Low Carbon Concrete Pilot Program: Task B Report – Proposed Low Embodied Carbon Concrete Mixtures for Further Testing and Analysis

Report

Original Submission Date: 12-20-21

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1 Introduction and background

Concrete is responsible for about 8.6% of the world's CO_2 emissions [1–3] despite the production of concrete having a relatively low carbon intensity compared to other building materials. The excessive release of CO_2 from concrete is due to the vast quantities of the material produced each year. Thus, reducing the environmental impacts of the overall construction industry, which is the largest consumer of natural resources, is a necessity. The Port Authority of New York and New Jersey (Port Authority) is committed to meeting the goals of the Paris Climate Agreement to reduce greenhouse gas emissions by at least 35% by 2025 and 80% by 2050 (The Port Authority of NY & NJ, 2021a, 2021b). Following these announced goals, the Port Authority initiated the Low Embodied Carbon Concrete Pilot Program research initiative to develop and test a set of low embodied carbon concrete (LECC) mixtures that could be used on Port Authority projects and thus reduce the overall embodied carbon of their construction [4,5].

LECC is a novel class of concrete mixtures that utilizes innovative and traditional mixture design techniques and components to producing concrete with a lower embodied carbon than current standard practice allows [6]. There is no current industry standard for what level of embodied carbon qualifies a concrete mixture as LECC [6]; however, policies being developed by local governments and within transportation agencies have started to set limits on the total amount of embodied carbon allowable in concrete, which requires LECC design techniques to meet. LECC mixtures can be produced using a broad range of tools such as using locally available materials, optimizing aggregate gradations, reducing the total amount of binder, using supplementary cementitious materials (SCMs), and through CO_2 mineralization and utilization [3,7–11].

In Task A of this research program, the research team studied the current state of embodied carbon in concrete mixtures procured for Port Authority construction projects. This work showed that the use of SCMs in concrete had a significant impact in reducing the embodied carbon of concrete mixtures procured by the Port Authority. Of these, systems that used ternary blends (systems containing portland cement and two different SCMs) were the most effective. The use of these systems could be affected without significantly reducing the strength or durability of the concrete [12], which is consistent with existing scientific literature on the topic [1,13–17].

This report summarizes the findings of Task B of the Low Embodied Carbon Concrete Pilot Program research initiative. The main goal of this task was to develop and propose 20 LECC mixtures, with embodied carbon lower than the existing standard Port Authority mixtures, for advanced testing and potential use in Port Authority projects. The report includes background information on LECC concrete, the research team's methodology in developing the mixtures, the mixture designs for the proposed mixtures, and an estimate of the embodied carbon of the proposed mixtures.

1.1 Background on concrete mixture technologies

Traditional concrete is composed of portland cement, coarse and fine aggregates, water, and air. While the absolute values of emissions for a concrete mixture will change depending on the cement content and strength target, the portland cement is generally responsible for much of the embodied carbon in a concrete mixture due to the amount of energy required to create cement, and the off gassing of CO_2 from limestone during the clinkering process of cement production [18]. The next major contributor to carbon footprint from concrete, though significantly lower than the portland cement, is the coarse aggregates [2,12]. Fine aggregates, admixtures, and placement procedures contribute relatively small amounts of CO_2 to the total emissions [12]. Further information on the embodied carbon of portland cement concrete can be reviewed in Appendix B. Despite good progress from the industry on reducing production side carbon releases through technological innovations, addressing the embodied carbon in portland cement concrete requires a new conceptual process for choosing concrete mixtures that includes changes in mixture design and utilization of different materials. This concept is generally referred to as low embodied carbon concrete (LECC). There are four general techniques for creating LECC mixtures. The overviews outlined below provide a brief description of each method.

1.1.1 Partial replacement of binder with lower embodied carbon alternatives

Given that portland cement is the main contributor to CO_2 emissions in the production of concrete, partial or total replacement of portland cement is a common technique for reducing the embodied carbon in concrete. Partial replacement of portland cement can be done using SCMs, including materials such as fly ash, slag, ground limestone and ground glass pozzolan. Typically, these materials are produced from waste materials or do not require as significant processing as portland cement to be used in concrete systems, as such they have significantly lower embodied carbon than portland cement [3]. While SCMs cannot be used to completely replace portland cement, they have been shown to be effective even at replacement levels reaching over 70% of the total binder content [19]. A combined evaluation of mechanical performance and environmental impacts gives a more complete understanding of the applicability of using SCMs in practice. A full overview of each of the SCMs considered as a part of Task B (fly ash, slag, ground limestone, and ground glass pozzolan) can be reviewed in Appendix B.

1.1.2 Total replacement of binder with lower embodied carbon alternatives

Total replacement of the portland cement binder can be achieved using alternative hydraulic cements or alkali-activated cements. These materials include things such as calcium sulfoaluminate cement (CSA) and geopolymers. CSA requires low amounts of $CaCO_3$ to be calcined during production, meaning a lower release of CO_2 during pyroprocessing but also require pyroprocessing at lower temperatures reducing the CO_2 production overall [20]. While not an appropriate cement for replacement of portland cement in all activities, CSA is very useful particularly for situations where rapid repair of concrete systems is required, or rapid construction is required because it can set and gain strength rapidly [15]. CSA systems produce high amounts of ettringite, rather than calcium silicates typically found in portland cement systems. The rapid reopening of facilities and roadways can offset the increased cost associated with CSA or blended systems.

Geopolymer systems, also known as alkali-activated cementitious materials, gain strength through a chemical reaction between an alkaline activator material and aluminosilicate-rich material. The alkaline activator materials most used include sodium hydroxide or potassium hydroxide, and the aluminosilicate rich material can be provided from fly ash or slag materials like those described above [15,21]. Currently, geopolymer systems are not generally available for purchase in North America. As such, the research team, in consultation with the Port Authority team, has decided to not include geopolymer mixtures in the testing matrix.

1.1.3 Reduction in the total amount of binder

Reduction of the total amount of binder used in a concrete mixture can be done through optimization of aggregate contents in the system. Concrete systems often utilize higher than necessary portland cement contents to achieve higher early strengths to speed up construction, increase factors of safety in concrete performance (beyond code mandated requirements), and improve workability of concrete systems [6]. However, these can lead to significant higher levels of portland cement than are necessary in concrete mixtures to meet project requirements. The tendency to over-design concrete mixtures can be combated by limiting the total portland cement content in a mixture through specifications, a technique already employed by the Port Authority [22]. However, additional reductions in the total amount of binder can be achieved through advanced mixture design techniques to maximize the amount of aggregate in a concrete mixture without impacting strength, durability, or workability. Several studies have shown that LECC can be produced with high quality technical characteristics by considering particle packing models with low binder concrete [11,23]. Reduction in cement contents up to 18% have been achieved through use of this design technique without impacting strength [11,24], which effectively reduces the carbon footprint of the system by a similar amount since cement is the major contributor to CO_2 in concrete. The total reduction capable is highly dependent on local aggregate sources, however, and requires significant analysis and testing.

1.1.4 Utilization of lower embodied carbon aggregate sources

Aggregates make up a substantial portion (60-75%) of total concrete volume, which can cause a significant demand on natural resources [25]. The total volume of aggregates produced each year also results in significant CO_2 production, if much lower than that of portland cement. Therefore, utilizing alternative and lower embodied carbon aggregate systems is vital to improving the overall sustainability of concrete. For the work presented here, two alternative aggregate systems were considered for use: (1) recycled concrete aggregates (RCA); and (2) carbonate coated aggregates

RCA, produced from demolished concrete or returned concrete, is a viable alternative to using natural aggregates in concrete. Concrete of good quality strength can be produced through the use of RCA [17,26–28]. RCA can reduce the emission due to aggregate production and transportation [29], however this is typically dependent on the distance the material is transported from demolition site, to recycling facility, to concrete facility.

The carbonate coated aggregates are a new product developed by a California-based company that uses captured CO_2 to create mineralized $CaCO_3$ that they use to coat aggregate pieces, effectively sequestering the CO_2 [30]. While this product has shown some adequate performance in preliminary applications, it is currently only available in small quantities from a facility in Vancouver, CA. As such the research team does not think that the carbonate coated aggregate material should be examined at this time.

1.1.5 CO_2 sequestration in concrete

There have been several advances in the past decade in technologies for sequestering CO_2 within concrete. These technologies have, primarily, been developed by private companies and the exact methodology is proprietary. The technologies range from mixing CO_2 directly into the concrete as a component of the concrete mixture to curing concrete elements in large chambers infused with CO_2 or components of concrete infused with CO_2. As a part of this work, the research team has focused on two such technologies: (1) in-situ carbonate seeding – a technology developed by CarbonCure Technologies; and (2) carbon impregnated fly ash – a technology developed by Carbon Upcycling.

In-situ carbonate seeding can be used for ready-mixed concrete and involves injecting liquid CO_2 as a separate component within concrete. During the hydration process, the CO_2 reacts with the calcium silicates present in the anhydrous cement and the mixing water to form calcium carbonate [3,31,32]. With this technology, the CO_2 is typically dosed at amounts ranging from 0.1% to 0.5% of total cement weight. The resultant formation of $CaCO_3$ improves concrete strength. While the amount of CO_2 sequestered is relatively small, the improvement in strength from the formation of calcium carbonate allows for a reduction in overall cement binder for a particular mixture (around 10%) [33]. Given the large contribution of cement to the overall embodied carbon in concrete, a 10% reduction in total cement content can have a relatively high impact on total embodied carbon.

The second technology, carbon impregnated fly ash (CFA), involves sequestering carbon within fly ash. The technology itself is material agnostic and can be applied to various materials used in concrete, though the current focus has been on improving fly ash. With this technology, standard fly ash is placed into a pressurized chamber into which CO_2 is added. During this process, CO_2 becomes embedded in the surface of the fly ash particle, up to 15% of the total material mass [34]. During this process, the surface of the fly ash particles is etched and roughened, which also increases the reactivity of the fly ash materials, improving overall concrete strength [34].

These four techniques described can be used alone or in tandem to produce LECC concrete systems that reduce the overall global warming potential of concrete construction. The Port Authority has been successful in recent years at implementing some of these strategies and reducing the overall embodied carbon in their concrete construction [12]. The Port Authority has mainly focused on utilizing SCMs and limiting the amount of portland cement used in concrete mixtures, to date. This work will examine the potential for further improvements through an examination of literature and an analysis of local systems that can be tested for acceptance by the Port Authority.

2 Objectives and research tasks

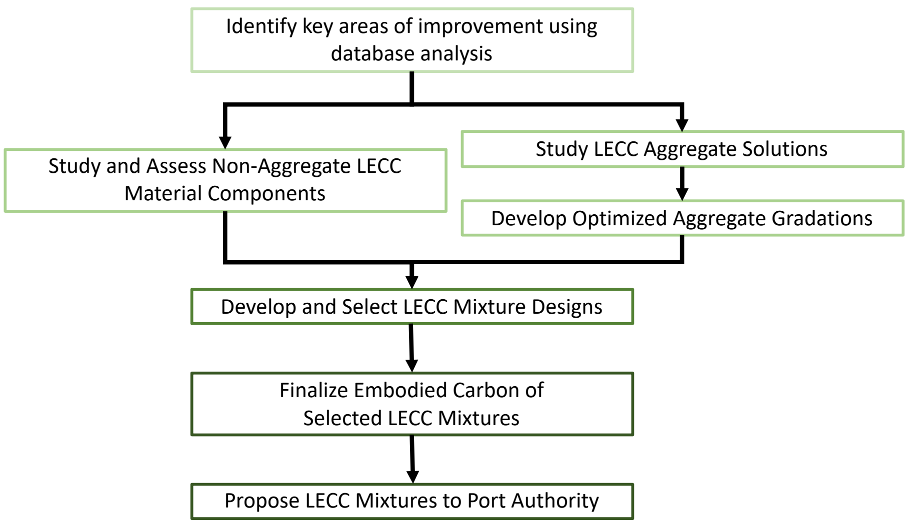

Figure 1: Methodology flowchart for determining LECC mixtures

The main goal of the LECC project is to provide the Port Authority with the ability to significantly reduce the embodied carbon of the concrete mixtures used in their construction activities. This research will support the agency-wide greenhouse gas reduction target of 80% by 2050. Task A of this project aimed to analyze and calculate the current state of embodied carbon in Port Authority concrete mixtures. In Task B, the research team seeks to develop a series of proposed low-embodied carbon concrete mixtures using data from the literature to optimize carbon reduction as compared to the Port Authority's baseline mixtures as determined in Task A. As such, Task B consists of a series of seven subtasks following the methodology shown in Figure 1.

The final proposed mixtures are limited to 20 mixtures per the research project guidelines. As such, not all permutations of LECC mixtures can be produced. In this report, the research team will present the 20 mixtures most likely to support the Port Authorities continuous improvement in the embodied carbon of their construction projects.

3 Key improvement areas in Port Authority concrete mixtures

3.1 Port Authority concrete mixture design requirements

The Port Authority's specifications provide descriptions of conforming materials that can be used for concrete mixture design [22]. Cementitious materials include Portland cement, (Types I, II, and III conforming to ASTM C150) [35]; silica fume conforming to ASTM C1240 [36]; Class N metakaolin confirming to ATM C618 [37]; Class F fly ash conforming to ASTM C618 [37], and slag conforming to ASTM C989 [38]. In the current specifications, the maximum Portland cement content is specified as 400 pounds per cubic yard; however, in mass concrete, concrete cast below grade and against the earth, and concrete that does not require labor finishing, cement content can be limited to 300 pounds per cubic yard. The minimum weight of supplementary cementitious materials is set at 30 percent of the total cementitious materials.

Coarse aggregates for normal weight concrete must comply with ASTM C33 [39], and ASTM C535 [40]. Fine aggregate must comply with ASTM C33, and ASTM C131 [41]. There is a minimum volume of 39% coarse aggregate that is required for all normal-weight concrete mixtures. Full-depth pavement mixtures require a minimum of 70% total aggregate volume.

The Port Authority uses a series of performance-based metrics that are used for the evaluation of concrete mixtures. Concrete mixtures are classified into six classifications/applications and include the following categories: Category I – full depth pavements and unbonded overlays; Category II – bonded pavement overlays; Category III – elevated structural overlays; Category IV – Structural (exposed to freeze-thaw and/or sulfates in addition to chlorides or marine environment); Category V – Structural (exposed to freeze-thaw and/or sulfates only); Category VI – Standard Structural (not exposed to freeze-thaw). The performance of concrete mixtures within a category is evaluated based on a series of performance criteria parameters which include water to cement ratio, air content, permeability, bond strength, compressive strength, flexural strength, pavement thickness, and chloride content.

In many of the performance categories, minimum or maximum performance metrics are established based on the specifications of a specific project; however, some properties are set for a given category. In terms of shrinkage, the absolute drying shrinkage cannot exceed 0.04% for Category II, III, IV, and V, and 0.03% for Category I. Permeability is measured by means of a rapid chloride penetration test (ASTM C1202) and the maximum accelerated Coulomb count at 28 days cannot exceed 1200 Coulombs for Category III and IV or 1700 Coulombs for concrete mixtures placed in a marine environment [22]. A minimum flexural strength is established in the specifications for Category I at 700 psi in accordance with ASTM C78 [22,42]. Compressive strength is specified based on contract documents and is typically tested at 28 days in accordance with ASTM C39 [22,43].

3.2 State of the Port Authority's current practice

In Task A of this research program, the research team examined historical concrete mixture design data from the Port Authority from 1999 to 2021. A summary of important mixture design data from the Task A Report of this research program and is presented in modified form in Table 1 [12]. The table has been modified to show the average mixture design quantities over the last three full calendar years (2018-2020) to show the Port Authority's current state of practice. Comparisons between longer-term and recent trends show that the Port Authority has already made promising headway in terms of lower carbon dioxide emissions, lower cement content, and increasing use of supplementary cementitious materials.

