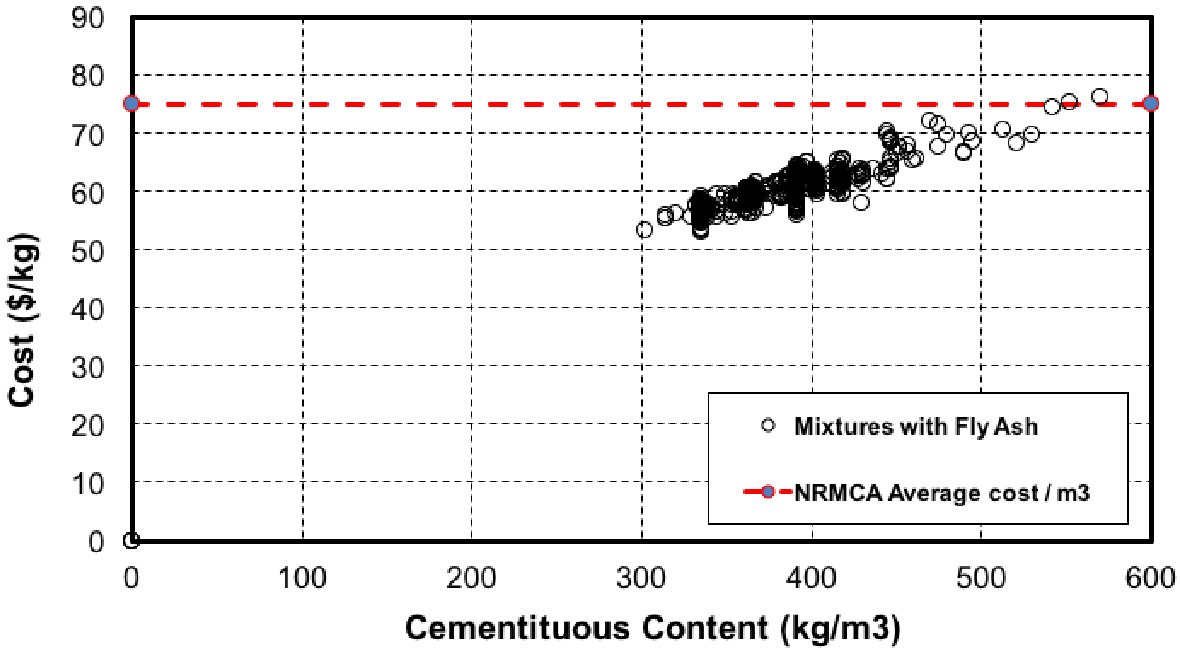

Figure 63: Cost vs. Cementitious Content of mixtures with Fraction Fly Ash Replacement

Figure 64 and **Figure 65** compare the lab design compression strength of CDOT's concrete mixtures to the economic cost of the mixtures in comparison to NRMCA's average cost data of $75/m^3. **Figure 64** shows the tradeoff for mixtures designed with cement only and **Figure 65** shows the tradeoff for mixtures designed with a fraction of fly ash replacement.

