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Research Article

Analysis of alternative sustainable approach to concrete mixture design

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ABSTRACT

Sustainability is a growing area of concern, especially amid the concrete industry. Concrete, especially traditional concrete, which contains Portland cement, is extremely harmful to the environment producing mass amounts of carbon dioxide. Additionally, the mining of the concrete materials, like lime, cause significant damage to waterways and ecosystems. For years, studies have found more sustainable alternatives that are structurally equivalent to traditional concrete. The Connecticut Department of Transportation does allow for the use of alternative "green" concretes if the mix designs meet the required specifications. Nevertheless, heavy highway construction seems reluctant to experiment with new substances and continues to fall back on the use of fly ash concrete. This solution, however, is not perfect, as fly ash is a finite material. By conducting a nationwide survey to the Departments of Transportation (DOT), the reliance on fly ash was evident. It was also found that the biggest concerns for DOTs was the cost and availability of the material. This study investigates presently accepted alternative concrete mixture designs and explores the solutions of volcanic ash concrete and ground glass concrete. Based on the results of the survey and construction practicality, this study suggests the incorporation of ground glass concrete for heavy highway construction. This solution provides the needed strength requirements per DOT specifications and is within the same price-range as fly ash concrete.

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1. INTRODUCTION

The Connecticut Department of Transportation currently adheres to the Federal Highway Administration's catchy slogan of "get in, get out, stay out", leaving them reluctant to experiment and possibly gamble with new concrete design mixtures that may not have the same longevity as traditional concrete mix designs or those that may require longer time to set risking unnecessary traffic delays. Current concrete mixture designs are up to the supplier who has the freedom to experiment as they see fit as long as they meet the strength specifications set by the Connecticut DOT [1]. Nevertheless, alternative concrete mixtures have been slow to make gains in heavy highway construction. Currently, the Connecticut DOT's most used sustainable concrete is fly ash concrete since it helps with concrete workability. However, while this is more eco-conscious than traditional concrete, it is not an in-

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definite solution. As climate change is a growing concern, the burning of coal, which produces fly-ash has declined, as this process also causes significant harm to the environment [2]. Further, even if countries were to continue to burn coal, the current rate of consumption will likely deplete coal by 2090 [3]. In turn, coal slag will become scarcer, and the cost will inevitably increase as well.

Therefore, with this future date in mind, it is now more critical than ever to explore alternative concrete mixture designs that will prove to have similar material properties as traditional concrete but will be more sustainable in terms of the environment and economy. Two alternatives to be explored are volcanic ash concrete and ground glass pozzotive concrete. With strengths able to meet DOT specifications, it is surprising that Departments of Transportations have not attempted to use the material in their heavy highway builds [4]. This prompts questions involving practicality and supply to determine how these materials, or any other alternative materials, may become a solution for Connecticut highway infrastructure. By surveying the Departments of Transportation nationwide as well as investigating concrete suppliers, it may be possible to see if this reluctance is limited to Connecticut, or if it is nationwide. In all, this project attempts to gather data on alternative concrete mixtures used by the Departments of Transportation nationwide in an effort to offer more sustainable long-term solutions to the Connecticut DOT.

2. SYNOPSIS OF EXISTING LITERATURE

The plan for this project initially began as a survey to the Departments of Transportation nationwide to gain insight on concrete usage, specifically pertaining to cost and composition in the heavy highway construction industry. Following the surveys, this project's focus has morphed in response to the survey replies and targeted two alternatives for fly ash concrete. Of the two options discussed, ground glass pozzolan concrete is much more likely to take off in the New England and Tri-State regions compared to the volcanic ash concrete. To assess these mixture designs more clearly in comparison to fly ash concrete, a literature review was performed.

Fly ash, which is the resultant of burning coal, is one of the most frequently used additives in concrete composition to offset the amount of Portland cement, which not only makes concrete stronger, but also benefits the environment. Nevertheless, this material will not be around forever, as coal powered plants have experienced a severe decline. In the past 60 years alone, the coal production in the United States dropped 24%, with only 535 million short tons produced [5]. The labor force has shrunk as well, with only 37,000 coal miners working today, as compared to 178,000 miners in 1985 [6]. Figure 1 shows the drastic decline in coal plants from just 2007 to 2016 as wind, solar, natural gas, and hydrothermal plants have become more prevalent [7]. Further, recent environmental movements have pushed against coal production in support of greener energy sources [3, 8, 9]. Additionally, one study explains that the American coal supply has been largely overstated, and as coal production declines this will become more apparent, with the U.S. only recovering roughly 20% of the government's reported coal reserves [10]. This information is startling when considering the significant reliance on fly ash for so many concrete suppliers, and the apparent lack of acknowledgment of this information is just as worrisome. New studies are needed to gain industry insight on this decline and investigate alternatives that suppliers may be looking into to combat future shortcomings.

To underscore the significance of the need for an alternative concrete mix design that is more sustainable, one must recognize the damage of traditional concrete design, chiefly, the incorporation of Portland cement. The damage and devastation the Portland cement industry causes on the environment is well known. Research shows concrete production, specifically the Portland cement industry, to be one of the leading contributors of Carbon-Dioxide (CO_2) emissions, with estimates ranging roughly around 5% to 7% of global CO_2 emissions stemming from Portland cement production [11]. Author Jonathan Watts, of The Guardian, paints the picture of the crisis we face, stating: "If the cement industry was a country, it would be the third largest carbon dioxide emitter in the world with up to 2.8 billion tons, surpassed only by China and the US" [11]. Considering this fact, and how the construction industry is just one small facet of life, it is imperative we change.