Table 1: Summary of average mixture design proportions for the Port Authority's concrete mixture design database over various time periods

Evaluation Period	Value	Cement (lb/yd^3)	Fly ash (lb/yd^3)	Slag (lb/yd^3)	Fine aggregate (lb/yd^3)	Coarse aggregate (lb/yd^3)	Water (lb/yd^3)
1999-2021	Mean	463	84	119	1711	1253	261
	Std. Dev.	146	88	135	246	158	27
2018-2020	Mean	426	87	140	1255	1728	255
	Std. Dev.	151	88	137	143	231	25
Evaluation Period	**Value**	**SCMs to binder ratio**	**Water to binder ratio**	**Binder to aggregate ratio**	**Compressive strength (lb/in^2)**	**RCPT Test Value (Coulombs)**	**GWP (Eq. CO_2 kg/m3)**
1999-2021	Mean	0.31	0.40	0.23	6,335	89	329
	Std. Dev.	0.18	0.05	0.23	1,786	285	75
2018-2020	Mean	0.35	0.39	0.22	6,153	316	309
	Std. Dev.	0.19	0.05	0.03	1,801	439	78

Several observations can be highlighted from these recent trends. Specifically, average cement content has decreased by approximately 8%, while fly ash content has increased by 3%, and slag content has increased by 17%. Additionally, a significant increase in coarse aggregate content (38% increase) has been observed in recent years, and a higher SCM to binder ratio has been reported. Finally, the average global warming potential has decreased from 329 Eq. CO_2 kg/m3 (for the 1999-2021 period) to 309 Eq. CO_2 kg/m3 (for the 2018-2020 period).

3.3 Areas for Improvements

Within this task, the research team has identified the following areas that can be improved to offer a wider set of LECC mixtures:

Alternative Cementitious Materials: Currently, the Port Authority limits cementitious and SCM materials to Type I, II, and III Portland cement, Class F fly ash, and slag. Alternative SCMs, such as ground glass pozzolans, finely ground limestone, and others have become more widely adopted and researched. These materials should be considered to provide a wider set of materials that can be used to lower carbon emissions and maintain high-performing concrete materials.

SCM Replacement Levels: The average SCM to binder ratio (based on data from the Port Authority's mixture design database) was approximately 0.35 (with a standard deviation of 0.19) over the last three years, which slightly exceeds the minimum required of 0.30 in the Port Authority's specifications. Based on an in-depth literature review, the research team believes that substantially higher replacement levels can be used while maintaining high-quality concrete that meets the needs of the Port Authority's applications. A series of recommended mixtures will be proposed later in the report with higher SCM content that will help lower the carbon footprint of the Port Authority's concrete mixtures.

Highly Blended SCM Systems: The concrete mixtures from Port Authority's mixture design database that were identified in Task A with the lowest global warming potential were primarily those with a ternary blend of fly ash, slag, and Portland cement. Blended systems identified in the database, in general, tended to be in relatively modest proportions. Based on a literature review, the research team believes that more highly blended systems with SCM contents well over 70% can be designed and achieve adequate performance and workability.

Optimized Aggregate Gradation: Aggregates are the largest material by volume and mass in a concrete mixture. By optimizing the gradation of aggregates, a comparably lower number of cementitious materials can be used, relative to a non-optimized material, while achieving the same (or better) performance. In this report, aggregate optimization techniques are investigated to improve the performance and lower the embodied carbon of the Port Authority's concrete mixtures.

4 LECC technologies proposed for use

A wide range of LECC technologies and mixture design techniques were reviewed and considered as a part of this research program. The following sections discuss each of these components, as well as conclusions on how they may or may not be useful for implementation in the final set of proposed mixtures.

4.1 Potential non-aggregate based LECC technologies

4.1.1 Use of SCMs

4.1.1.1 <u>Currently used SCMs in Port Authority concrete mixtures</u>

Currently, the Port Authority allows a wide array of SCMs such as fly ash, slag, silica fume, and metakaolin. However, current Port Authority specifications do not provide provisions for the use of finely ground limestone, either standalone or as part of a blended portland-limestone cement system, ground glass pozzolans, or calcined clays. Finely ground limestone and ground glass pozzolan are becoming widely available in the NYC metropolitan region and are projected to be readily available in the future whereas supplies of fly ash and slag may decline due to a reduction in steel making and coal burning in the United States [44]. As such, the research team has examined systems that included these two items as a significant component. Calcined clays, while becoming more popular internationally and in the research community, still have no production program in development in the United States, as such the research team did not consider them for use in this research program [45,46]. The research also team did not examine systems that included silica fume or metakaolin as a part their work, as directed by the Port Authority team.

4.1.1.2 Methodology for developing preliminary mixtures with high SCM content

To develop potential concrete mixtures with high contents of SCMs that could be used by the Port Authority, the research team began by completing a thorough review of literature, including collecting data on numerous concrete mixtures containing fly ash, slag, ground glass pozzolan, finely ground limestone, and combinations thereof. Mixture design data was input into a database, including strength values where available. After identifying a representative number of concrete mixtures, filtration of the data was conducted based on several factors. For example, data was filtered to include only certain levels of SCM content (to remove mixtures that did not exceed existing Port Authority mixtures). Further, the data was filtered to target a minimum compressive strength (5000 psi), maximum cement content (400 lb/yd^3), and other specifications and limitations based on Port Authority specifications. The research team then used their expertise to make modifications to the mixtures identified in the literature based on material availability, practicality, and other factors. The following subsections present data from mixtures for each SCM identified through the literature search. The database referenced throughout this section will be made available for the Port Authority's use and analysis.

4.1.1.3 Preliminary mixture selection based on type of SCM

The following section describes modifications made to a set of mixtures chosen from literature that present potential improvements over existing Port Authority mixtures or examine different SCMs that are currently in use. The full set of mixtures from literature examined as a part of this study, and how the filtering was completed for different SCMs can be reviewed in Appendix B.

Fly Ash - From a wide array of mixtures reviewed in literature that used high volumes of fly ash two mixtures, presented in Table 2, were chosen as the basis for higher fly ash content mixtures beyond the baseline system.

Table 2: Mixture proportions of potential high fly ash mixtures

Database Mix ID	Proportion (lb/yd^3)					Ratio		Strength (psi)
	Cement	Fly ash	Coarse aggregate	Fine aggregate	Water	w/b	SCM/b	28 days Comp. strength
R85	337	337	1709	1247	303	0.45	0.5	6237
R2	405	270	1996	1153	275	0.4	0.4	4299

From these mixtures, further refinement was completed to develop the FA_40% mixture, which includes a 40% replacement of portland cement with fly ash, and FA_50% mixture, which includes a 50% replacement of portland cement with fly ash. Mixture R2 was modified to reduce the portland cement content and increase the aggregate content while maintaining a w/b ratio of 0.40 and a fly ash content of 40%. Aggregate contents were also modified based on the properties of the proposed aggregates that will be use in the concrete mixtures. These changes should result in a higher density of aggregate packing that reduces the total binder content required, without impacting strength. Mixture R85 was modified to reduce the portland cement content and the w/b ratio while maintaining a 50% fly ash replacement.

Aggregate contents were also modified based on the properties of the proposed aggregates that will be used in the concrete mixtures. These changes allow for a lower total binder content, which is offset by using a lower w/b ratio to maintain a similar compressive strength. The full proposed mixture designs for the FA_40% and FA_50% can be reviewed in the Appendix in Table A1.

Slag - From a wide array of mixtures reviewed in literature that used high volumes of slag two mixtures, presented in Table 3, were chosen as the basis for higher slag content mixtures beyond the baseline system.

Table 3: Mixing proportions of mixtures produced with slag

Database Mix ID	Proportion (lb/yd^3)					Ratio		Strength (psi)
	Cement	Slag	Coarse aggregate	Fine aggregate	Water	w/b	SCM/b	28 days Comp. strength
R88	337	337	1709	1305	303	0.45	0.5	9863
R78	190	631	1967	937	273	0.33	0.77	5947

From these mixtures, further refinement was completed to develop the SLAG_60% mixture, which includes a 60% replacement of portland cement with slag, and the SLAG_77% mixture, which includes a 77% replacement of portland cement with slag. Mixture R88 was modified to reduce the total binder content and increase the aggregate content, as well as reducing the w/b to a 0.40 to maintain strength. Aggregate contents were also modified based on the properties of the proposed aggregates that will be use in the concrete mixtures. These changes should result in a higher density of aggregate packing that reduces the total binder content required, without impacting strength. Mixture R78 was modified slightly to reduce the total binder content based on the particle packing required from the base aggregates, while increasing the w/b to maintain workability. While this may result in a decrease in strength, the R78 already provides a 28-day compressive strength of almost 5947 psi, and as such would likely still be a usable mixture. It is anticipated, however, that this high level of slag may have difficulty setting and gaining adequate strength. Therefore, the team has proposed a variation on this mixture, SLAG_65%, which should provide adequate setting capabilities at a lower slag content. The SLAG_65% mixture will be used if the SLAG_77% mixture is not viable. The full proposed mixture designs for the SLAG_60%, SLAG_77%, and SLAG_65% can be reviewed in the Appendix in Table A1.

Ground glass pozzolans - From a wide array of mixtures reviewed in literature that used ground glass pozzolan two mixtures, presented in Table 4, were chosen as the basis for mixtures including ground glass pozzolan.

Table 4: Mixing proportions of mixtures produced with ground glass pozzolans

Database Mix ID	Proportion (lb/yd^3)					Ratio		Strength (psi)
	Cement	Ground Glass Pozzolan	Coarse aggregate	Fine aggregate	Water	w/b	SCM/b	28 days Comp. strength
R28	448	192	1718	1254	312	0.49	0.3	4931

From these mixtures, further refinement was completed to develop the GGP_30% mixture, which includes a 30% replacement of portland cement with GGP. The proposed mixture maintains relatively the same ratio of portland cement and GGP as in the R28 mixture, but the total binder content is reduced. To offset any reduction in strength from the reduction in binder content, the w/b ratio was also reduced in the GGP_30% mixture compared to R28. Aggregate contents were also modified based on the properties of the proposed aggregates that will be use in the concrete mixtures. The w/b was reduced to 0.40 to ensure that the mixture is more comparable to other LECC mixtures proposed. The full proposed mixture design for the GGP_30% can be reviewed in the Appendix in Table A1.

High blend SCM systems - Several ternary and quaternary systems that included portland cement with multiple SCMs were also reviewed from literature. From this review it was observed that systems with replacement levels as high at 75% had been completed with satisfactory strength properties [28]. Given this, the research team proposes two ternary blended systems that will look at blends of systems using slag and fly ash, and slag and GGP. The Ternary_FA_SLAG system will include a 76% SCM replacement level, evenly split between fly ash and slag. The Ternary_SLAG_GGP system will include a 62% SCM replacement level – 13.5% of the binder content being GGP and 48.5% of the binder being slag. The full proposed mixture design for the GGP_30% can be reviewed in the Appendix in Table A1.

Portland-limestone cement/finely ground limestone - A review of literature of mixtures containing finely ground limestone has shown that the majority of mixtures studied in literature that directly replaced a portion of the portland cement with finely ground limestone were done using portland cement contents in excess of 500 lb/yd^3 [47], exceeding the limits on total portland cement allowable in Port Authority concrete mixtures. Despite this, a significant body of literature has shown that the preblended PLC systems can be used as a direct replacement for OPC in concrete systems, including in systems that use other SCMs. Therefore, the research team proposes doing a replacement of the portland cement in one of the previously proposed mixtures with PLC that contains 12% limestone, resulting in an additional reduction in total cement content. The proposed mixture that includes the PLC in place of the portland cement is SLAG_50%_PLC. Other systems that included PLC were considered during discussions but were ultimately not included due to the limitation on the number of mixtures to be tested as a part of this program The full proposed mixture design for this system can be reviewed in the Appendix in Table A1.

4.1.1.4 Preliminary mixture selection for CSA mixtures

A review of literature has indicated that mixtures made with CSA cements typically have cement contents at or above 700 lb/yd^3 [48]. As a cement that is typically used in rapid repair situations or other situations where high early strengths are needed, the high cement content promotes higher early strengths. However, given that CSA systems have an inherently lower embodied carbon than portland cement systems with the same cement content, it is still prudent to test this system for comparison and evaluation purposes. Therefore, the research team proposes the CSA mixture which contains 700 lb/yd^3 CSA cement. The full proposed mixture design for the CSA system can be reviewed in the Appendix in Table A1.

4.2 Study of aggregate LECC material components

4.2.1 Current aggregate systems used in Port Authority concrete mixtures

The Port Authority utilizes several different aggregate sources in their concrete mixtures, depending on which concrete company they procure their concrete from and the location of the construction project. For the work presented here, aggregates from several quarries were considered. Coarse aggregates from Eastern Concrete Materials in Hamburg, NJ (referred to herein as Hamburg Coarse) and Weldon Materials in Watchung, NJ (referred to herein as Weldon Coarse), A fine aggregate, from Clayton Sand Co. (referred to herein as as Clayton Fine), and intermediate sized aggregate from US Concrete in Wantage, NJ (referred to herein as Wantage Intermediate) were all examined for use in the proposed concrete mixtures. These aggregates have been employed in Port Authority projects and meet the applicable requirements set forth in the Port Authority concrete specifications [22]. The Weldon Coarse and Clayton Fine were chosen for use in all proposed concrete mixtures without optimized aggregate gradations.

4.2.2 *Aggregate Optimization for Low-Embodied Carbon Concrete*

An aggregate optimization study was developed as part of this research task to understand how natural aggregate systems commonly used by the Port Authority can be optimized to lower cement content and reduce the embodied carbon, without impacting other concrete properties. The methodology, results, and findings from this study are outlined in the proceeding subsections and Appendix B.

4.2.2.1 Methodology

Aggregate Gradation

The type and properties of different types of aggregates used in this study are summarized in Table 2. The particle size distribution of aggregates, which can be seen in Appendix B, was determined by sieve analysis according to ASTM C33 [39].

Table 2: Properties of individual aggregate

Aggregate	Type	Specific Gravity	Percent Absorption (%)	Bulk Density (lb/yd^3)	
				Loose	Compacted
Hamburg Coarse	#57 stone	2.62	-	2098	2538
Weldon Coarse	#57 stone	2.85	-	2218	2619
Wantage Intermediate	#8 stone	2.8	1.7	2279	2667
Clayton Fine	Natural Sand	2.63	0.6	2715	3159

Evaluation of Packing Degree

The full process for the evaluation of the packing degree of the aggregates can be reviewed in Appendix B.

4.2.2.2 Results of Aggregate Packing Work

Binary and Ternary Experimental and Analytical Packing

The experimental and analytical packing degrees for the binary combination of coarse and fine aggregate are presented in Figure 2. The best experimental packing degree was achieved as 77.30% and 77.70% for a relatively sandy blend of the Hamburg and Weldon series, respectively. The fine aggregate volume percent pertaining to the highest packing degree was found to be both 60% and 50% for Hamburg and Weldon series, respectively. The modified-Toufar model predicted a slightly higher value of packing degree than experimental values for Hamburg and Clayton blends. On the other hand, for Weldon and Clayton blends, the modified-Toufar model closely agrees with the experimental values. f

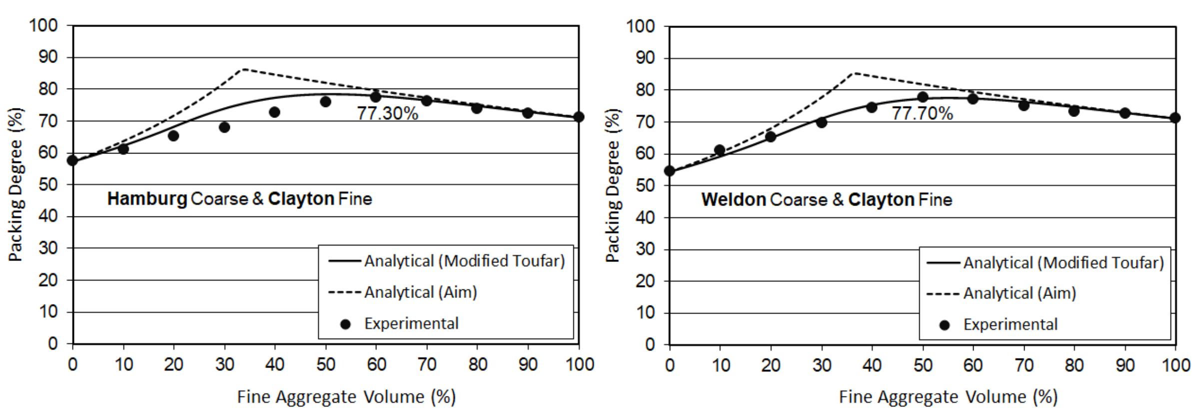

Figure 2: Experimental and analytical packing degree for binary aggregate combination.