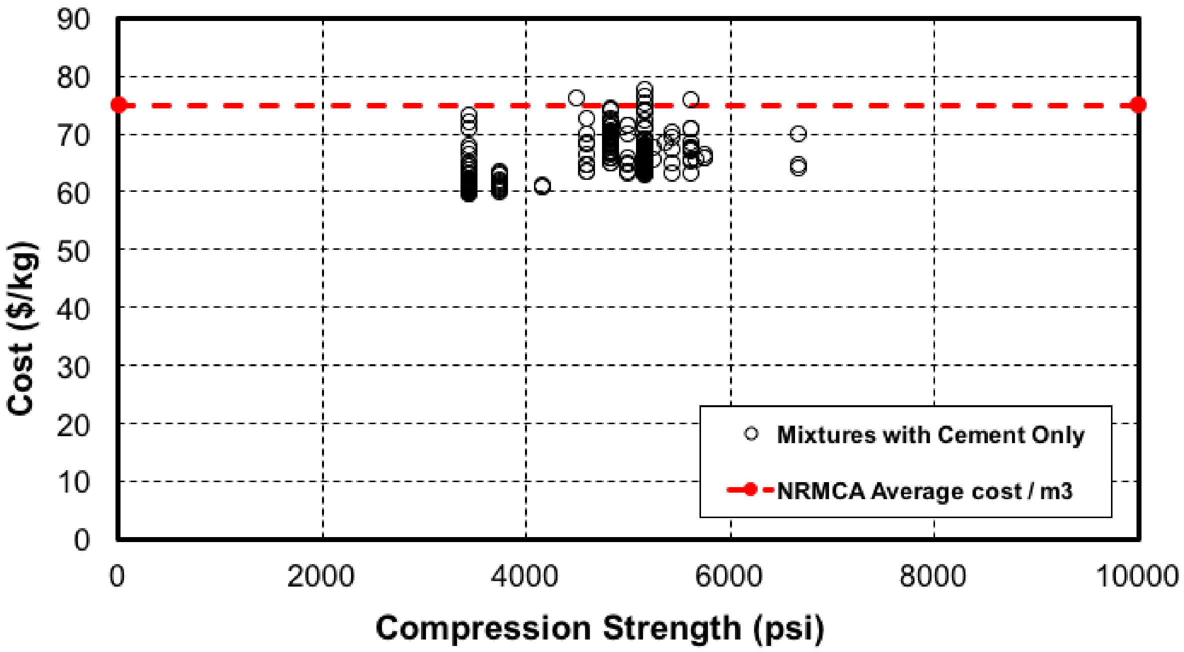

Figure 64: Cost vs. Compressive Strength of mixtures with Cement Only

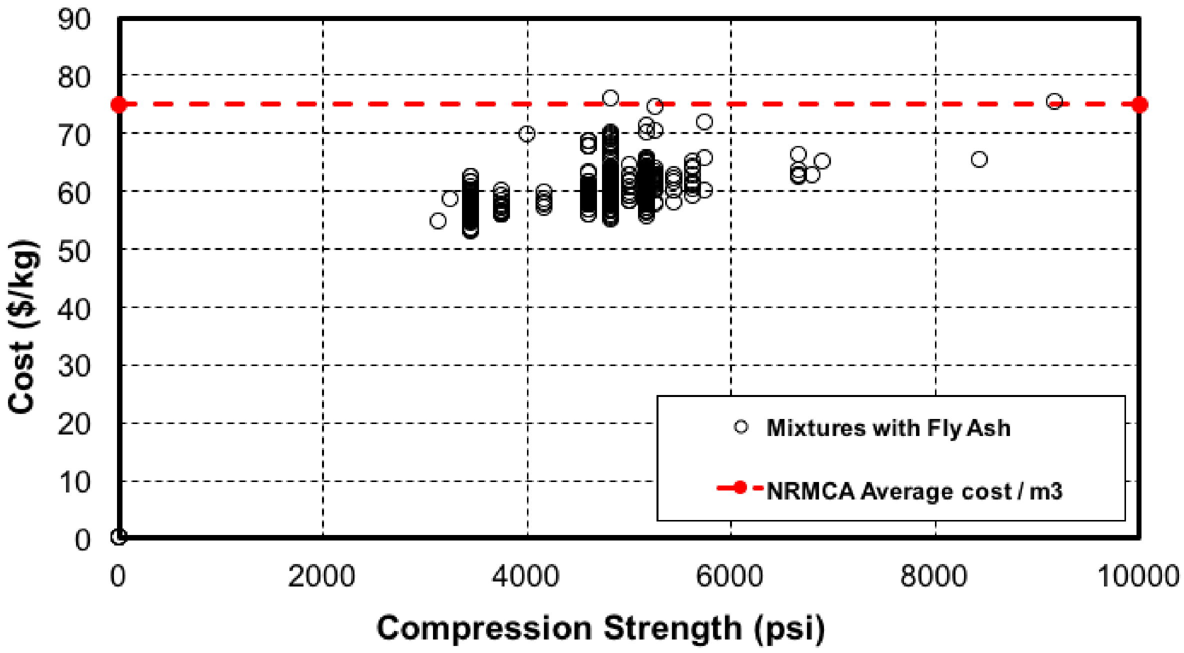

Figure 65: Cost vs. Compressive Strength of mixtures with Fraction Fly Ash Replacement

The results of **Figure 62**, **Figure 63,** **Figure 64** and **Figure 65** are good indicators of how designing concrete to the correct specification and strength can impact the overall life cycle economic cost. The graph justifies that the addition of portland cement adds both strength and cost simultaneously.