Further, the making of cement is not the only factor in the concrete process that causes harm to the environment. The harvesting of natural materials causes significant irreparable damage to the Earth [12]. In one study, titled 'Green Concrete Mix Using Solid Waste and Nanoparticles as Alternatives- a Review,' the researchers argued for the implementation of natural waste materials to form Green Concrete [13]. Examining the currently used avenues of solid waste management, they focused on the harmful effects of landfills and recycling costs, as well as the harmful damage from cement manufacturing [12]. Breaking down the significant harmful effects of the concrete industry on the environment, it is clear the construction industry needs to strive for a more eco-conscious alternative concrete that will not wreak havoc on natural resources or pollute the Earth [13]. With these facts in mind, there is no turning back to traditional Portland cement concrete.

While States have their own specifications for concrete mixtures, the Federal Highway Administration (FHWA) sets general parameters that must be followed. The FHWA also advises on the general benefits of the incorporation of fly ash concrete, touching on improved workability, decreased water demand, reduced permeability, and improved durability [14]. While these points are all valid, it is important to address a difference between Connecticut State and

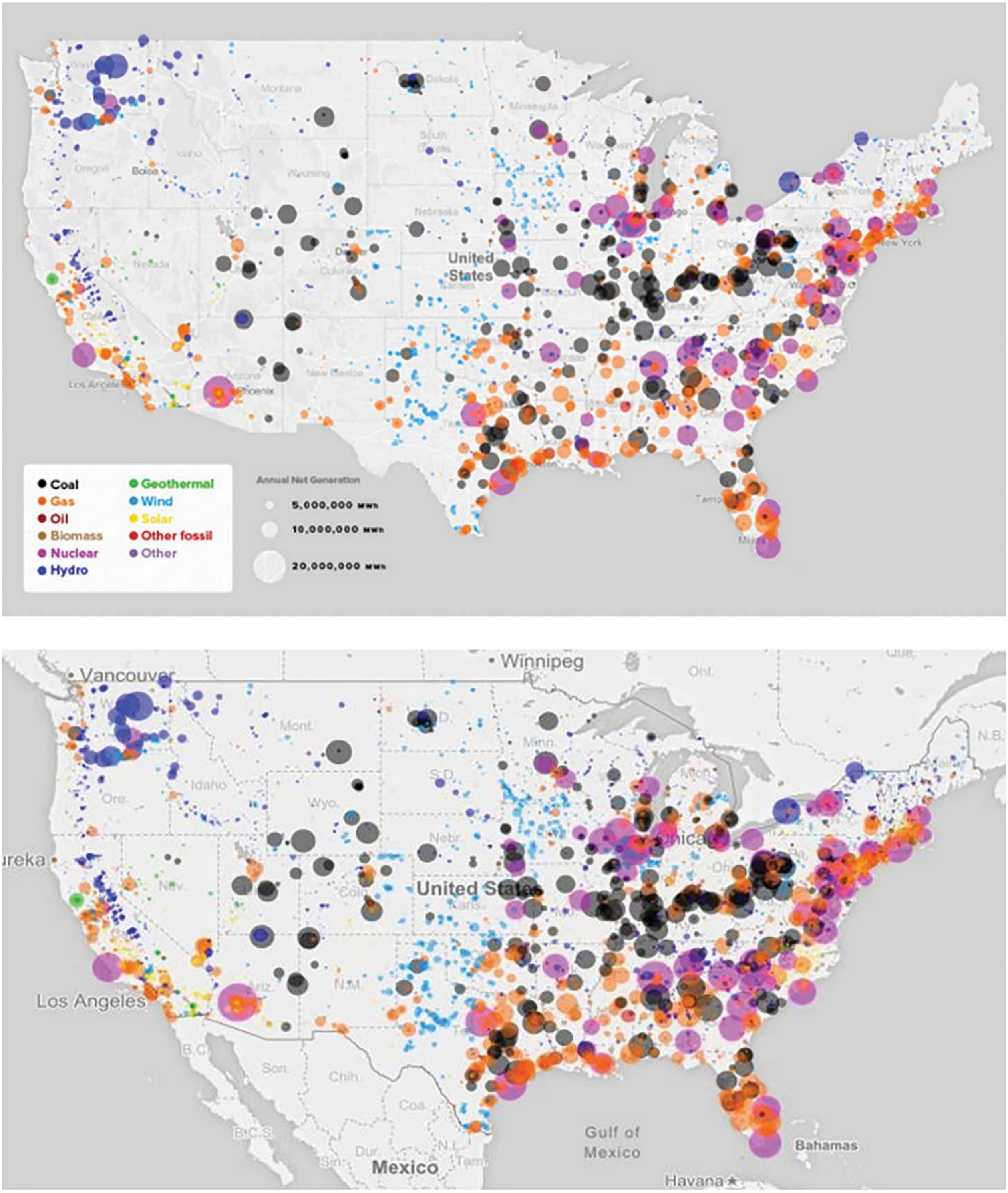

Figure 1. Map of Decline of Coal Power in the United States 2007 (top) and 2016 (bottom) [7].