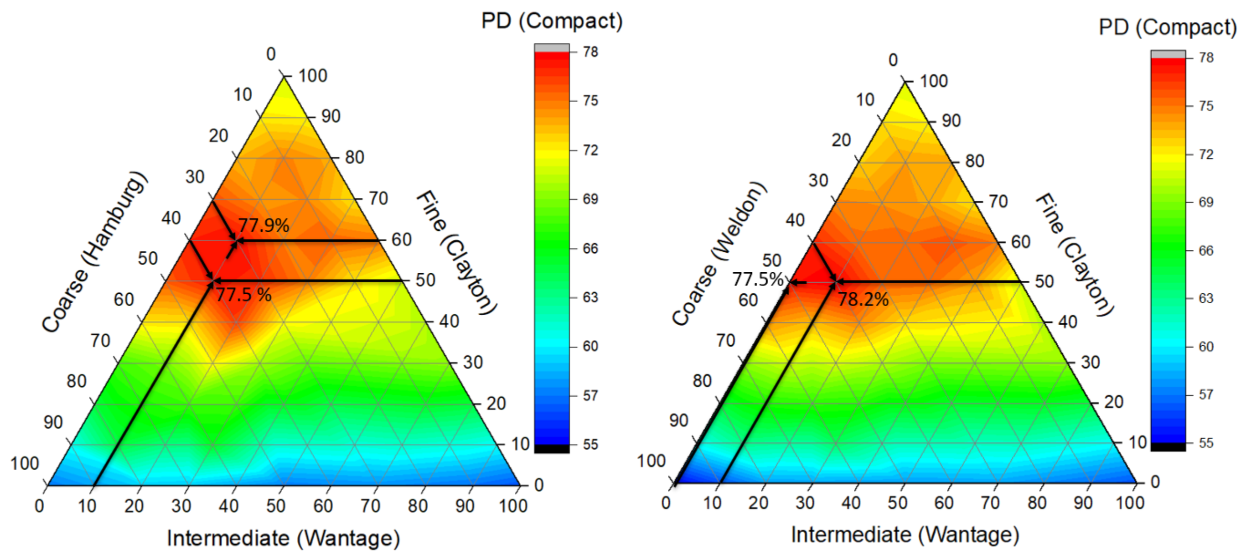

Figure 3: Experimental packing degree for ternary aggregate combination.

Ternary plots showing the packing degree for the coarse, intermediate, and fine blends are presented in Figure 3. It was observed that the packing degree was slightly improved with a substitution of 10% coarse aggregate with the intermediate aggregate from the optimal binary blend. Interestingly, multiple peaks of packing degree were observed in the case of both the Hamburg and Weldon series. For the Hamburg series, two peaks of 77.9% and 77.5% were observed hence forming a region of high packing degree for the fine aggregates from 50% to 60% and the intermediate aggregate of 10%. A similar pattern was observed for the Weldon series with a high packing degree region for 50% fine aggregates and 0% to 10% of the intermediate aggregate. The corresponding peak values of packing degree for the Weldon series were observed to be 77.5% and 78.2%.

The combined aggregate gradations for the optimally blended systems described can be seen in Appendix B along with comparison power curves and Shilstone charts for a wide range of aggregate combinations.

4.2.2.3 Aggregate Packing Conclusions

Multiple criteria were used to evaluate the effect of packing density on concrete performance. The aggregate packing was used as an effective criterion to optimize the aggregate blends of concrete. The continuous power curves served as an additional criterion to optimize the blend. The Shilstone coarseness chart assisted in expanding the level of workability and coarseness of the blends with binary or ternary aggregates. The chart was used to study the aggregate blends for the mixtures with various cement contents and aggregate combinations in terms of on-field application.

The experimental results for Hamburg coarse showed the highest packing degree of 77.3% for the binary combination of 40% coarse and 60% fine, respectively. The corresponding values for Weldon coarse were found to be 77.5% for a binary mix of 50% coarse and 50% fine, respectively. The results obtained from the modified-Toufar analytical model closely matched the experimental results. Furthermore, for both the Hamburg and Weldon ternary series, it was observed that the 10% of substitution of coarse aggregate with the intermediate slightly improves the packing degree.

Power curves were used as an effective tool for the optimization of aggregate proportions. The mixtures with higher fine aggregates contents were fitted to smaller power curve exponents such as 0.35–0.45, while mixtures with a lower volume of fine aggregates were closer to 0.5–0.7 power gradings. The addition of intermediate aggregates oriented the PSD more toward power curves. Finally, Shilstone charts provided an insight into the practical handling of the various blends in terms of workability and coarseness factors.

Several mixtures were chosen to utilize optimized aggregate packing using a ternary blend of Weldon Coarse, Wantage Intermediate, and Clayton Fine aggregates. The optimized aggregate packing allowed for higher amounts of aggregates to be utilized, resulting in a total reduction of binder content from the baseline mixture from which they were modified. The research team proposes providing optimized aggregate modified versions of the baseline fly ash and slag mixtures, the mixture with 40% fly ash, and the mixture with 60% slag; referred to, respectively, as FA_30%_OA, SLAG_50%_OA, FA_40%_OA, and SLAG_60%_OA. These mixtures should provide the Port Authority with an adequate understanding of impact that optimized aggregates have on the overall performance of their concrete systems. The full proposed mixture design for these mixtures can be reviewed in the Appendix in Table A1.

4.2.3 Alternative aggregate systems

As noted earlier, two different alternative aggregate systems were considered for use in the research program: RCA and aggregates that sequester carbon through calcium carbonate deposition on the surface of an aggregate. As the carbonate coated aggregates are not readily available in the market, the research team has decided not to include them in proposed mixtures. However, the research team does propose making one of the baseline mixtures with RCA. Despite the relatively low impact on embodied carbon, there are many other sustainability impacts that come along with using RCA.

4.2.3.1 Preliminary mixture selection for RCA mixtures

The research team chose one baseline mixture to make with RCA, using a full replacement of coarse RCA in place of the natural aggregates procured from the NYC Department of Transportation. Further data on the RCA proposed for use can be seen in Appendix B. The research team proposes modifying the SLAG_50% baseline mixture to incorporate the aggregates. The mixture design modifications considered incorporating aggregates on a per volume basis, as such the total aggregate mass was modified with respect to the specific gravity of the coarse RCA aggregates. The proposed modified mixture, SLAG_50%_RCA, can be reviewed in the Appendix in Table A1.

4.3 Carbon sequestration methods

4.3.1 Preliminary mixture selection for in-situ carbonate seeded mixtures

The research team proposes to use the technology developed by CarbonCure for mixing CO_2 directly into concrete mixtures. The research team proposes completing three mixtures using the CarbonCure technology. These include modifications of the baseline FA_30% and SLAG_50% mixtures as well as the SLAG_60% mixture. These will be referred to as, respectively, FA_30% CO2, SLAG_50%_CO2, and SLAG_60%_CO2. The predicted dosage rate of the CO_2 for mixtures is 0.10% by weight of the portland cement, and it is predicted that this can reduce the portland cement content 6-10%, depending on the mixture [8,31,33]. The proposed mixtures using the CarbonCure technologies can be reviewed in the Appendix in Table A1.

4.3.2 Preliminary mixture selection for carbon impregnated fly ash mixture

In addition to using a standard class F fly ash, the research team also proposes testing a mixture that uses fly ash that has been carbonated through the treatment process developed by Carbon Upcycling Technologies, referred to herein as CFA. We recommend using this technology in place of standard fly ash in the concrete mixture with 40% fly ash described earlier in this report. The full proposed mixture design for mixture containing the carbonated fly ash from Carbon Upcycling is called CFA_40% and can be reviewed in the Appendix in Table A1.

5 Embodied carbon calculations for proposed mixture designs

5.1 Greenhouse gas emission coefficients of raw materials

Table 3: GHG emission coefficients of concrete raw materials

Raw materials	GHG emission coefficient (lb/lb)	References
Portland cement	1.048	[12]
Portland-limestone cement (12% limestone) (PLC)	0.951	Calculation based on EPD, [121-122]
Calcium sulfoaluminate (CSA)	0.7336	[115]
Fly ash (FA)	0.328	[12]
Carbonated Fly Ash [CFA]	0.279	[58]
Granulated blast furnace slag (GBFS)	0.264	[12]
Ground glass pozzolan (GGP)	0.0556	[120]
Crushed aggregate (CA)	0.00372	[12]
Sand & gravel (SG)	0.00258	[12]
Recycled aggregate (RCA)	0.0012	[124]
CarbonCuring	-0.001 (0.1% CO_2 utilization, with respect to the mass of cement)	[56]

A description of the production processes of raw materials used in different concrete mixtures and the calculation methods of GHG emission coefficients are summarized in Appendix B. The GHG emissions coefficients of raw materials used in the calculation of concrete GWP are summarized in Table 3.

Based on the GHG emission coefficients and the usage amounts of raw materials, the concrete GWP can be calculated as the summation of GHG emission from producing all the raw materials. The calculation method is shown in the following equation:

$$\mathrm{GWP} = \sum_{\mathrm{i}=1}^{\mathrm{n}} M_{\mathrm{i}} \cdot Coef_{\mathrm{i}}$$

Where, GWP is GHG emission of a concrete mixture; M_{i} is the mass (lb) of raw material; $Coef_{\mathrm{i}}$ is the corresponding GHG emission coefficient of each raw material; and n is the total number of raw materials in concrete mixture.

The GWP for all proposed mixtures described earlier in this report can be seen in Figure 4.

The GWP values and relative reduction in GWP when compared to the baseline mixtures are summarized in Table 4. The baseline portland cement concrete presents the highest GWP: 613 CO_2 eq. lb/yd^3. The baseline fly ash mixture (FA_30%) and baseline slag mixture (SLAG_50%) have GWPs of 487 CO_2 eq. lb/yd^{3}and 436 CO_2 eq. lb/yd^3, respectively. By increasing the content of SCMs significant reductions in concrete GWPs could be observed. The concrete GWP of FA_50%, Slag_77% and GGP_30% could be reduced by 31%, 55% and 37% respectively compared to the baseline portland cement mixture. The use of carbonated fly ash in a mixture with 40% resulted in a reduction of GWP by 12% over the baseline 30% fly ash mixture, which was more GWP reduction than the 40% fly ash system that did not use the carbonated fly ash. The ternary systems had similar reductions in GWP compared to the baseline portland cement mixture as the slag mixtures. The use of PLC in place of portland cement further reduced GWP. The SLAG_50%_PLC mixture had a 6% GWP reduction compared to the baseline slag mixture, which contains the same amount of slag. Overall, higher

Table 4: GWP and Relative GWP Reductions of Proposed Systems

Mixture ID	Concrete GWP, CO2 eq. lb/yd3	Reduction in GWP Compared to Baseline PC Mixture	Reduction in GWP Compared to Baseline FA Mixture	Reduction in GWP Compared to Baseline Slag Mixture
Baseline Mixtures				
PC	613	-	-	-
FA_30%	487	21%	-	-12%
SLAG_50%	436	29%	10%	-
Modified Baseline Fly Ash Mixtures				
FA_30%_OA	424	31%	13%	3%
FA_30%_CO2	445	27%	9%	-2%
Modified Baseline Slag Mixtures				
SLAG_50%_OA	344	44%	29%	21%
SLAG_50%_RCA	430	30%	12%	1%
SLAG_50%_PLC	405	34%	17%	7%
SLAG_50%_CO2	409	33%	16%	6%
High Replacement Fly Ash Mixtures				
FA_40%	466	24%	4%	-7%
FA_50%	423	31%	13%	3%
FA_40%_OA	388	37%	20%	11%
CFA_40%	430	30%	12%	1%
High Replacement Slag Mixtures				
SLAG_60%	357	42%	27%	18%
SLAG_60%_OA	303	51%	38%	31%
SLAG_60%_CO2	332	46%	32%	24%
SLAG_77%	275	55%	43%	37%
SLAG_65%	323	47%	34%	26%
Ground Glass Pozzolan Mixture				
GGP_30%	386	37%	21%	11%
Ternary Mixtures				
Ternary_FA_SLAG	307	50%	37%	30%
Ternary_SLAG_GGP	327	47%	33%	25%
CSA Mixture				
CSA	522	15%	-7%	-20%

SCM contents resulted in lower GWP. However, these results will need to be balanced with setting time needs and strength needs, which will be further examined in Task C.

The use of in-situ carbonate seeding also resulted in further reductions in GWP compared to mixtures using the same amount of SCMs. For example, the SLAG_60% mixture had a GWP reduction of 18% compared to the baseline slag mixture, but the SLAG_60%_CO2 mixture had a 24% GWP reduction compared to the baseline slag mixture – an additional 6 percentage point reduction. This shows that the use of the CarbonCure technology can support further GWP reductions over standard techniques, however, as a standalone technology it may not be the most cost-effective way to reduce GWP.

The optimized aggregate systems resulted in significantly less cementitious materials compared to the mixtures of which they were modifications; this translated into further reductions in GWP. For example, the SLAG_50%_OA mixture had a 21% increase in GWP reduction compared to the baseline slag mixture and the FA_30%_OA mixture had a 29% increase in GWP reduction compared to the baseline fly ash mixture. This indicates that simple aggregate design improvements may be able to produce significant improvements in GWP.

The CSA system had a 15% reduction in GWP compared to the baseline portland cement mixture but had higher GWP than the baseline fly ash (7% higher) and baseline slag (20% higher) mixtures. This indicates that while the CSA systems may be better than comparable portland cement mixtures for high early strength applications, they should be used sparingly and only where their properties are needed.

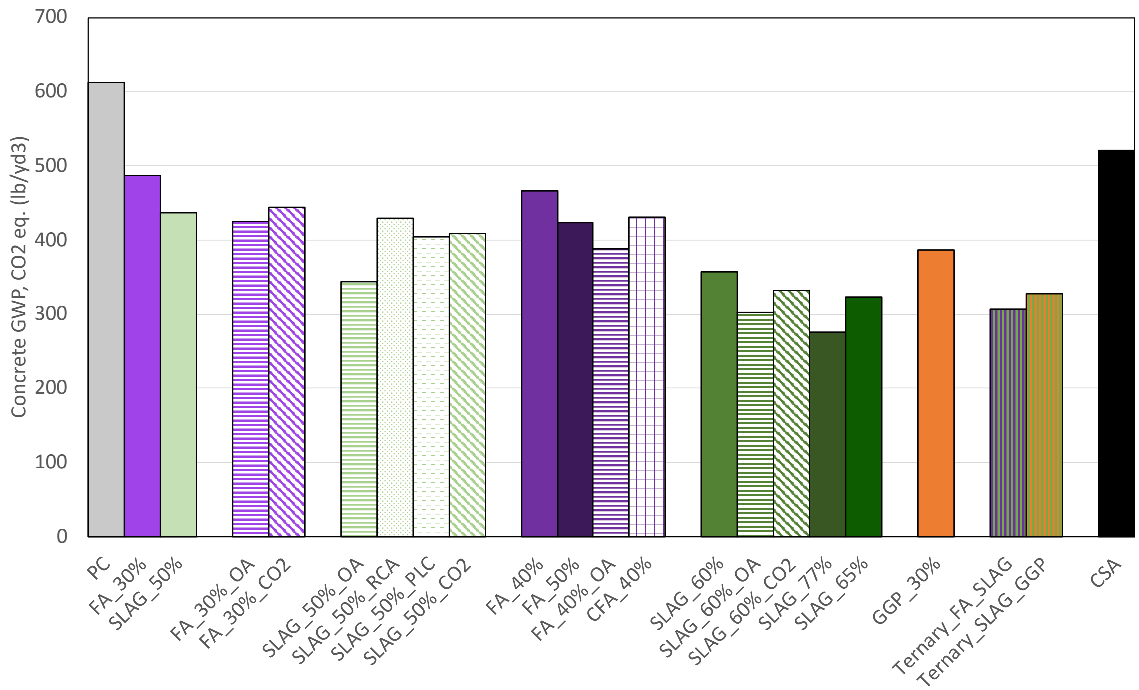

Figure 4: GWP of proposed mixtures.