CDOT's substantial concrete usage is used to compute a subjective total average economical cost spent on concrete per year. Using NRMCA's average cost data of \$75/m^3, **Table 15,** estimates from 2006 to 2016, CDOT has spent \$197,198,793 on concrete for just life cycle stages A1-A2. This is an approximation and does not include the 20% of projects that are design-build, as specified previously.

Table 15: CDOT's Approximate Yearly Cost of Concrete with exclusion of Design-Build Projects

Year	Total Average Cost
2006	\$20,252,144
2007	\$26,884,564
2008	\$5,197,043
2009	\$22,239,491
2010	\$13,311,055
2011	\$16,576,833
2012	\$8,357,370
2013	\$39,056,872
2014	\$22,209,356
2015	\$15,158,431
2016	\$7,955,634
Total	\$197,198,793

4.4. LCA Analysis Trends

The LCA results show two main trends: (1) the use of fly ash in concrete mixtures reduces the environmental impact of the mixture and (2) the percentage of cement content in the concrete mixture highly influences the overall environmental impact.

Fly ash is one of the largest types of industrial waste generated in the United States. The American Coal Ash Association's *Coal Combustion Product Production & Use Survey Report* reported nearly 130 million tons of coal ash was generated in 2014 [36]. Fly ash is produced from the combustion of coal in electric power generating plants. It is captured in exhaust gas by electrostatic precipitators. It can only be disposed of in surface impoundments, landfills or discharged into a nearby waterway. Fly ash disposal has negative repercussions to the environment because it contains contaminants like mercury, cadmium and arsenic which can pollute waterways, ground water, drinking water, and the air [36].

The EPA supports the 'beneficial use' of waste products and defines it as "*the reuse in a product that provides a functional benefit, replaces a product made from virgin raw materials, conserves natural resources and meets product specifications and industry standards. Beneficial use of waste products can contribute to a sustainable future by reducing production costs, reducing energy consumption and greenhouse gasses"* [37]. Because of this, fly ash is considered to be burden free when incorporated into concrete mixtures with the exception of the transportation stage for Athena. Additionally, it is also reducing the amount of cement in each mixture which has shown to have high environmental impacts. The separate plots shown in this study for mixtures with cement only and mixtures with a fraction of fly ash replacement depicts how the use of fly ash affect the environmental impacts of the mixtures.

Athena's assumptions for portland cement are not disclosed to the public but are set to date in the United states and are not considered to be burden free like fly ash. The results of this study show the trend of the results of how more cement in mixtures increases the environmental impact correlating to both trends found from this study.

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS

With CDOT using approximately 2,629,317 m^3 of concrete from 2006 to 2016, the implications this amount of concrete to the environment and economy are significant. This study only evaluated CDOT's concrete usage, however, there are many other large consumers of concrete in both the developed and, in particular, the developing world. The lifecycle analysis (LCA) and life cycle cost analysis (LCCA) conducted of CDOT's concrete mixtures has led to these final conclusions:

- In general, CDOT's concrete mixtures exceed national and regional environmental impact benchmarks in five out of the seven impact categories addressed in this LCA. Although not every single mixture performs better than the benchmarks in these categories, the vast majority of mixtures meet this goal in these five categories.
- In accordance with other published studies, the addition of fly ash into concrete mixtures reduces the environmental impacts of the mixture, further substantiating that low-cement mixtures and mixtures containing supplementary cementitious materials can aid in achieving sustainability goals.
- With the assumptions used in this LCCA, the cost of CDOT's mixtures economic per m^3 of concrete are generally lower than the NRMCA average cost of \$75/m^3. The NRMCA average is a national average, so further

research would need to be conducted to determine how the mixtures compare to an average specific go the Rocky Mountain region.

CHAPTER 6 REFERENCES

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