Federal guidelines. Per the FHWA, "Fly ash is used to lower the cost and to improve the performance of PCC. Typically, 15% to 30% of the Portland cement is replaced with fly ash, with even higher percentages used for mass concrete placements. An equivalent or greater weight of fly ash is substituted for the cement removed. The substitution ratio for fly ash to Portland cement is typically 1:1 to 1.5:1" [14]. This is higher than the guidelines provided Connecticut.

Reviewing the DOT's specifications listed under section M.03.01 titled 'General Composition of Concrete Mixes,' the State of Connecticut allows any qualified composition of concrete if it meets the specifications listed per concrete grade. The design details are as follows: "Portland cement concrete shall consist of an intimate mixture of Portland cement, other approved cementitious material (when used), fine aggregate, coarse aggregate, water, and admixtures, if ordered or permitted by the Engineer, proportioned in accordance with the following requirements" [15]. Essentially, discussing strength alone, Class A and C concrete must meet 3,000 psi (20.7 MPa) compressive strength at 28 days, and Class F must meet 4,000 psi (27.6 MPa) at 28 days. Regarding fly ash replacement in the mixture, Connecticut allows for up to 15% replacement of Portland cement, pound for pound. Therefore, as long as the materials have been sourced and verified by the Division of Materials Testing, and the concrete meets the specified requirements, the engineer may choose any mixture design they deem suitable.

Additionally, it is important to point out the need for curing in Connecticut, especially in the colder months. While most concrete work is performed in the warmer months, CT DOT section 4.01 does specify supplemental needs including the laying of straw or hay for protection on days or nights where the temperatures may drop below 35 degrees Fahrenheit (2 degrees Celsius) [16]. Also, if any concrete freezes before it is fully cured, it must be removed and replaced at the contractor's expense [16]. Therefore, for any new concrete mixture designs to take off in New England, they must be suitable for work in colder temperatures, and not delay projects with longer cure times, which can lead to concrete damages if the material freezes before it is fully cured.

Fly ash concrete, either Class C or Class F types, is a commonly accepted alternative concrete mixture in which Portland cement is replaced partially with fly ash. The main difference between these two types of concrete is the chemical makeup of the ash itself. Boral Resources, a leading American supplier of coal combustion products, like fly ash, concisely summarizes these differences, explaining: "Class F fly ash is highly pozzolanic, meaning that it reacts with excess lime generated in the hydration of Portland cement, Class C fly ash is pozzolanic and also can be self-cementing" [17]. This manufacturer further explains specifications and requirements set forth by the American Society for Testing Materials [18]. This society per section ASTM C618 "requires that Class F fly ash contain at least 70% pozzolanic compounds (silica oxide, alumina oxide, and iron oxide), while Class C fly ashes have between 50% and 70% of these compounds. Typically, Class C fly ash also contains significant amounts of calcium oxide – over 20%. Most Class F fly ash contains little calcium oxide; however, some Class F fly ash sources may contain intermediate levels (8% to 16%) of calcium oxide" [17].

Fly ash concrete has long been studied and is widely accepted in the heavy highway industry [19–22]. However, none of these studies discuss the impending loss of the material or possible solutions. Notably though, one study in 2014 in Wisconsin did address the lack of the fly ash material (Class C) and suggested an expansion of their current specifications to allow for the incorporation of Class F fly ash concrete [23]. It is remarkable that this study was completed seven years ago, and the problem remains the same. Furthermore, it will not be feasible in the long run to adopt a different fly ash mixture since this would be a temporary fix; a permanent solution is needed for the heavy highway construction industry.

To expand further on the limitations and finite timeline of fly ash concrete, fly ash is the byproduct of burning coal for energy production, while energy production is becoming less reliant on coal. As the world moves greener and environmental crisis shapes the world, new initiatives are implemented to become more environmentally conscious in all areas of life, especially in significant areas such as electricity. In recent years the production of coal has declined due to shortages, as well as its harmful effects and toxicity. Even disregarding the environmental and health risks of coal consumption, research has shown coal supply is shrinking and may become extinct in the 70 years [8, 9, 24]. Therefore, as power plants move from burning coal to more environmentally friendly options like natural gas or hydroelectricity, the loss of fly ash might be sooner than predicted.

The future of sustainable alternative concrete must take into consideration materials that are in abundance and not comprised of finite resources, like fossil fuels. Natural pozzolans, like volcanic ash, have a great potential as a substitute for fly ash. The volcanic ash used for concrete mixtures can be obtained in several ways: explosive volcanic eruptions, phreatomagmatic eruptions, and the transports in pyroclastic density currents. However, it is important to note that these variations can result in different mechanical properties [25]. Nevertheless, harvesting this material is significantly less damaging to the environment in comparison to the mining of lime to create Portland cement. Collecting this material also eliminates the negative effects of volcanic eruption to human life [25]. In the United States alone, there are 169 volcanoes. Most are in Alaska, but they are across the U.S. as well. Harvesting this material is not damaging to the Earth in the same way that lime mining is, and the process for refining this ash to be useable in concrete does not release the same amount of carbon as Portland cement or burning coal [26, 27].

The chemical properties of this material make this a strong cementitious material with a comparable compressive strength to traditional concrete mixture designs with ranges of 6% to 10% replacement of Portland cement [28]. Interestingly, cure time for this material is roughly comparable to traditional concrete [29]. It is also important to note that one study identified volcanic ash as beneficial in improving the ability of concrete to resist freeze–thaw cycles with limited mass loss ratios

(2.1–2.3%) [30], which is extremely important in regions with fluctuating temperatures, like New England.