Overall, the slag systems tended to produce concrete with lower GWP, because systems including slag had significantly lower portland cement contents. This indicates that reducing portland cement content is still the best method for reducing GWP. However, the optimized aggregate systems, PLC, and in-situ carbonate seeding may be necessary to be combined with high SCM contents to meet the goals for carbon reduction from the Port Authority.

6 Proposed LECC mixture designs

Based on the work presented in this report, the research team has proposed 20 mixtures for analysis and testing using a variety of LECC technologies. In addition to the 20 proposed mixtures, the research team will also conduct complimentary studies on a baseline all portland cement mixture for comparison. This mixture will utilize the same aggregates as the other mixtures. The 20 mixtures are described, briefly, in Table 5. The full mixture designs can be reviewed in the Appendix in Table A1.

Additional mixtures that were considered, but ultimately not included because of the limitation on the number of mixtures that could be tested as a part of this program include a PLC version of the FA_40% mixture, a PLC version of the Ternary_FA_SLAG mixture, and optimized aggregate versions of the higher SCM replacement systems. Determinations on which mixtures were not included were based on what the team determined was best in terms of scientific understanding for the project. While the team was interested in the total reduction in embodied carbon of some of the mixture not included, it was decided that this needed to be balanced with understanding of how individual technologies could impact a particular concrete mixture. Therefore, we chose a combination of systems that resulted in high reductions in embodied carbon, as well as those that would provide technical data to the Port Authority on how technologies may impact their concrete mixtures.

It should be noted that the proposed mixture designs are preliminary and are subject to modification during testing. The research team has planned that each mixture will need to be cast several times to understand the workability and the number of admixtures needed. Should some of the proposed mixture not be able to achieve adequate workability, setting time, or strength, the mixtures will have to be modified. This will be done in consultation with the Port Authority. The research team will strive to cast mixtures as close to the approved mixtures as possible.

Table 5: Proposed LECC mixtures for further analysis in Task C

Mixture Number	Mixture ID	Cementitious Materials (% of total)						Notes	Concrete GWP, CO2 eq. lb/yd3
		Type I Portland Cement Content	Portland-Limestone Cement (12% Ground Limestone)	Type F Fly Ash	Ground Granulated Blast Furnace Slag	Ground Glass Pozzolan (Pozzotive)	Calcium Sulfoaluminate Cement		
				Baseline Mixtures					
0	PC	100%	-	-	-	-	-		613
1	FA_30%	70%	-	30%	-	-	-		487
2	SLAG_50%	50%	-	-	50%	-	-		436
				Modified Baseline Mixtures					
3	FA_30%_OA	70%	-	30%	-	-	-		424
4	FA_30%_CO2	67%	-	33%	-	-	-	With 0.10% Carbon Dioxide Intermixed	445
5	SLAG_50%_OA	50%	-	-	50%	-	-	Ternary Aggregate Blend	344
6	SLAG_50%_RCA	50%	-	-	50%	-	-		430
7	SLAG_50%_PLC	-	50%	-	50%	-	-		405
8	SLAG_50%_CO2	50%	-	-	50%	-	-	With 0.10% Carbon Dioxide Intermixed	409
				Fly Ash Mixtures					
9	FA_40%	60%	-	40%	-	-	-		466
10	FA_50%	50%	-	50%	-	-	-		423
11	FA_40%_OA	60%	-	40%	-	-	-	Ternary Aggregate Blend	388
12	CFA_40%	60%	-	40%	-	-	-	Carbon Impregnated Fly Ash	430
				Slag Mixtures					
13	SLAG_60%	40%	-	-	60%	-	-		357
14	SLAG_60%_OA	40%	-	-	60%	-	-	Ternary Aggregate Blend	303
15	SLAG_60%_CO2	38%	-	-	63%	-	-	With 0.10% Carbon Dioxide Intermixed	332
16-A	SLAG_77%	25%	-	-	75%	-	-		275
16-B	SLAG_65%	35%	-	-	65%	-	-		323
				Ground Glass Pozzolan Mixtures					
17	GGP_30%	70%	-	-	-	30%	-		386
				High Blend Mixtures					
18	Ternary_FA_SLAG	24%	-	38%	38%	-	-		307
19	Ternary_SLAG_GGP	38%	-	-	48%	14%	-		327
				CSA Mixture					
20	CSA	-	-	-	-	0%	100%		522

7 Conclusions

This report presents the proposed mixtures for further study as a part of Task C. The proposed mixtures were developed based off of a thorough study of available literature, as well as a study of the aggregates that will be used during Task C. These mixtures have not been tested, and so performance of them cannot be guaranteed. Further studies carried out as a part of Task C will verify the applicability of these mixtures for Port Authority construction projects.

The proposed mixtures that utilize SCMs include fly ash, slag, carbonated fly ash, and ground glass pozzolan SCMs at various replacement levels; as well as ternary systems with slag and fly ash and slag and GGP. Several systems that include in-situ carbonate seeding utilizing the technology developed by CarbonCure Technologies are also proposed. Systems that include aggregate optimization are proposed as well, which will help further reduce GWP over just the use of SCMs, and one mixture utilizing RCA will be cast as a proof of concept for the Port Authority. Based off the GWP values presented in Table 8, increasing SCM content has the most significant impact on reducing GWP values. However other technologies such as optimizing aggregates, switching cement for PLC, and utilizing in-situ carbonate seeding can help support overall carbon reductions for mixtures that may already be using the maximum amount of SCM technically possible.

8 References

[1] S.A. Miller, The role of cement service-life on the efficient use of resources, Environ. Res. Lett. 15 (2020) 24004. https://doi.org/10.1088/1748-9326/ab639d.

[2] S.A. Miller, V.M. John, S.A. Pacca, A. Horvath, Carbon dioxide reduction potential in the global cement industry by 2050, Cem. Concr. Res. 114 (2018) 115–124. https://doi.org/https://doi.org/10.1016/j.cemconres.2017.08.026.

[3] S.A. Miller, A. Horvath, P.J.M. Monteiro, Readily implementable techniques can cut annual CO 2 emissions from the production of concrete by over 20%, Environ. Res. Lett. 11 (2016) 74029. https://doi.org/10.1088/1748-9326/11/7/074029.

[4] The Port Authority of NY & NJ;, Environmental Initiatives - Sustainability: We're taking action, (2021). https://www.panynj.gov/port-authority/en/about/Environmental-Initiatives.html.

[5] The Port Authority of NY & NJ;, Port Authority unveals clean construction program during climate week, setting industry-leading approach to sustainable construction and design, (2020).

[6] M.P. Adams, Concrete Solutions to Climate Change: How Local Policy Can Promote Sustainable Construction Activities, Albany, NY, 2021.

[7] J. de Brito, R. Kurda, The past and future of sustainable concrete: A critical review and new strategies on cement-based materials, J. Clean. Prod. 281 (2021). https://doi.org/10.1016/j.jclepro.2020.123558.

[8] CarbonCure, CarbonCure Onboarding Presentation, in: 2020.

[9] J. Rosen, Turning carbon into concrete could win UCLA team a climate victory — and $7.5 million, LA Times. (2020).

[10] P. Taylor, T. van Dam, Concrete Pavement Sustainability: State of the Practice, 2012.

[11] M. Moini, I. Flores-Vivian, A. Amirjanov, K. Sobolev, The optimization of aggregate blends for sustainable low cement concrete, Constr. Build. Mater. 93 (2015) 627–634. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2015.06.019.

[12] P. Authority, Task A report, LECC project , (2021).

[13] A.F. Omran, D.M. Etienne, D. Harbec, A. Tagnit-Hamou, Long-term performance of glass-powder concrete in large-scale field applications, Constr. Build. Mater. 135 (2017) 43–58. https://doi.org/10.1016/j.conbuildmat.2016.12.218.

[14] A. Kaminsky, M. Krstic, P. Rangaraju, A. Tagnit-Hamou, M.D.A. Thomas, Ground-Glass pozzolan for use in concrete, Concr. Int. November (2020) 24–31.

[15] M.C.G. Juenger, F. Winnefeld, J.L. Provis, J.H. Ideker, Advances in alternative cementitious binders, Cem. Concr. Res. 41 (2011) 1232–1243. https://doi.org/https://doi.org/10.1016/j.cemconres.2010.11.012.

[16] P. Van den Heede, N. De Belie, Environmental impact and life cycle assessment (LCA) of traditional and 'green' concretes: Literature review and theoretical calculations, Cem. Concr. Compos. 34 (2012) 431–442. https://doi.org/https://doi.org/10.1016/j.cemconcomp.2012.01.004.

[17] M.P. Adams, T. Fu, A.G. Cabrera, M. Morales, J.H. Ideker, O.B. Isgor, Cracking susceptibility of concrete made with coarse recycled concrete Aggregates, Constr. Build. Mater. 102 (2016) 802–810. https://doi.org/10.1016/j.conbuildmat.2015.11.022.

[18] L.K. Turner, F.G. Collins, Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC cement concrete, Constr. Build. Mater. 43 (2013) 125–130. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2013.01.023.

[19] C. Li, L. Jiang, Utilization of limestone powder as an activator for early-age strength improvement of slag concrete, Constr. Build. Mater. 253 (2020). https://doi.org/10.1016/j.conbuildmat.2020.119257.

[20] A. Hasanbeigi, L. Price, E. Lin, Emerging energy-efficiency and CO2 emission-reduction technologies for cement and concrete production: A technical review, Renew. Sustain. Energy Rev. 16 (2012) 6220–6238. https://doi.org/https://doi.org/10.1016/j.rser.2012.07.019.

[21] J.L. Provis, Alkali-activated materials, Cem. Concr. Res. 114 (2018) 40–48. https://doi.org/https://doi.org/10.1016/j.cemconres.2017.02.009.

[22] The Port Authority of NY & NJ;, Division 03, Section 033010, Portland Cement Concrete, Long Form, in: Port Auth. Constr. Specif., Port Authority of NY and NJ, New York, NY, 2020.

[23] M. Moini, K. Sobolev, I. Flores-Vivian, S. Muzenski, L.T. Pham, S. Cramer, M. Beyene, Durability of Concrete Mixtures Containing Supplementary Cementitious Materials in Rapid Chloride Permeability Test, ACI Mater. J. 116 (2019) 67–76.

[24] K. Sobolev, M. Moini, S. Muzenski, R. Pradoto, M. Kozhukhova, I. Flores-Vivian, S. Cramer, A. Faheem, Laboratory Study of Optimized Concrete Pavement Mixtures, 2015.

[25] R. V Silva, J. De Brito, R.K. Dhir, Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production, Constr. Build. Mater. 65 (2014) 201–217. https://doi.org/10.1016/j.conbuildmat.2014.04.117.

[26] A. Jayasuriya, E.S. Shibata, T. Chen, M.P. Adams, Development and statistical database analysis of hardened concrete properties made with recycled concrete aggregates, Resour. Conserv. Recycl. 164 (2021) 105121. https://doi.org/https://doi.org/10.1016/j.resconrec.2020.105121.

[27] A. Jayasuriya, M.P.M.P. Adams, M.J.M.J. Bandelt, Generation and numerical analysis of random aggregate structures in recycled concrete aggregate systems, ASCE J. Mater. Civ. Eng. 32 (2020). https://doi.org/10.1061/(ASCE)MT.1943-5533.0003113.

[28] H. Guo, C. Shi, X. Guan, J. Zhu, Y. Ding, T.-C. Ling, H. Zhang, Y. Wang, Durability of recycled aggregate concrete – A review, Cem. Concr. Compos. 89 (2018) 251–259. https://doi.org/https://doi.org/10.1016/j.cemconcomp.2018.03.008.

[29] X. Shi, Z. Grasley, A. Mukhopadhyay, D. Zollinger, Use of recycled aggregates in concrete pavement: Pavement design and life cycle assessment, in: Harvey et al. (Ed.), Pavement, Roadway, Bridg. Life Cycle Assess. 2020, Taylor and Francis, London, 2020.

[30] Blue Planet, Blue Planet: Economically sustainable carbon capture, (2015).

[31] S. Monkman, Utilization of CO2 in Ready Mixed Concrete Production: A Case Study, in: Proc. Concr. 2021, Concrete Institute of Australia, Perth, Australia, 2021.

[32] CSA, Development of state of the art techniques in cement manufacturing: trying to look ahead, in: CSI?ERCA - Technol. Pap., US Environmental Protection Agency, 2009.

[33] C.C. Technologies, Frequently Asked Questions for Engineers, 2021.

[34] C.U. Technologies;, Carbon Upcycling Technologies, Technology. (2021).

[35] ASTM C150/150M-21 Standard specification for portland cement, (2021).

[36] ASTM C1240-20: Standard specification for silica fume used in cementitious mixtures, (2020).

[37] ASTM C618-19: Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete, (2019).

[38] ASTM C989/C989M-18a: Standard specification for slag cement for use in concrete and mortars, (2018).

[39] ASTM C33/C33M-18, Standard Specification for Concrete Aggregates, ASTM Int. (2020).

[40] ASTM C535-16: Standard test method for resistance to degradation of large-size coarse aggregate by abrasion and impact in the los angeles machine, (2016).

[41] ASTM C131/C131M-20: Standard test method for resistance of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine, (n.d.).

[42] ASTM International, C78/C78M-18 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading), (2018).

[43] A. International, C39/C39-18 Standard test method for compressive strength of cylindrical concrete specimens, (2019).

[44] J. Davidson, Concrete doesn’t have to be an ecological nightmare, Curbed. (2021).

[45] K. Scrivener, F. Martirena, S. Bishnoi, S. Maity, Calcined clay limestone cements (LC3), Cem. Concr. Res. 114 (2018) 49–56. https://doi.org/https://doi.org/10.1016/j.cemconres.2017.08.017.

[46] S. Sánchez Berriel, A. Favier, E. Rosa Domínguez, I.R. Sánchez Machado, U. Heierli, K. Scrivener, F. Martirena Hernández, G. Habert, Assessing the environmental and economic potential of Limestone Calcined Clay Cement in Cuba, J. Clean. Prod. 124 (2016) 361–369. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.02.125.

[47] F. Lollini, E. Redaelli, L. Bertolini, Effects of portland cement replacement with limestone on the properties of hardened concrete, Cem. Concr. Compos. 46 (2014) 32–40. https://doi.org/https://doi.org/10.1016/j.cemconcomp.2013.10.016.

[48] E. Bescher, Calcium Sulfoaluminate-Belite Concrete: Structure, Properties, (2015).