Another promising alternative to fly ash concrete is the supplementation of ground glass pozzolan as a partial replacement for Portland cement in concrete. Several studies have assessed this mix design and found it to be comparable, if not stronger than traditional Portland cement concrete [31–35]. For this mixture, 20% to 25% may be most optimal for heavy highway construction [31–33]. The chemical properties of this material make this a strong cementitious material with increased compressive strengths of 16% with only a 15% replacement of Portland cement [32], and increased compressive strength with 10% glass replacement [33]. Moreover, Khudair et al. [34] reason compressive strength could be the result of "pozzolanic activity", in which glass particles react with the cement hydrates forming new gel bonds, which can block the pores of the concrete, making pores smaller and not connected, which leads to greater density. Additionally, studies have also concluded this material to be longer lasting, with estimated service life five times greater than traditional concrete [36]. Cure time may be slightly longer than traditional concrete, however if protected properly from the elements and properly planned for in scheduling, this should not be a significant issue.

Silica Fume is another alternative mix concrete that has proven to increase strength and durability, while also reducing the carbon impact by replacing varying quantities of the Portland cement. Several studies have focused on this material, all finding it suitable for both lightweight and heavyweight concrete construction [37–40]. While this material has great benefit, there are drawbacks including potential cost increases or fluctuations in various regions where this material may not be readily available. The extra cost of the material is examined in one study in which quarry dust was incorporated as a filler in addition to silica fume, to strengthen the concrete mix while lessening the amount of silica fume or fly ash for regions that may not have as much access to these materials [41]. This information is useful as it shows that research is expressing concern over availability and cost of materials, however, there is not a similar study like it for just fly ash which is especially needed now as coal production declines.

It is also important to examine what other surveys and studies have assessed the current market of concrete production. Overall, there are relatively few studies in this regard. Most closely related is a survey completed in 2015. In this study, the scholars surveyed concrete suppliers and manufacturers to gain insight on the intersection of academic knowledge in comparison to industry production [42]. This study surveyed numerous suppliers, one trade organization, as well as the Ohio Department of Transportation. This study concluded that the most used concrete mixtures were fly ash (Class C and F), ground granulated blast-furnace slag (GGBFS), Silica fume, and shale. This study provided insight on manufacturers understanding and usage of alternative concrete mixture designs. Nevertheless, given how stringent state public jobs can be, more investigation is needed to see the concrete materials States would allow in their heavy highway jobs. Additionally, it would be useful to compare the results of the study that was done seven years ago with the results presented in this paper, specifically to evaluate if new concrete admixtures are being used by the various Departments of Transportations.

Table 1. Department of transportation concrete mixture survey

What is the traditional makeup of your concrete?		
What is your concrete budget?		
Do you use flyash?	Yes	
	Class C/Class F	No
How much does your flyash concrete cost?		
Do you use ground glass/ Pozzotive concrete?	Yes	No
Do you use Volcanic Ash?	Yes	No
Do you use other types of "green" admixtures to concrete?	Yes	No

3. STUDY METHODOLOGY

The primary goal of this study was to identify what concrete mixtures that are allowed by the Departments of Transportation across the nation. The secondary goal of this study was to evaluate the availability these materials, and hopefully highlight the practicality of these alternative compositions. To complete these tasks, a comprehensive literature review was completed that identified possible alternative mixture designs, as well as an investigation was performed that identified major suppliers, by state, of sustainable mixes currently produced in America. Then, with the aim of producing findings for the Connecticut DOT, a survey was sent out to the Departments of Transportation nationwide. To increase the likelihood of gaining information on concrete suppliers and materials currently in use while not being a customer, a thorough review of leading suppliers was completed to assess the materials they advertise and offer for more sustainable options.

Table 1, inserted below, shows the survey sent to the Departments of Transportation. This survey addressed questions regarding annual budget, concrete mixtures used, and concrete cost. To increase the likelihood of responses, the survey was kept short. Respondents did elaborate on their answers and provided further insight and thoughts on sustainable concrete mix designs. The survey was sent to the Materials Testing Divisions, and other relevant departments, listed publicly on the Departments of Transportation websites. If specific emails were not found, the survey was sent to the general forum in hopes of it being passed to the appropriate department.

The next step of this study was to interpret the various data these surveys provided. The results revealed information on various materials, costs, sale percentages, concrete usage and more. This information was illustrated by graphical representations. Additionally, the analysis of the data from the survey responses will lead to further investigation of alternative materials and refine plausible solutions that is expected to be helpful to the Connecticut Department of Transportation to provide a more permanent sustainable alternative of concrete mixture for heavy highway construction.

4. RESULTS

This survey was sent out nationwide to multiple divisions of each the State's Departments of Transportation excluding Connecticut, as the information was obtained directly from the Connecticut DOT interviews. The authors received responses from 12 States. The data pooled revealed several important trends and identified more areas for future surveys to research. The results of the interview and the surveys are as follows.

4.1. Connecticut DOT Interviews

In effort to study sustainable construction and green alternatives for concrete specifically for heavy highway construction, interviews with the Connecticut DOT were conducted. The first interview was with the Pavement Design division, who explained that most of their work is rehabilitation and not new construction. It was explained that the DOT currently uses Recycled Asphalt Pavement (RAP), Recycled Asphalt Shingles (RAS), Ground Tire Rubber (GTR) in chip seals. Interestingly, this division will continue to use RAP, GTR as well as polymers and recycled plastics to improve the durability of mixes and reuse materials.

The second interview was with the Bridge Design division. It was explained that the Connecticut DOT does not use large concrete amounts to make a huge difference in carbon emissions, therefore low-embodied carbon concrete is not mandated from suppliers. However, the DOT is supportive of alternative mixes as long as they have the required strength at 28 days. It was also explained that DOT would use of pozzolan (recycled ground glass) in concrete mixes, but it was noted that the drawback is the longer curing time which is a significant disadvantage as it will slow down construction progress, causing delays and more expenses. It was also pointed out that the DOT references the work of organizations such as the Connecticut Green Building Council, the Connecticut Ready Mixed Concrete Association, and the Connecticut Concrete Promotion Council.

The third interview was with a Connecticut DOT Engineer, who discussed concrete alternatives for heavy highway construction, where the biggest concern is the long-term behaviour of green concrete. The DOT has the responsibility to ensure the continued performance of their projects and cannot risk having to go back and repair any damage or complications further delaying traffic. Therefore, significant research and experimentation needs to be conducted to address durability concerns. This stresses the need for an alternative concrete that is as strong or stronger than traditional concrete. Furthermore, it was explained that the leading cause of concrete damage is permeability. It was also clarified that fly ash is the most used substitute they worked with, however they do realize that this a limited resource and other alternatives must make way in the heavy highway construction industry to prevent any regression back towards traditional concrete.

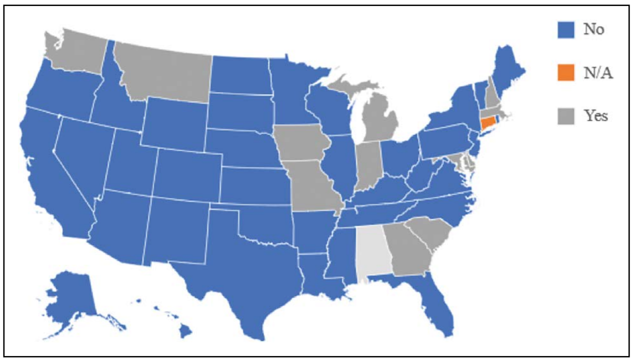

Figure 2. Geographic response rate.

The biggest concerns for the DOT are cost, strength, and durability. The insight gained from the Connecticut DOT interviews helped the researchers with the development of the survey questions, and the issues faced to adopt green alternative concrete mixtures. The interviews helped narrow down the project's objective.

4.2. Survey Response Rate

The survey (shown in Table 1) was sent out to 49 States, excluding Connecticut, and 12 states responded. The responses to the survey came from the following states: Georgia, Indiana, Washington, Delaware, Michigan, Montana, New Hampshire, Missouri, Iowa, South Carolina, Massachusetts, and Maryland. The response rate was 24%. It is also helpful to review the responses in a map formation (Fig. 2), as it will help identify any possible trends based off the region the responses are in. This may reveal common elements or shared concerns if the respondents expanded on the survey questions. Additionally, by looking at the responses geographically, it is more obvious which regions had no responses and areas that further investigative research would be needed to answer any specific questions this survey may have prompted.

By assessing this map, it is clear there was no reported data from the West Coast and South-West, as well as limited data from the South. Nevertheless, there is a wide range of responses scattered across the U.S., which does allow for a general nationwide interpretation of the results, as well as a look at the concerns that individual regions may be facing.

4.3. Survey Question Response – Concrete Composition

The first question addressed in the survey was the composition of each State's concrete in the hopes of being able to identify some common mixture design. Most of the re-

Table 2. Concrete composition

State	Georgia	Indiana	Washington	Delaware	Michigan	Montana
Makeup of concrete	Cement, sand, stone, air	Cement, sand, stone, air entrainment admixture, water reducing admixture, and depend on the type of structures and month of construction can include "additions" such as slag, fly ash, silica fume, and other "chemical admixtures".	Cementitious blends of portland cement, fly ash, slag, and limestone aggregate/water and chemical admixtures dependent on application. We see a lot of blended hydraulic cement such as type il cements with the use of fly ash and slag replacing portland cement	Our traditional concrete is made up of water, sand, stone, cement and flyash or slag. It also has the admixtures water reducer and aer in it. We add accelerating and retarding admixtures depending on outside temperatures	Natural fine aggregate and coarse aggregate, Type I (transitioning to Type IL) Portland cement, slag cement (ASTM C989)	Typically, is made of 1–2 coarse/medium aggregates, sand, cement, and admixtures dependent the producer.
Additives mentioned		Slag Fly ash Silica fume Chemical admixtures	Chemical admixtures	Fly ash Slag Admixture Retarding and accelerators	Slag	Admixture

Table 3. Concrete Composition (continued)

State	New Hampshire	Missouri	Iowa	South Carolina	Massachusetts	Maryland
Makeup of concrete	4000 psi with 50% slag or 25% fly ash	Average* 645 pounds per cubic yard of cementitious material (including fly ash, cement, etc.) and average w/c ratio of 0.41.///Average 76 pounds per cubic yard of fly ash counting all mixes, even ones without fly ash. Average fly ash content of 122 pounds per cubic yard counting only mixes containing fly ash	We use cement, coarse and fine aggregates, water, chemical admixtures and SCMs such as fly and GGBFS.	Our concrete is typically made up of cement (and often fly ash), water, fine aggregate, coarse aggregate, and chemical admixtures.	Cement, fly ash or slags, admixtures, aggregates and water	It can be 100% cement in concrete, or it can be 25% to 50% slag cement added, or 10% to 25% flyash added
Additives mentioned	Fly ash	Fly ash	Fly ash Ground granulated blast furnace slag (GGBFS)	Fly ash Chemical Admixtures	Admixtures	Slag Fly ash

sponses were in agreement with their concrete compounds consisting of crushed stone, sand, water, cement, air, and differing in terms of the addition of chemical admixtures or cement substitution admixture.