Appendix A: Mixture Designs

		Cementitious Materials (lb/yd^3)										Aggregates (lb/yd^3)					Important Values									
Mixture Number	Mixture ID	Type I Portland Cement Content	Portland-Limestone Cement (12% Ground Limestone)	Type F Fly Ash	Type C Fly Ash	Ground Granuluated Blast Furnace Slag	Ground Glass Pozzolan (Pozzotive)	Calcium Sulfoaluminate Cement	Geopolymer	CO_2 (CarbonCure) (% wt of cement)	Water (lb/yd^3)	Weldon Coarse Aggregate	Midsize Aggregate	Clayton Fine Aggregate	Coarse Recycled Concrete Aggregate	Air (% Volume)	Total Portland Cement	Total Cementitious Materials Content	w/b	SCM (%)	Total aggregate volume (%)	Fine /coarse aggregate (V%)	Fine /coarse aggregate (m%)	Concrete GWP, CO2 eq. kg/m3	Concrete GWP, CO2 eq. lb/yd3	Comments
Baseline Mixtures																										
0	PC	575									230	1836		1386		6	575	575	0.40	0.00	0.69	0.45	0.43	364	613	Baseline Portland Cement Mixture
1	FA_30%	400		175							230	1808		1365		6	400	575	0.40	0.30	0.68	0.45	0.43	289	487	Baseline Fly Ash Mixture
2	SLAG_50%	325				325					260	1738		1312		6	325	650	0.40	0.50	0.66	0.45	0.43	259	436	Baseline Slag Mixture
Modified Baseline Mixtures																										
3	FA_30%_OA	348		149							255	1441	351	1662		6	348	497	0.51	0.30	0.72	0.56	0.54	252	424	Baseline Fly Ash Mixture with Optimized Aggregates
4	FA_30%_CO2	360		175						0.10%	214	1853		1399		6	360	535	0.40	0.33	0.70	0.45	0.43	264	445	Baseline Fly Ash Mixture with CarbonCure
5	SLAG_50%_OA	254				254					259	1441	351	1662		6	254	508	0.51	0.50	0.72	0.56	0.54	204	344	Baseline Slag Mixture with Optimized Aggregates
6	SLAG_50%_RCA	324				324					259.2			1314	1325	6	324	648	0.40	0.50	0.66	0.45	0.50	255	430	Baseline Slag Mixture with 100% Coarse Recycled Aggregates
7	SLAG_50%_PLC		325			325					260	1736		1311		6	286	650	0.40	0.56	0.66	0.45	0.43	240	405	Baseline Slag Mixture with PLC
8	SLAG_50%_CO2	304				304				0.10%	246.2	1786		1349		6	304	608	0.40	0.50	0.67	0.45	0.43	242	409	Baseline Slag Mixture with Carbon Cure
Fly Ash Mixtures																										
9	FA_40%	360		240							240	1930		1188		6	360	600	0.40	0.40	0.67	0.40	0.38	277	466	
10	FA_50%	300		300							240	1920		1181		6	300	600	0.40	0.50	0.64	0.40	0.38	251	423	50% Fly Ash Mixture
11	FA_40%_OA	298		199							255	1441	351	1662		6	298	497	0.51	0.40	0.65	0.56	0.54	230	388	50% Fly Ash Mixture with Optimized Aggregates
12	CFA_40%	360		240							240	1930		1188		6	360	600	0.40	0.40	0.64	0.40	0.38	255	430	50% Fly Ash Mixture with Carbonated Fly Ash
Slag Mixtures																										
13	SLAG_60%	240				360					240	1956		1203		6	240	600	0.40	0.60	0.65	0.40	0.38	212	357	50% Slag Mixture
14	SLAG_60%_OA	202				304					258	1441	351	1662		6	202	506	0.40	0.60	0.72	0.56	0.54	180	303	50% Slag Mixture with Optimized Aggregates
15	SLAG_60%_CO2	216				360				0.10%	230.4	1985		1221		6	216	576	0.40	0.63	0.66	0.40	0.38	197	332	50% Slag Mixture with CarbonCure
16-A	SLAG_77%	142.5				437					231.8	1978		1217		6	142.5	579.5	0.40	0.75	0.61	0.40	0.38	163	275	77% Slag Mixture
16-B	SLAG_65%	203				377					232	1980		1218		6	203	580	0.40	0.65	0.61	0.40	0.38	191	323	
Ground Glass Pozzolan Mixtures																										
17	GGP_30%	350					150				200	2040		1308		6	350	500	0.40	0.30	0.72	0.41	0.39	229	386	30% GGP Mixture
High Blend Mixtures																										
18	Ternary_FA_SLAG	150		236		236					205.26	1967		1211		6	150	622	0.33	0.76	0.60	0.40	0.38	182	307	Ternary Blend with Fly ash and Slag
19	Ternary_SLAG_GGP	225				288	81				196	1959		1309		6	225	594	0.33	0.62	0.62	0.42	0.40	194	327	Ternary Blend with Slag and Ground Glass Pozzolan
CSA Mixture																										
20	CSA							700			280	1291		1279		6	0	700	0.40	-	0.64	0.52	0.50	309	522	CSA Mixture

Low Carbon Concrete Pilot Program: Task B Report – Proposed Low Embodied Carbon Concrete Mixtures for Further Testing and Analysis

Appendix B

Submission Date: 12-20-21

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Appendix B

This appendix provides an in-depth overview of the technologies proposed in the Task B report. Additionally, this appendix includes the full example methodologies for mixture selections using high SCM contents, optimized aggregates, and other items. Finally, this document discusses the full procedure for determining the global warming potential (GWP) of the proposed concrete mixtures. The mixtures that were chosen

B.1 Further background on the embodied carbon of portland cement concrete

Portland cement is a major contributor to the embodied carbon of concrete because the manufacturing process requires the calcination of limestone and heating the raw materials to over 2600°F in a large kiln. Portland cement requires CaO to produce the primary compounds required to give cement its binding properties. CaO is created from the calcination of limestone, or calcium carbonate ($CaCO_3$). Calcination occurs when limestone is heated, during this process the $CaCO_3$ is broken down into CaO and CO_2 [1–3]. In current standard practice, the CO_2 is released to the atmosphere and accounts for 60% of the embodied carbon associated with portland cement production. The remaining embodied carbon comes from heating the production kiln (~40% of the embodied CO_2), and processing and grinding of the raw materials prior to introduction to the kiln and grinding of the cement clinker produced from the kiln [4,5].

There have been significant efforts within the cement industry to lower the energy cost of producing cement, increase kiln efficiency, collecting and sequestering the CO_2 emissions at the plant, and using non-fossil fuels to heat the kiln [6–9]. However, methods that have been successful and economical have typically seen widespread application at plants within the US. Therefore, targeting the reduction or elimination of portland cement, reducing the total cementitious materials content, sequestering carbon within the concrete system, and using alternative aggregates will provide the most value for reducing carbon footprints. Focusing on reducing the embodied carbon through efficiency improvements in the production process of individual constituents, alone, will not provide the most economical or achievable CO_2 reductions.

B.2 Further background on proposed supplementary cementitious materials

The following sections provide a background on the types of SCMs considered while developing the proposed mixtures.

B.2.1 Fly ash

Fly ash is the byproduct of coal combustion and has been shown to significantly increase both the strength and durability of concrete when used as a substitute for portland cement [10–13]. Additions of fly ash are common up to 25% of the total cementitious materials content, though successful applications with uses over 50% have been observed. Characteristics of fly ash will depend on the type of coal burned and if it was co-burned with other fuels but is split into two main categories – class F (siliceous) and class C (calcareous). Fly ash reacts pozzolanically with hydrates produced when cement is mixed with water. Both types of fly ash will improve concrete workability, early age strength, and long-term durability, and can help reduce the heat of hydration of cement. However, fly ash will retard early strength gains increasing construction times in some projects, this is exacerbated at higher replacement levels [13]. Fly ash is one of the most widely used by-products in construction [14]. For this work, because of local availability, only Type F fly ash was considered.

B.2.2 Ground granulated blast furnace slag

Ground granulated blast furnace slag, or just slag, is the by-product of the steel making and is formed when the silica and alumina impurities in the iron ore combine with lime and magnesium fluxing agents. This slag can then be crushed to a fine powder and used as an SCM in concrete mixtures with addition rates as high as 95% of the total cementitious materials content, but typically are used around 60% addition or lower [15–18], and historically have been used in higher amounts than fly ash. Slag reacts hydraulically with water to form cement hydrates, but at a slower rate; and shows some pozzolanic activity but at a much lower level than fly ash. Slag will retard early strength gains, depending on replacement level, but provide better long-term strengths and improve durability [17,19,20].

B.2.3 Finely ground limestone

The use of *finely ground limestone* (FGLS) as an SCM in modern concrete began in the 1970s and continues to be incorporated in cements today. While FGLS is not a by-product, because it does not need pyroprocessing the carbon footprint of the material is much smaller than that of concrete. FGLS has been shown to accelerate early-age strength gain and not impact long-term strength when used at 15% or less of the overall binder content [21,22]. PLCs have been found to increase setting only slightly time [22]. For this work, instead of using FGLS as a standalone material, the research team proposes the use of portland limestone cement (PLC) systems. These systems are preblended binary systems that contain 12% finely ground limestone and 88% portland cement by volume. PLCs are becoming common in North America and are readily available for purchase [22].

B.2.4 Ground glass pozzolan

Ground glass pozzolan (GGP) is a class of SCM that is produced from waste glass that has been finely ground [23–25]. From an availability standpoint, GGP represents a promising SCM since glass is a major component of solid waste as it is approximately 6% of solid waste worldwide [26]. Relative to other SCMs, GGP is high in silica content. When used as a substitute for portland cement and milled to a micro-level, GGP has been shown to have the same or a slight increase in compressive strength at later ages (e.g., 90 days) and can cause minor improvements in ASR performance [27,28]. Several field applications have shown promising behavior of GGP in civil infrastructure and public works projects [26,29,30].

B.3 Further background on preliminary mixture selection based on type of SCM

This section shows the full methodology for preliminary mixture design selection based on the type of SCM. This information further supports what is shown in the main report.

B.3.1 Fly Ash

A baseline fly ash mixture, based on mixture ratios found in the database provided by the Port Authority [31], was selected as an initial point of comparison and minimum replacement ratio of fly ash for consideration by the Port Authority. The baseline mixture, called FA_30%, includes a 30% replacement of portland cement with fly ash. Additional chosen fly ash mixtures are proposed to reduce the embodied carbon of this baseline mixture. The full mixture design for the FA_30% Mixture is provided in the Appendix in Table A1.

Figure B1 presents the fly ash/binder ratio, water to binder ration (w/b) and 28-day compressive strength for over 35 concrete mixtures detailed in literature [25,32–47].

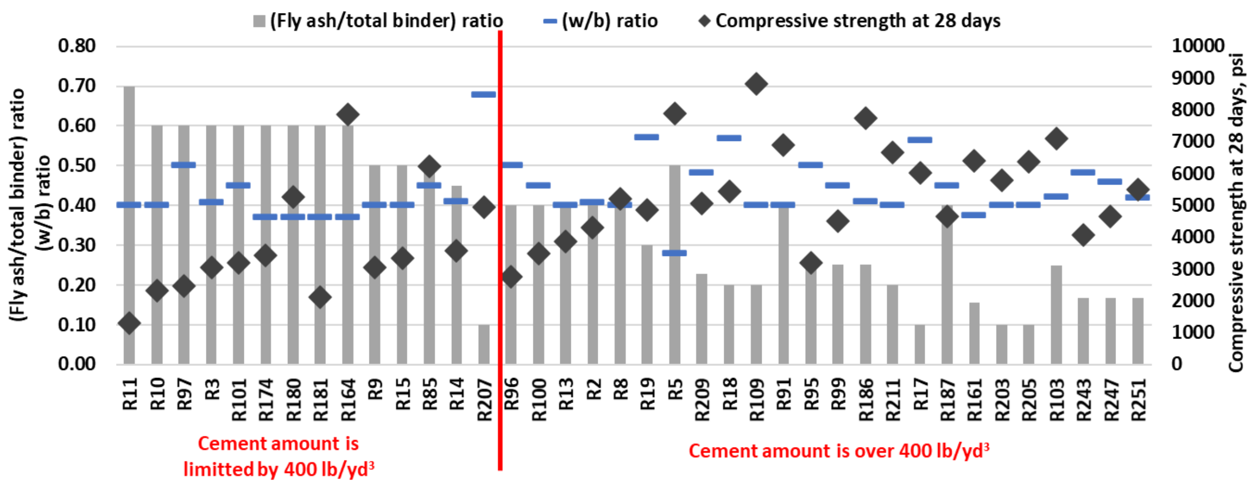

Figure B1: Concrete mixtures produced with the incorporation of fly ash

The mixtures shown in Figure B1 are only some of the mixtures found from literature (the full set can be seen in the database provided to the Port Authority) and contain mixtures with cement contents of both more than and less than 400 lb/yd^3. To comply with current Port Authority specifications, the mixtures with more than 400 lb/yd^3 were filtered out from our list of potential mixtures. From this, it can be observed that concrete made with high substitution levels of fly ash (i.e. >30% of the total binder content) can be produced that meet a range of compressive strength. The binder content, aggregate content and aggregate properties are responsible for the variability in properties of these mixtures. From this group of fly ash mixtures, two mixtures, presented in Table B1, were chosen as the basis for higher fly ash content mixtures beyond the baseline system.

Table B1: Mixture proportions of potential high fly ash mixtures

Database Mix ID	Proportion (lb/yd^3)					Ratio		Strength (psi)
	Cement	Fly ash	Coarse aggregate	Fine aggregate	Water	w/b	SCM/b	28 days Comp. strength
R85	337	337	1709	1247	303	0.45	0.5	6237
R2	405	270	1996	1153	275	0.4	0.4	4299

From these mixtures, further refinement was completed to develop the FA_40% mixture, which includes a 40% replacement of portland cement with fly ash, and FA_50% mixture, which includes a 50% replacement of portland cement with fly ash. Mixture R2 was modified to reduce the portland cement content and increase the aggregate content while maintaining a w/b ratio of 0.40 and a fly ash content of 40%. Aggregate contents were also modified based on the properties of the proposed aggregates that will be use in the concrete mixtures. These changes should result in a higher density of aggregate packing that reduces the total binder content required, without impacting strength. Mixture R85 was modified to reduce the portland cement content and the w/b ratio while maintaining a 50% fly ash replacement. Aggregate contents were also modified based on the properties of the proposed aggregates that will be used in the concrete mixtures. These changes allow for a lower total binder content, which is offset by using a lower w/b ratio to maintain a similar compressive strength. The full proposed mixture designs for the FA_40% and FA_50% can be reviewed in the Appendix in Table A1.

Slag

A baseline slag mixture, based on mixture ratios found in the database provided by the Port Authority [31], was selected as an initial point of comparison and minimum replacement ratio of slag for consideration by the Port Authority. The baseline mixture, called SLAG_50%, includes a 50% replacement of portland cement with fly ash. Additional chosen slag mixtures are proposed to reduce the embodied carbon of this baseline mixture. The full mixture design for the SLAG_50% Mixture is provided in the Appendix in Table A1.

Figure B2 presents the slag/binder ratio, water to binder ration (w/b) and 28-day compressive strength for over 30 concrete mixtures from the literature produced by different substitution ratios of slag [39,41,48–58]. The mixtures shown in Figure B2 are the slag mixtures found from literature (the full set can be seen in the database provided to the Port Authority) and contain those mixtures with cement contents of both more than and less than 400 lb/yd^3. To comply with current Port Authority specifications, the mixtures with more than 400 lb/yd^3 were filtered out from our list of potential mixtures. From this, it can be observed that concrete made with high substitution levels of slag (i.e. >40% of the total binder content) can be produced that meet a range of compressive strengths.

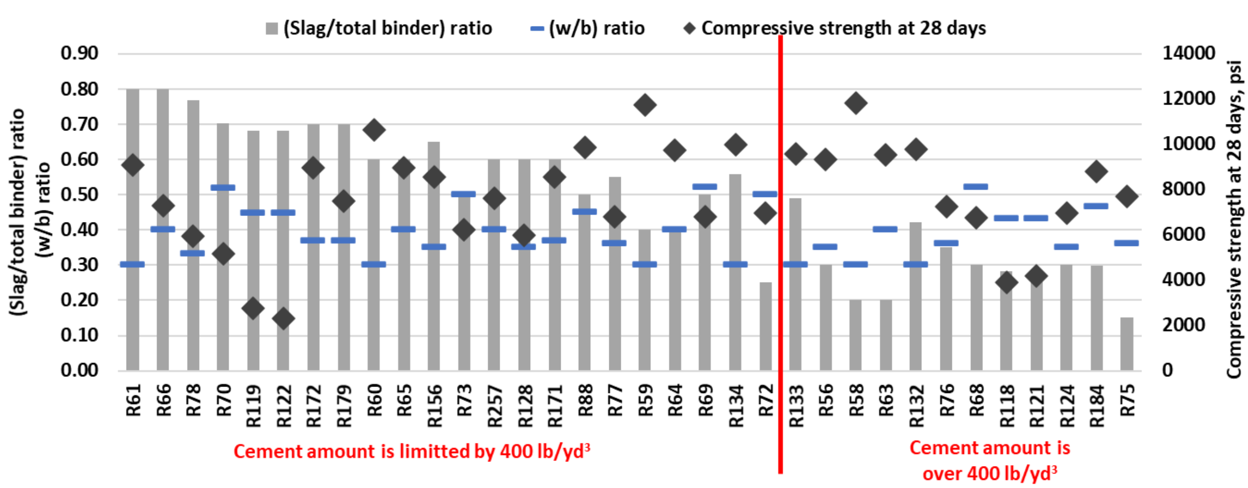

Figure B2: Concrete mixtures produced with the incorporation of slag

The binder content, aggregate content and aggregate properties are responsible for the variability in properties of these mixtures. From this group of slag mixtures, two mixtures, presented in Table B2, were chosen as the basis for higher slag content mixtures beyond the baseline system.