When the surveys were initially sent out, the question was intended to ask the participants to identify their percentage of concrete substitute used and what materials they often used. However, due to the open-ended nature of the question, the responses were rather general, with varying degrees of information provided from each state discussing the basic makeup of concrete. The results of this question are broken into two tables (Table 2, and Table 3) of six states each.

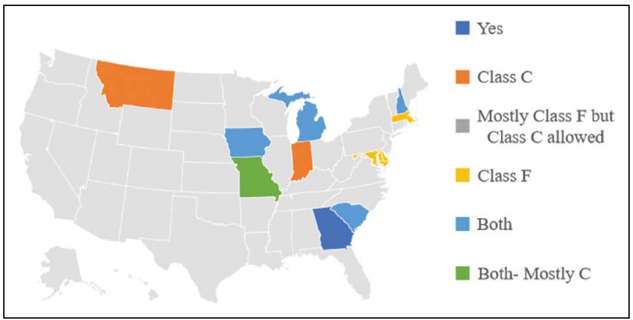

Figure 3. Geographic comparison of fly ash used.

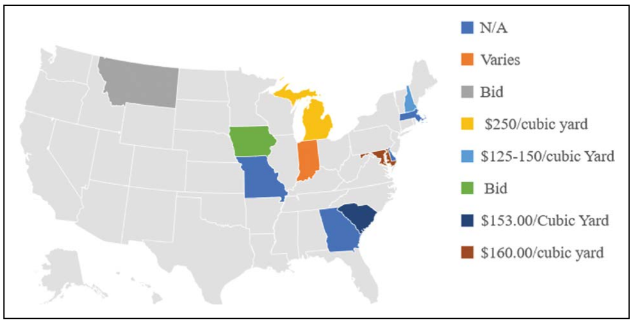

Figure 5. Fly ash cost by region.

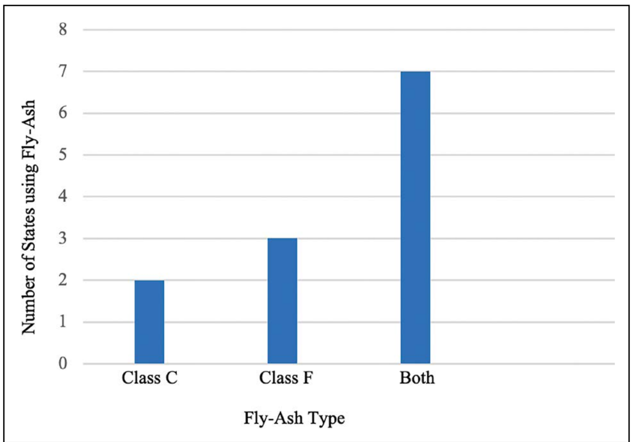

Figure 4. States fly ash usage by type.

Interestingly, several states, like Indiana, Washington, Delaware, and South Carolina reported usage of admixtures in their concrete. This is interesting as admixtures may serve several different functions and are classified by function, such as air-entraining, water-reducing, retarding, accelerating, and plasticizers [43]. However, only Delaware commented on the usage of the admixtures to influence acceleration or retardation depending on the weather. While the other states did not provide further insight on whether these admixtures were used in a similar fashion, or, in comparison, if they were to possibly inhibit corrosion, reduce shrinkage, influence silica reactivity, or improve workability. Overall, the bulk of the responses included the usage of some sort of cement substitution whether it be Fly Ash, Slag, or Silica Fume.

4.4. Survey Question Response – Concrete Budget

The second question in this survey was regarding the annual budget for concrete per state. It was assumed that most states would not have a strict annual budget as the amount of concrete work needed each year could change. Nevertheless, cost is a crucial concern, and it was important to inquire regardless of the anticipated answer. Fortunately, the received responses revealed some financial insight. Washington reported approximately a $200 million annual budget (including pavement, bridge structures, and other miscellaneous uses), and Iowa reported $23 to $30 million budget. The other responses were either not applicable or reported the budget changed annually due to the needs of the State and the various projects that are actively in the works. Additionally, Maryland reported that Districts have specified budgets and how they use their funds depends on the given project.

This data is useful as it shows most states do not provide a specific budget or limit of concrete usage but allow the districts or regions to determine their individual needs. Therefore, if there is no definitive cost cap, and a state may be able to petition for more funds than the previous year to switch to a more sustainable concrete material. For example, if the funds are received per job, if the cost of materials varied, or was slightly higher from one year to the next, it will not be obvious if it was due to the cost of the concrete itself, or if it was due to some other project factor.

4.5. Survey Question Response – Use of Fly Ash

The third question asked was to determine if all of the States are still using fly ash concrete and, if so, which class. Determining the current usage of fly ash concrete is imperative because if some states are not using fly ash, it is important to identify what they may have switched to, or if they are using it, do they have any plans to switch in the near future.

Of the responses received, every state responded yes to the use of fly ash. Figure 3 and Figure 4 depict the different fly ash class in use per state. In whole, most states allow both Class C and Class F fly ash in their projects, but Indiana and Montana reported only using Class C fly ash, and Delaware, Massachusetts, and Maryland reported only using Class F.

4.6. Survey Question Response – Fly Ash Cost

The fourth question in this survey was to investigate the cost of fly ash concrete (Fig. 5). The responses varied with some states being unaware since the cost is included in the project bid, but some states, including Michigan, South Carolina, Maryland, and New Hampshire, were able to provide an average cost per cubic yard. Michigan reported the highest cost out of the responses at roughly $250.00 per cubic yard (cy), while New Hampshire, South Carolina, and Maryland were closer together at $125.00 to $150.00/cy, $153.00/

Table 4. Use of ground glass concrete

State	Georgia	Indiana	Washington	Delaware	Michigan	Montana
Use of ground glass concrete	No	No	No	No	No	No

Table 5. Use of ground glass concrete (continued)

State	New Hampshire	Missouri	Iowa	South Carolina	Massachusetts	Maryland
Use of ground glass concrete	No	No	GGBFS concerns are there is not enough material available locally.	No	Allowed-Not used	Yes

cy and $160.00/cy, respectively. While the other States were unable to provide a definitive price range for material, it is interesting to see the varying cost range between just these three States. This does prompt further questions regarding why Michigan's cost might be so much higher, and if it could be due to a supply shortage in that area.

Interestingly, in response to this question, Montana stated that they do not often use fly ash concrete. Therefore, returning to their response to the first question, it is likely that the bulk of their concrete usage is Slag concrete mixtures rather than fly ash, as long as it reaches the required concrete strength of 4,000 psi (27.6 MPa).

4.7. Survey Question Response – Use of Ground Glass Concrete

The fifth question in this survey inquired on the usage of Ground Glass Concrete or Pozzotive. It was anticipated that this material has little usage, and this question would have a low response rate, but hopefully this question would prompt further discussion or insight on the material through the eyes of the Departments of Transportation. The responses are shown in Table 4 and Table 5.

The question did provide valuable insight. Only two States, Massachusetts and Maryland allow ground glass concrete, with only Maryland using the material so far. Additionally, Iowa commented on this material, stating that they use ground granulated furnace slag, but not ground glass as they are concerned about supply and need material that will be readily available. This is critical to note as Iowa is likely not the only state that would have this concern at the forefront of their minds. Low supply undoubtedly means higher costs and the potential risks of delays or failure to complete work. For ground glass concrete to become a first choice for DOTs, manufacturers must combat this fear and provide reassurance that there is enough material and long-term supply.

4.8. Survey Question Response – Use of Volcanic Ash Concrete

The sixth question in this survey was regarding volcanic ash concrete, another potentially viable replacement for fly ash concrete. The anticipated response was again low, but the hope was to receive insight on the material. It was also anticipated that this material will be used in regions with volcanos in proximity.

From the responses, 11 states replied that they do not use volcanic ash in concrete mix designs, with only Washington replying yes, allowing pumice natural pozzolan in their concrete mixtures. This is interesting as it shows more suppliers must be experimenting with more alternative materials in their projects and are opening the door for natural Pozzolans in heavy highway construction. This response from Washington is also in agreement that a region with volcanos in proximity would be more likely to begin working with the material rather than a region that may have to import the material.

4.9. Survey Question Response – Use of other "Green" Admixtures

The final question asked in this survey was regarding other "green" admixtures in concrete. This question was asked in the hopes of allowing the respondents the chance to expand on the survey or offer a material not explored in this survey. Of the responses, several states replied no other "green" admixtures were in use, while several states provided valuable insight shown in Table 6 and Table 7. In summary, several states, including Maryland, Missouri, and Michigan reported Silica Fume usage. Additionally, Georgia responded that they use recycled aggregate and Metakaolin. Also, Washington state expanded their response stating that they allow fly ash, slag, natural pozzolans, and blended cements, explaining that blended cements are most commonly used with fly ash and slag as replacement for Portland cement. Interestingly, Iowa, expanded their response as well, stating their long-standing use of ground granulated blast-furnace slag (GGBFS) and fly ash for over 40 years, with a significant decrease in their cement content, and have approved the use of CarbonCure with a 3% cement reduction.

5. REVIEW OF CONCRETE MANUFACTURERS

It was important to look to the leading concrete suppliers and evaluate the feasibility of different alternative mixture designs. For this study, four leading suppliers were researched: CalPortland and Cemex, Inc., each in a different region of the country, and two Connecticut suppliers, Tilcon and Urban Mining. Urban Mining was of particular interest, as they only manufacturer ground glass concrete.