Table B2: Mixing proportions of mixtures produced with slag

Database Mix ID	Proportion (lb/yd^3)					Ratio		Strength (psi)
	Cement	Slag	Coarse aggregate	Fine aggregate	Water	w/b	SCM/b	28 days Comp. strength
R88	337	337	1709	1305	303	0.45	0.5	9863
R78	190	631	1967	937	273	0.33	0.77	5947

From these mixtures, further refinement was completed to develop the SLAG_60% mixture, which includes a 60% replacement of portland cement with slag, and the SLAG_77% mixture, which includes a 77% replacement of portland cement with slag. Mixture R88 was modified to reduce the total binder content and increase the aggregate content, as well as reducing the w/b to a 0.40 to maintain strength. Aggregate contents were also modified based on the properties of the proposed aggregates that will be use in the concrete mixtures. These changes should result in a higher density of aggregate packing that reduces the total binder content required, without impacting strength. Mixture R78 was modified slightly to reduce the total binder content based on the particle packing required from the base aggregates, while increasing the w/b to maintain workability. While this may result in a decrease in strength, the R78 already provides a 28-day compressive strength of almost 5947 psi, and as such would likely still be a usable mixture. It is anticipated, however, that this high level of slag may have difficulty setting and gaining adequate strength. Therefore, the team has proposed a variation on this mixture, SLAG_65%, which should provide adequate setting capabilities at a lower slag content. The SLAG_65% mixture will be used if the SLAG_77% mixture is not viable. The full proposed mixture designs for the SLAG_60%, SLAG_77%, and SLAG_65% can be reviewed in the Appendix in Table A1.

B.3.2 Ground glass pozzolans

Figure B3 presents the slag/binder ratio, water to binder ration (w/b) and 28-day compressive strength for over 50 concrete mixtures from the literature produced by different substitution ratios of GGP [25,28,29,33,47,59–67].

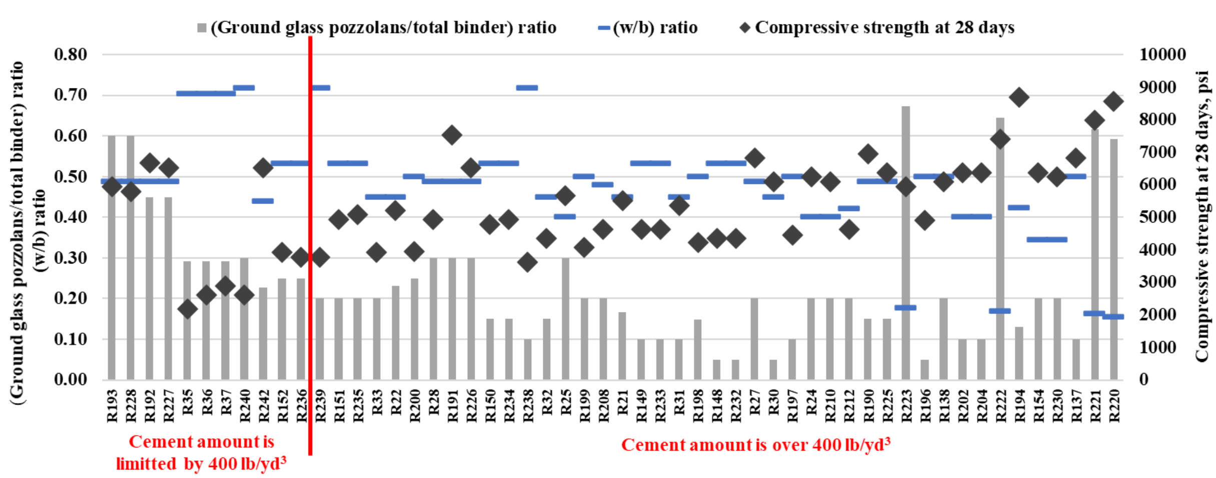

Figure B3: Concrete mixtures produced the incorporation of ground glass pozzolans

The mixtures shown in Figure B3 are only some of the mixtures found from literature (the full set can be seen in the database provided to the Port Authority) and contain mixtures with cement contents of both more than and less than 400 lb/yd^3. To comply with current Port Authority specifications, the mixtures with more than 400 lb/yd^3 were filtered out from our list of potential mixtures. From this, it can be observed that concrete made with high substitution levels of GGP have shown some promise with regards to adequate compressive strength, but most mixtures used from 20% to 30% GGP content. The binder content, aggregate content and aggregate properties are responsible for the variability in properties of these mixtures. From this group of GGP mixtures, one mixture, presented in Table B3, were chosen as the basis for the GGP mixtures.

Table B3: Mixing proportions of mixtures produced with ground glass pozzolans

Database Mix ID	Proportion (lb/yd^3)					Ratio		Strength (psi)
	Cement	Ground Glass Pozzolan	Coarse aggregate	Fine aggregate	Water	w/b	SCM/b	28 days Comp. strength
R28	448	192	1718	1254	312	0.49	0.3	4931

From these mixtures, further refinement was completed to develop the GGP_30% mixture, which includes a 30% replacement of portland cement with GGP. The proposed mixture maintains relatively the same ratio of portland cement and GGP as in the R28 mixture, but the total binder content is reduced. To offset any reduction in strength from the reduction in binder content, the w/b ratio was also reduced in the GGP_30% mixture compared to R28. Aggregate contents were also modified based on the properties of the proposed aggregates that will be use in the concrete mixtures. The w/b was reduced to 0.40 to ensure that the mixture is more comparable to other LECC mixtures proposed. The full proposed mixture design for the GGP_30% can be reviewed in the Appendix in Table A1.

B.3.3 High blend SCM systems

Several ternary and quaternary systems that included portland cement with multiple SCMs were also reviewed from literature. From this review it was observed that systems with replacement levels as high at 75% had been completed with satisfactory strength properties [68]. Given this, the research team proposes two ternary blended systems that will look at blends of systems using slag and fly ash, and slag and GGP. The Ternary_FA_SLAG system will include a 76% SCM replacement level, evenly split between fly ash and slag. The Ternary_SLAG_GGP system will include a 62% SCM replacement level – 13.5% of the binder content being GGP and 48.5% of the binder being slag. The full proposed mixture design for the GGP_30% can be reviewed in the Appendix in Table A1.

B.4 Further information on the study of aggregate LECC material components

B.4.1 Methodology for the evaluation of the packing degree

The particle size distribution of aggregates, which can be seen in Figure B4, was determined by sieve analysis according to ASTM C33 [69].

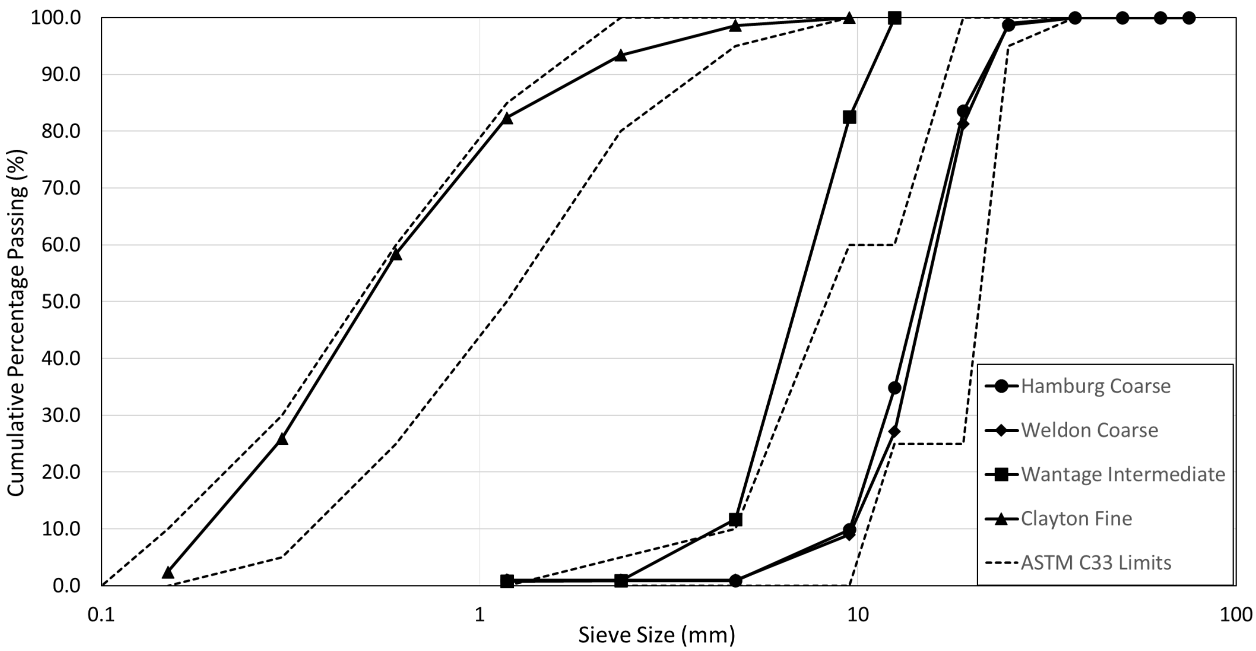

Figure B4: Sieve Analysis of individual aggregate

Experimental Evaluation of Packing Degree - The Vee-Bee Consistometer (VB) apparatus was initially developed for zero slump concrete and is currently used to measure the consistency and density of roller-compacted concrete. In this study, the packing degree of different aggregate combinations was evaluated using the VB Vibro-compacting apparatus (ASTM C1170, method A) [70]. The aggregate blends were selected based on different volume proportions of individual aggregates. The total weight of the aggregate blend was kept as 5.0 kg. Aggregates were mixed before placing the entire sample as a conical pile into the cylindrical mold of the VB apparatus. The conical pile was flattened using a scoop to achieve a flat surface. The plastic plate attached at the base of the surcharge was then carefully lowered and positioned on the flat surface. The distance between the bottom of the plastic plate and the internal base of the mold was calculated using the average of four different points. Following this initial setup, the VB apparatus was vibrated for the compaction of the aggregate sample. A vibration period of 45 s was found to be an appropriate time for compaction of most of the aggregate combinations [71]; however, a vibration period of 10 s was kept for the binary aggregate blends with fine content of 80% and higher. The reduced time was chosen as a significant amount of sand started to move above the plastic plate for the vibration period higher than 10 s. The bulk packing density (γ) of the aggregate blends was calculated using the following equation:

$$\gamma = \frac{4000\,W}{\pi\,D^2(H - \Delta h)}$$

where $\boldsymbol{\gamma}$ is the bulk packing density of combined aggregate (kg/m^3); W is the weight of the aggregate blend (5 kg); H is the height of container (mm); $\boldsymbol{\Delta h}$ is the reduction in height for compacted aggregate (mm) ($\boldsymbol{\Delta h}$ = 0 for the loose state of aggregates). The packing degree (PD) of loose and compacted aggregate state was determined using the following equation:

$$\varphi = \gamma . \sum_{i=1}^{n} \frac{A_i}{\rho_i}$$

Where $\boldsymbol{\varphi}$ is packing degree of the combined aggregate (%); $\boldsymbol{A_i}$ is the volume proportion of the individual aggregate (%); $\boldsymbol{\rho_i}$ is the grain density of the individual aggregate (kg/m^3); $\boldsymbol{\gamma}$ is the bulk packing density of combined aggregate (kg/m^3), and n is the number of individual aggregates in the combined blend.

Analytical Evaluation of Packing Degree - Analytical assessment of the combined packing degree was conducted using discrete modified-Toufar theoretical model [71,72] and Aim & Goff model [73], based on the physical characteristics of the individual aggregate's sources (fine, coarse, or intermediate). The Aim and Goff model considers the interaction of large particles with smaller particles based on the Furnas theory [74]. Based on the Aim and Goff model, the packing degree was calculated using the following two equations:

$$\varphi = \frac{\varphi_2}{1 - y_1}, \quad y_1 < y^*$$

$$\varphi = \frac{1}{\frac{y_1}{\varphi_1} + (1 - y_1) \times (1 + 0.9 * \frac{d_1}{d_2})}, \quad y_1 > y^*$$

where φ_1 and φ_2 are Eigenpacking degrees of fine and coarse aggregates, respectively; y_1 and y_2 are grain volume of the fine and coarse aggregates; and d_1 & d_2 are characteristic diameters of fine and coarse aggregates. The packing degree of individual aggregates is called the Eigenpacking degree. The y* defines the borderline between the two cases for fine and coarse aggregate dominance and is defined by the following equation:

$$y^* = \frac{p}{1 + p}$$

where p can be defined as follow,

$$p = \frac{\varphi_1}{\varphi_2} - \left(1 + 0.9 * \frac{d_1}{d_2}\right) * \varphi_1$$

Modified-Toufar model [75] assumes the larger particles (e.g., coarse, or intermediate) are distributed discretely throughout the matrix of smaller particles (e.g., fine aggregates), and the total packing degree of combined aggregates is described as the following equation:

$$\varphi = \frac{1}{\frac{y_1}{\varphi_1} + \frac{y_2}{\varphi_2} - r_2(\frac{1}{\varphi_2} - 1) k_s k_d}$$

where φ_1 and φ_2 are Eigenpacking degrees of fine and coarse aggregates, respectively; y_1 and y_2 are grain volume of the fine and coarse aggregates; k_d considers the ratio of the diameters between the coarse and fine aggregate; and k_s is a statistical factor that considers the probability of the number of interstices between four coarse particles surrounding a fine particle surrounded.

Combined Aggregate Gradation of Optimal Blend - The sieve analysis for maximum aggregate proportions with respect to packing degree for both Hamburg and Weldon are presented in Figures B5 and B6. The ASTM C33 limits for the combined aggregate were calculated by proportioning the ASTM C33 limits of individual aggregate. It was observed that the maximum proportion of aggregates complies with ASTM C33 standards [69].

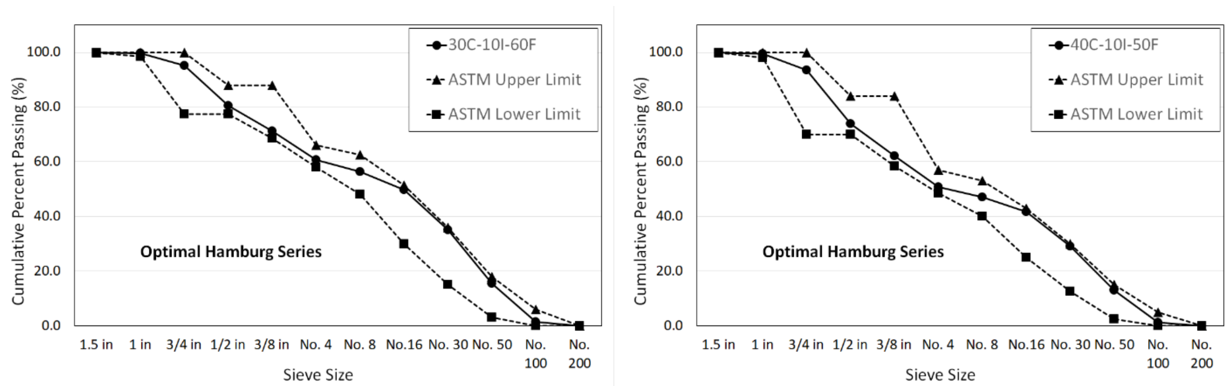

Figure B5: Sieve analysis of the maximum combined aggregate proportion of the Hamburg series.

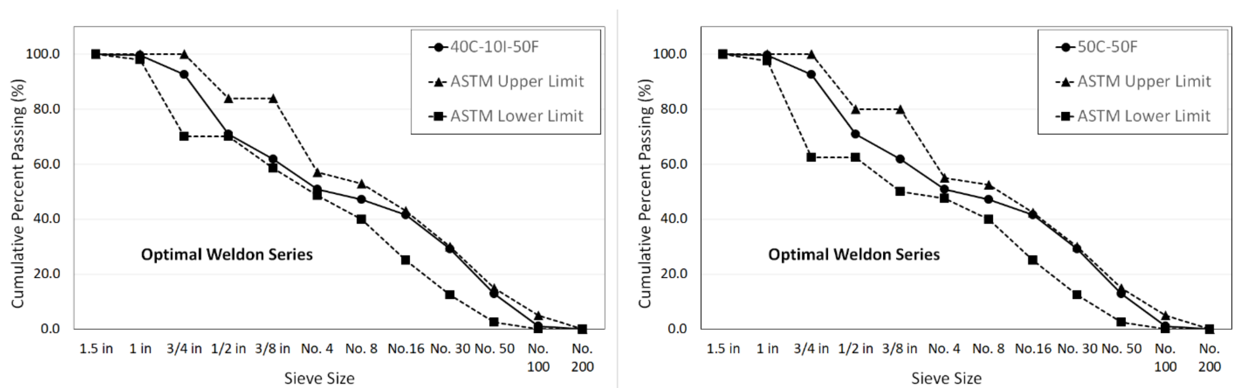

Figure B6: Sieve analysis of the maximum combined aggregate proportion of the Weldon series

Comparison with Power Curves - Analysis of combined aggregate gradations was conducted using Fuller-Thomson Gradation curves, 0.35, 0.45, 0.5, and 0.7, the selection of which depends on the application (a.k.a. Power reference curves) [76]. Power curves 0.45 have been traditionally used for optimizing aggregate gradations in asphalt and minimizing the binder content. The set of existing aggregates gradation was compared with properly selected reference power curves enabling suggestion for improved gradation by adjusting the proportions of a binary gradation and by introducing realistic proportions of Wantage intermediate aggregate. Figures B7 and B8 show the comparison of the particle size distribution (PSD) of combined aggregates (binary and ternary) to different power curves for the Hamburg and Weldon series, respectively. An increase in the fine content pushed the PSD of combined binary aggregate from 0.7 to 0.45 power curve. Furthermore, the addition of intermediate aggregates into the combined aggregate blend aligned the PSD more with the power curves.

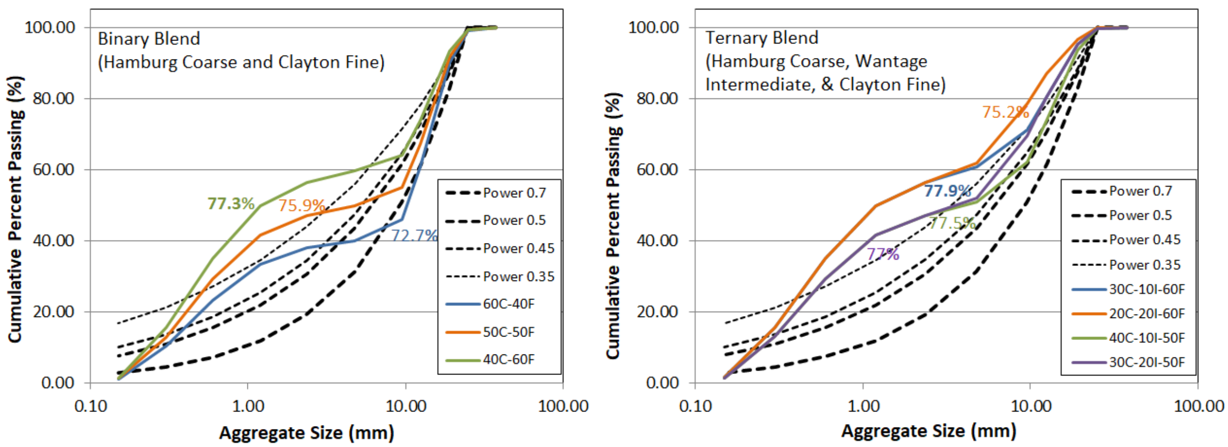

Figure B7. Particle size distribution of experimental aggregate blend of Hamburg series. (Accompanied with the Packing degree, %)

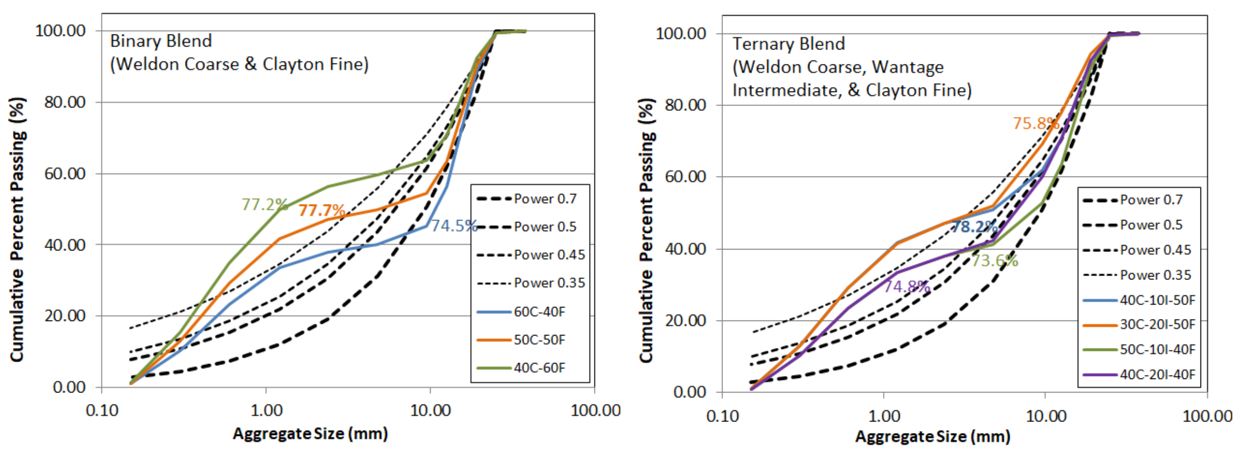

Figure B8. Particle size distribution of experimental aggregate blend of Weldon series. (Accompanied with the Packing degree, %)

Shilstone Chart - Shilstone coarseness factor chart specifies the Coarseness Factor (CF) and Workability Factor (WF) ranges for various blends of aggregate [77]. These charts assess the practicality of the proposed aggregate gradation. The relation between grading and concrete performance is developed by specifying a well-graded zone in the Shilstone chart as Zone II. The empirical WF and CF parameters depend on the composition, grading, and cement content of the mix and are defined as follow,

$$CF = 100 \times \frac{R_{9.5}}{R_{2.36}}$$

$$WF = P_{2.36} + 0.045 \times (C - 335)$$

where, $P_{2.36}$is cumulative percent passing from 2.36 mm (#8) sieve, C is cement content (kg/m^3), $R_{2.36}$ is cumulative percent retained on 2.36 mm sieve (#8) sieve, and $R_{9.5}$ is cumulative percent retained on 9.50 mm sieve (#3/8) sieve.

Table B4: Coarseness and Workability Factors for the different proportion of aggregates

S. No.	Aggregate Ratio	Binder Content 660 (lb/yd^3)		Binder Content 500 (lb/yd^3)		Packing Degree (Compact)
		Coarseness Factor	Workability Factor	Coarseness Factor	Workability Factor	
SH1	40C-60F	82.7	58.9	82.7	54.7	77.30%
SH2	**30C-10I-60F**	**66**	**58.9**	**66**	**54.7**	**77.90%**
SH3	20C-20I-60F	49.3	58.9	49.3	54.7	75.20%
SH4	50C-50F	85.3	49.7	85.3	45.4	75.90%
SH5	**40C-10I-50F**	**71.5**	**49.7**	**71.5**	**45.4**	**77.50%**
SH6	30C-20I-50F	57.8	49.7	57.8	45.4	77%
SH7	60C-40F	87.1	40.4	87.1	36.2	72.70%
SH8	50C-10I-40F	75.4	40.4	75.4	36.2	72.80%
SH9	40C-20I-40F	63.7	40.4	63.7	36.2	76.70%
SW1	40C-60F	83.5	59	83.5	54.7	77.20%
SW2	30C-10I-60F	66.7	59	66.7	54.7	75.50%
SW3	20C-20I-60F	49.8	59	49.8	54.7	75.70%
SW4	**50C-50F**	**86.2**	**49.8**	**86.2**	**45.5**	**77.70%**
SW5	**40C-10I-50F**	**72.2**	**49.8**	**72.2**	**45.4**	**78.20%**
SW6	30C-20I-50F	58.3	49.8	58.3	45.4	75.80%
SW7	60C-40F	88	40.5	88	36.2	74.50%
SW8	50C-10I-40F	76.1	40.5	76.1	36.2	73.60%
SW9	40C-20I-40F	64.3	40.5	64.3	36.2	74.80%

**SH and SW sample corresponds to Hamburg and Weldon coarse sample series, respectively.*

The WF is controlled primarily by the fine aggregate content, and the CF is defined by the ratio of fine aggregates to combined fine and intermediate aggregate size groups. Table B4 shows the coarseness and workability factors for different blends of aggregates for Hamburg ('SHx' samples) as well as the Weldon ('SWx' samples) series. Furthermore, these samples in Table B4 are plotted on the Shilstone chart in Figures B9 and B10 for Hamburg and Weldon series, respectively. SH1-SH3 and SW1-SW3 were out of the bounds of the charts, hence they were not plotted. SH4-SH6 and SW4-SW6 have high WF reflecting high fine aggregate content and hence lie in the sandy Zone IV of the Shilstone chart.

It was observed that the CF decreases with the replacement of coarse aggregate with the intermediate aggregate, however, WF remained unchanged. Based on the 660 lb/yd^3 binder content, aggregate blends with 40% fine content and 10-20% intermediate content were positioned in the well-graded Zone II. However, it is evident from Figure B9 and Figure B10 that the WF significantly reduced with the decrease in the binder content from 660 lb/yd^3 to 500 lb/yd^3. This reduction pushed the samples in the sandy zone more toward Zone-II. Hence, the amount of cement can be further reduced in the mix design to use the relatively sandy mix with a higher packing degree as the optimal aggregate proportion.

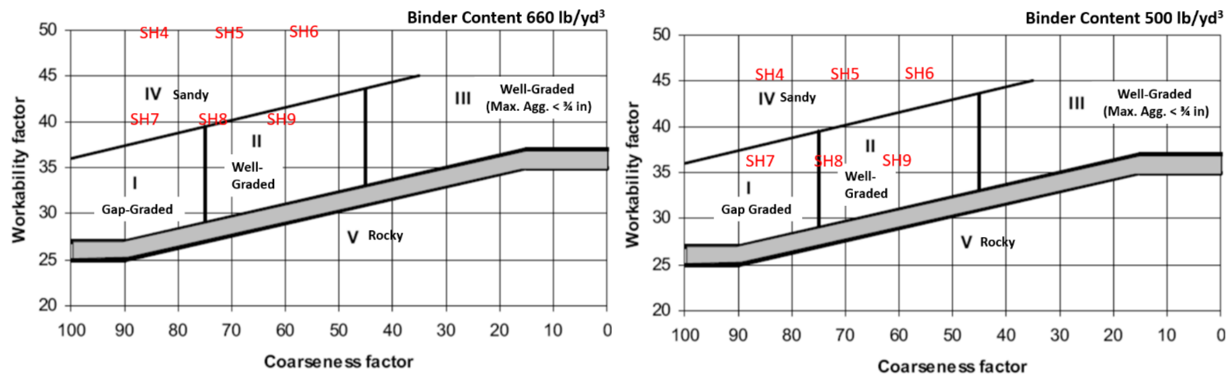

Figure B9: Coarseness chart of aggregate mixtures of Hamburg series.

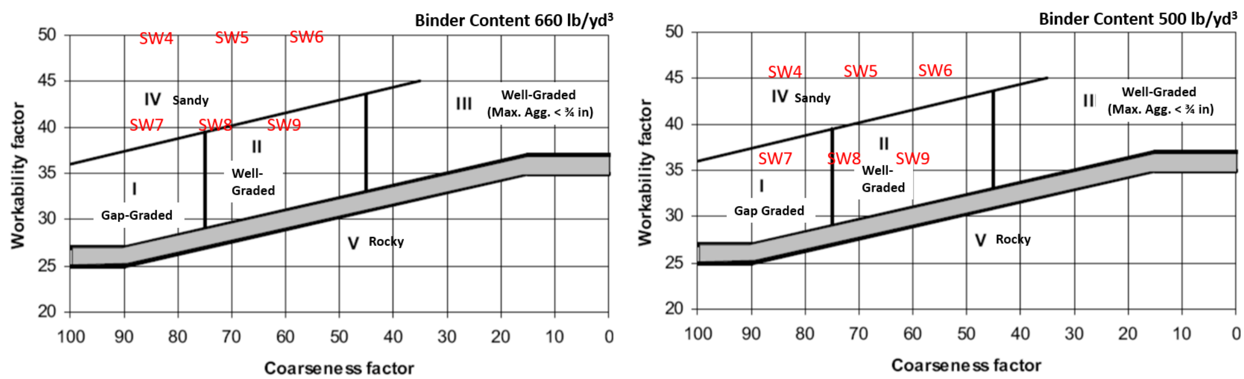

Figure B10: Coarseness chart of aggregate mixtures for Weldon series.

B.4.2 Further data on the RCA that will be used in the proposed mixtures

The RCA chosen for use from the NYC Department of Transportation has a specific gravity of 2.17 and an absorption capacity of 3.85%. The aggregate gradation for the proposed RCA can be observed in Figure B11.

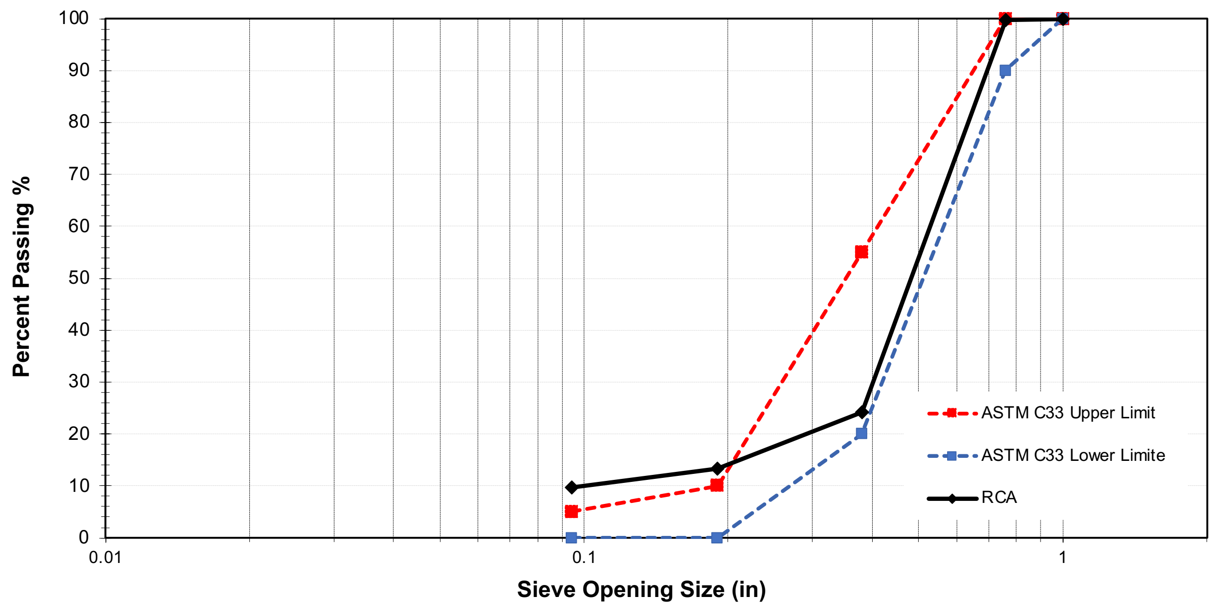

Figure B11: Sieve analysis for RCA aggregates.