Table 6. Other types of "green" admixtures in concrete

State	Georgia	Indiana	Washington	Delaware	Michigan	Montana
Other types of "green" admixtures in concrete	Slag, recycled agg, metakaolin	No	Fly ash, slag, natural pozzolans, and blended cementitious materials. We see a lot of blended hydraulic cement such as type IL cements with the use of fly ash and slag replacing portland cement	Slag	ASTM C595 blended cements and C1240 dry-densified silica fume	No

Table 7. Other types of "green" admixtures in concrete (continue)

State	New Hampshire	Missouri	Iowa	South Carolina	Massachusetts	Maryland
Other types of "green" admixtures in concrete	No	Ground granulated blast furnace slag, silica fume	We have been doing fly ash and GGBFS for over 40 years, we have optimized our gradations and reduced our cement contents, we use IL cements, we have approved the use of carbon cure with a 3% cement reduction	No	No	Silica fume and metakaolin

Urban Mining, in Beacon Falls, Connecticut is a local Connecticut concrete plant which has revolutionized the process of making ground glass concrete even more sustainable as it can accommodate all types of glass containers, including ceramic and other "nontraditional" glass bottles [44]. This is significant, as it maximizes the options of resources to make Pozzotive concrete, their brand of pozzolan. Recently, Connecticut has attempted to increase recycling statewide, specifically that of beverage bottles (and cans). To reduce littering and increase recycling, the state's legislature introduced the Connecticut Bottle Modernization Bill (Section 8 of PA 21-58) [45]. In 2020, Urban Mining commented on this bill, requesting the Department of Energy and Environmental Protection to make the Beacon Falls facility an important element of the in-state processing option for wine and liquor beverage containers sold in this state [44]. Urban Mining argued the addition of Pozzotive is aligned with the new bill's objectives of "finding 'the highest and best use' for glass, and the addition of Pozzotive to concrete mixes creates stronger and longer lasting concrete for our communities while reducing the carbon footprint of concrete on a nearly ton-for-ton basis" [44]. Urban Mining further explains that the use of Pozzotive ground glass concrete is "five times more impactful in reducing global CO_2 emissions than repurposing the glass back into bottles or fiberglass" [44]. Overall, this is promising, and this bill should increase the likelihood of recycling. By keeping the recycled glass in Connecticut and making it easier for people to participate, the amount of glass available will likely increase.

Tilcon is renowned as a reliable and long-standing concrete supplier in Connecticut. Comprised of 20 facilities, this company has supplied concrete, aggregates, and asphalt for 100 years, and provides a significant amount of the concrete for the Connecticut DOT's various concrete projects. In 2020, Tilcon's environmental report recorded 46% of their revenue came from sustainable products, 36.5 million tons of alternative materials and alternative fuels recycled, and 1 million tons of CO_2 emissions were prevented [46]. This information is significant and shows what great efforts for the environment have begun to take shape in leading plants, while still providing their high-quality products.

CalPortland is one of the largest suppliers on the West Coast with facilities in Oregon, Washington, California, Nevada, and Arizona. This supplier is a leading manufacturer of concrete and has worked to provide reliable and strong blended concretes with a variety of different materials including: limestone, slag, fly ash, and silica fume. Additionally, this company has introduced calcined clay as a natural pozzolan into their concrete mixes. Further, in 2020, this company released a new environmentally friendly ASTM C595 blended cement. This material offers greater Green House Gas and is comprised of a blend of SCMs including limestone, natural pozzolan, or other approved materials [47]. This reinforces the responses provided by Washington's survey as they commented on the frequent usage of ASTM C595. Between the survey responses and the information provided from CalPortland's website, it can be argued that ASTM C595 blended cement is a viable option for Connecticut as well. However, this material seems to rely on the addition of limestone. While this is a great solution, it stands to reason that Connecticut can progress further towards sustainable construction on all levels.

Cemex, Inc. is headquartered in Houston, Texas and readily serves the surrounding Southern region. This company advertises their sustainable progress in several ways, including safety actions, environment efforts, and their agreement with Climate Action policy. Their site details their mixtures of fly ash and slag cement, along with their incorporation of chemical admixtures. However, there is no reported data on the use or incorporation of natural pozzolans or ground glass in their mixture designs. While this supplier is a leading supplier in the South and reinforces the sustainable efforts that other top suppliers are attempting, there was little additional data found.

6. CONCLUSION

In summary, this study provided further data on the current status of the Departments of Transportation concrete usage, materials used, cost, and use of alternative "green" mixtures. In comparison to the two studies completed in 2014 [23] and 2015 [42], it's clear how little has changed in the means of concrete manufacturing and how reliant states are on fly ash concrete especially. Nevertheless, by carefully analysing the answered surveys, and through careful investigation of these top suppliers, it can be argued that most states may be open to alternative mixture designs, if they meet the required build specifications, and that states are more concerned with product availability and means. Further, the survey responses received do correlate with the advertised materials from the several concrete manufacturers previously reviewed. This is interesting because, if the larger suppliers market this material more and continue to push it into production on projects, it is more likely that it will be fully accepted by government and state agencies overtime as the material will be less "new". This survey also expressed the significant amount of fly ash currently used, which raises red flags. This reinforces the concern and critical need for an alternative replacement compound that is fully sustainable on all levels to make its way into heavy highway construction. The time to begin the switch to this new mixture design is now, as the depletion of fly ash only continues with each build and with less availability comes increase in cost.

This study leaves room for future studies to attempt interviews with suppliers and investigate pipeline mixture designs as well as marketability for future mixture designs. The authors feel it is important to focus on the economics of alternative concrete use as it would have a major impact encouraging the States to use green concrete more frequently. It is thought provoking to look at the cost of alternative concrete and compare it with traditional concrete, comparing not only its cost of production, but the environmental savings from the recycled material and its lower carbon footprint. Sustainability is a growing area of concern, especially surrounding the concrete industry.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

PEER-REVIEW

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