As shown in Figure B11, the aggregates are slightly out of spec, particularly at the smaller sizes. However, the research team recommends using the aggregates as they are produced, since further processing would only increase the embodied carbon of the aggregates.

B.5 Further information on the embodied carbon calculations for proposed mixture designs

B.5.1 Greenhouse gas emission coefficients of raw materials

A description of the production processes of raw materials used in different concrete mixtures and the calculation methods of GHG emission coefficients are summarized as follows:

B.5.1.1 Hydraulic Cements

Portland Cement

During cement production, GHGs are emitted mainly from fuel combustion and limestone calcination, with smaller contributions from quarrying and crushing of limestone. The production process of portland cement includes quarrying and crushing, transportation from the source to cement plant, raw meal preparation, pyro-processing, and finish grinding.

Based on the analysis in Task A, the GHG emission coefficient of portland cement was calculated as 1.048, which is very close the value of 1.04 in the published EPD from Portland Cement Association (PCA) [78]. In general, one kilogram of CO_2 eq. is generated for every one kilogram of cement produced.

Calcium sulfoaluminate cement

The production of CSA is similar to portland cement but with different raw materials, containing significant amounts of sulfates. Due to different raw materials, the calcination temperature for CSA is 1250 °C, whereas portland cement is usually calcinated at 1500 °C. Additionally, the CSA clinker is much softer compared to portland clinker, which reduces the energy input and the resulting CO_2 emissions during the griding process [79]. However, excessive SO_x gas is generated during the combustion process of CSA, causing a negative impact to environment. Therefore, the SO_x gas must be treated by reaction with calcium oxide (CaO) and oxygen to produce solid calcium sulfate. The treatment process has non-negligible carbon footprint as extra CO_2 is generated during the calcination of limestone to produce CaO that is used as the absorbent. At the same time, the calcium sulfate that is produced can replace the natural gypsum used as an inter-grinding additive in the manufacturing of cement from clinker.

Considering the trade-off between the production of CSA and the treatment of SO_x emissions, the GHG emission coefficient of CSA was found to be about 25% to 35% lower than portland cement [80].

B.5.2 Supplementary cementitious materials

The production processes of SCMs vary significantly depending on the type of SCM and the treatment of SCMs as waste materials or industry by-products. If SCMs are treated as waste materials, the system boundary only includes the secondary process. However, both primary and secondary processes are considered if SCMs are regarded as industry by-products [81,82].

Based on an analysis in Task A, the GHG emission coefficients of fly ash (FA) and granulated blast furnace slag (GBFS) are 0.328 and 0.264 when considered as industry by-products when using economic allocation method to consider the emissions from primary process [31]. The carbonated fly ash can embed 15% of the mass with CO_2 compared to standard fly ash by up to 15%, however no broad based EPDs are available yet for this product, as such a reduction of 15% in the GHG emission coefficient was assumed (0.279) [83].

Ground glass pozzolan:

Three glass sources (container glass, plate glass, and E-glass) can be used to produce ground glass pozzolan. The production process of the ground glass pozzolan includes extraction, separation, pre-grinding, transportation, deep grinding into required size, packaging and waste handling and treatment. The typical replacement percentage is 10% to 40% of cement based on ASTM C-1866 *Standard Specification for Ground-Glass Pozzolan for Use in Concrete* .

Based on the published EPD from Vitro Minerals, the GHG emission coefficient of ground glass pozzolan is 0.096 to 0.15 [84]. The ground glass pozzolan used in this project is Pozzotive® made from 100% recycled glass by Urban Mining Industries, NY. Based on the LCA conducted by Climate Earth, the GHG emission coefficient is 0.0556 [85]. Variations can be caused by the difference in the source of waste glass and the target grinding size.

Portland-limestone cement

PLC is made by replacing part of the clinker in portland cement with ground limestone. Since the production of limestone is like aggregate production that has much lower GHG emissions than clinker calcination, the GHG emission of PLC can be effectively reduced based on the content of limestone. According to ASTM C595 - *Standard Specification for Blended Hydraulic Cements*, the limestone content in PLC is usually more than 5% but less than or equal to 15% by mass of the blended cement.

Based on the published EPDs for Portland cement and PLC [86,87], the GHG emission coefficients of portland cement and PLC (with 10.8% of limestone) were calculated as 0.922 and 0.846, respectively. The limestone is substituted with clinker, then the mixed clinker undergoes a grinding process that releases certain amounts of GHG emission. The calculation of GHG emission of PLC is illustrated in the following equation:

$$GHG_{plc} = (GHG_{pc} - GHG_{grind}) \times (1 - r) + GHG_{limestone} \times r + GHG_{grind}$$

Where, GHG_{plc}, GHG_{pc}, and $GHG_{limestone}$ are the GHG emissions of portland-limestone cement, portland cement, and limestone, respectively; GHG_{grind} is the GHG emission generated during the final grinding process; and r is the percentage of limestone. Considering that the production process of the limestone is similar to aggregate production, including extraction, crushing, screening, and transportation, the GHG emission of limestone is assumed to be the same as fine aggregate (0.00258). The GHG emission generated by the final grinding process can be calculated as 0.216, which is approximately 23% of the total GHG emission of portland cement.

It is noted that the GHG emission of portland cement provided by the EPD only considers the combustion stage [86]. By replacing the clinker with limestone, the upstream GHG emission of portland-limestone cement would also be reduced. If using the GHG emission coefficient of 1.048 from Task A report and assuming the GHG emission by final grinding is 23% of total emission, the GHG emission coefficient of PLC with 12% of limestone is calculated as 0.951.

B.5.2.1 Aggregate Materials

Natural aggregates

The production process of crushed aggregate includes blasting, wet drilling, product loading in an open truck, unloading, crushing, screening, conveyor transfer, storage piles, and transportation. The activities of sand or gravel production are product loading in an open truck, material transfer and conveying, screening, pile forming with a stacker, storage piles, and bulk loading.

Based on the analysis in Task A, the calculated GHG emission coefficients of aggregates are 0.00372 and 0.00258 for crushed aggregate and sand & gravel, respectively. In the published EPDs from several quarries in the west coast of the United States [88], the range of GHG emission coefficients is 0.00155 to 0.0077 and 0.00165 to 0.00749, r, for crushed aggregate and sand & gravel, respectively. These variations are mainly caused by the differences in transportation distance and truck type.

The mixture designs with optimized aggregate (OA) were realized by controlling the aggregate gradation. The OA systems can provide better interlocking and abrasion effects to enhance the general mechanical properties of concrete. The GHG emission coefficient of the OA is defined as the average value of coarse and fine aggregate, depending on the size range of OA.

Recycled concrete aggregate

The production process of RCA includes transportation of construction and demolition (C&D) waste to the plant and additional processing. It is assumed that the C&D waste will be processed for landfill even if it is not recycled for other uses.

The GHG emission coefficient of RCA from C&D waste was found to be between 0.0009 and 0.0012 [89]. The reduction in GHG emissions of RA is not significant compared with natural aggregate, without considering the reduction of GHG emission by transportation to landfilling and the process of landfilling.

B.5.2.2 Carbon sequestration techniques

In-situ carbonate seeding

The in-situ carbonate seeding method is achieved by injecting a certain amount of CO_2 into concrete to further improve the hydration process and initiate the enhanced carbonation reaction during curing stages. The typical utilization rate of CO_2 ranges from 0.05% to 0.12% by mass of cementitious material [90]. For instance, for using every one ton of cement, 0.5 kg to 1.2 kg CO_2 emission could be reduced through carbon curing; however, the injection of CO_2 requires energy consumption and can also produce carbon emission, which is about 8.4% of the mass of captured CO_2.

Considering the amount of captured CO_2 and the generated CO_2 in the injection process, the GHG emission coefficient for the Carbon Cure system used to develop this method was found to be 0.00046 to 0.00115 (with respect to the mass of cement) [90]. Although the avoided GHG emission by this technique is small, less cement is needed to achieve comparable concrete performance. Thus, the major reduction in GHG emission of in-situ carbonate seeding will be realized by the reduced cement usage.

B.6 Appendix References

[1] S.A. Miller, A. Horvath, P.J.M. Monteiro, Readily implementable techniques can cut annual CO 2 emissions from the production of concrete by over 20%, Environ. Res. Lett. 11 (2016) 74029. https://doi.org/10.1088/1748-9326/11/7/074029.

[2] M.H. Youn, K.T. Park, Y.H. Lee, S.-P. Kang, S.M. Lee, S.S. Kim, Y.E. Kim, Y.N. Ko, S.K. Jeong, W. Lee, Carbon dioxide sequestration process for the cement industry, J. CO2 Util. 34 (2019) 325–334. https://doi.org/https://doi.org/10.1016/j.jcou.2019.07.023.

[3] L.K. Turner, F.G. Collins, Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC cement concrete, Constr. Build. Mater. 43 (2013) 125–130. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2013.01.023.

[4] H. Wang, C. Thakkar, X. Chen, S. Murrel, Life-cycle assessment of airport pavement design alternatives for energy and environmental impacts, J. Clean. Prod. 133 (2016) 163–171. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.05.090.

[5] K.L. Scrivener, V.M. John, E.M. Gartner, Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry, Cem. Concr. Res. 114 (2018) 2–26. https://doi.org/https://doi.org/10.1016/j.cemconres.2018.03.015.

[6] D.L. Thomas Harrison, Martyn Roderick Jones, The production of low energy cements, in: M.L. Peter C. Hewlett (Ed.), Lea's Chem. Cem. Concr., Fifth Edit, Butterworth-Heineman, Oxford, UK, 2019: pp. 341–363.

[7] CSA, Development of state of the art techniques in cement manufacturing: trying to look ahead, in: CSI?ERCA - Technol. Pap., US Environmental Protection Agency, 2009.

[8] J. Rosen, Turning carbon into concrete could win UCLA team a climate victory — and $7.5 million, LA Times. (2020).

[9] E.G. L. Barcelo, J. Kline, G. Walenta, Cement and carbon emissions, Mater. Struct. 47 (2014) 1055–1065.

[10] T.D.D. Michael John McCarthy, Pozzolanas and Pozzolanic Materials, in: P.C. Hewlett, M. Liska (Eds.), Lea's Chem. Cem. Concr., Fifth Edit, Butterworth-Heineman, Cambridge, UK, 19AD.

[11] R. Dhir, Pulverized Fuel Ash, in: R. Swamy (Ed.), Cem. Replace. Mater., Surrey University Press, Glasgow, UK, 1986.

[12] M. McCarthy, G.S. Islam, L. Csetenyi, M. Jones, Investigating techniques for rapidly assessing fly ash reactivity for use in concrete, World of Coal Ash, Lexington, KY, 2013.

[13] M. Thomas, Optimizing the Use of Fly Ash in Concrete, Skokie, IL, 2007.

[14] J. Krithika, G.B.R. Kumar, Influence of fly ash on concrete - A systematic review, in: Mater. Today Proc., Elsevier Ltd, 2020: pp. 906–911. https://doi.org/10.1016/j.matpr.2020.06.425.

[15] D. Roy, G. Idorn, Developments of structure and properties of blastfurnace slag cements, J. Am. Concr. Inst. 87 (1982) 444–457.

[16] ASTM C595-20, Standard Specification for Blended Hydraulic Cements, West Conshohocken, PA, 2020.

[17] M. Moranville-Regourd, S. Kamali-Bernard, Cements Made From Blastfurnace Slag, in: P.C. Hewlett, M. Liska (Eds.), Lea's Chem. Cem. Concr., Fifth Edit, Butterworth-Heineman, Cambridge, UK, 2019: pp. 469–507.

[18] A.M. Rashad, An overview on rheology, mechanical properties and durability of high-volume slag used as a cement replacement in paste, mortar and concrete, Constr. Build. Mater. 187 (2018) 89–117. https://doi.org/10.1016/j.conbuildmat.2018.07.150.

[19] H. Smolczyk, Slag structure and identification of slag, in: Proc. Seventh Int. Congr. Chem. Cem., Paris, FR, 1980: p. Vol I, Theme II: 1-17.

[20] K. Luke, F. Glasser, Internal chemical evolution of the constitution of blended cements, Cem. Concr. Res. 18 (1988) 495–502.

[21] F. Lollini, E. Redaelli, L. Bertolini, Effects of portland cement replacement with limestone on the properties of hardened concrete, Cem. Concr. Compos. 46 (2014) 32–40. https://doi.org/https://doi.org/10.1016/j.cemconcomp.2013.10.016.

[22] P.C. Association, Portland -limestone cement, Skokie, IL, 202AD.

[23] G.M.S. Islam, M.H. Rahman, N. Kazi, Waste glass powder as partial replacement of cement for sustainable concrete practice, Int. J. Sustain. Built Environ. 6 (2017) 37–44. https://doi.org/10.1016/j.ijsbe.2016.10.005.

[24] A. Kaminsky, M. Krstic, P. Rangaraju, A. Tagnit-Hamou, M.D.A. Thomas, Ground-Glass pozzolan for use in concrete, Concr. Int. November (2020) 24–31.

[25] A.F. Omran, D.M. Etienne, D. Harbec, A. Tagnit-Hamou, Long-term performance of glass-powder concrete in large-scale field applications, Constr. Build. Mater. 135 (2017) 43–58. https://doi.org/10.1016/j.conbuildmat.2016.12.218.

[26] R. Nasser, P. Soroushian, Field investigation of concrete, J. Solid Waste Technol. Manag. 37 (2011) 307–319.

[27] M. Kamali, A. Ghahremaniezhad, Effect of glass powders on the mechanical and durability properties of cementitious materials, Constr. Build. Mater. 98 (2015) 407–416.

[28] A.M. Matos, J. Sousa-Coutinho, Durability of mortar using waste glass powder as cement replacement, Constr. Build. Mater. 36 (2012) 205–215. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2012.04.027.

[29] A. Shayan, A. Xu, No Title, (2006) 457–468. https://doi.org/10.1016/j.cemconres.2005.12.012.

[30] M. Krstic, J.F. Davalos, Field application of recycled glass pozzolan for concrete, ACI Mater. J. 116 (2019) 123–131.

[31] P. Authority, Task A report, LECC project , (2021).

[32] K.A.A. Al-Sodani, M.M. Al-Zahrani, M. Maslehuddin, O.S.B. Al-Amoudi, S.U. Al-Dulaijan, Chloride diffusion models for Type I and fly ash cement concrete exposed to field and laboratory conditions, Mar. Struct. 76 (2021). https://doi.org/10.1016/j.marstruc.2020.102900.

[33] N. Schwarz, H. Cam, N. Neithalath, Influence of a fine glass powder on the durability characteristics of concrete and its comparison to fly ash, Cem. Concr. Compos. 30 (2008) 486–496. https://doi.org/10.1016/j.cemconcomp.2008.02.001.

[34] F.U.A. Shaikh, S.W.M. Supit, P.K. Sarker, A study on the effect of nano silica on compressive strength of high volume fly ash mortars and concretes, Mater. Des. 60 (2014) 433–442. https://doi.org/10.1016/j.matdes.2014.04.025.

[35] R. Sharma, R.A. Khan, Sustainable use of copper slag in self compacting concrete containing supplementary cementitious materials, J. Clean. Prod. 151 (2017) 179–192. https://doi.org/10.1016/j.jclepro.2017.03.031.

[36] R. Siddique, Performance characteristics of high-volume Class F fly ash concrete, Cem. Concr. Res. 34 (2004) 487–493. https://doi.org/10.1016/j.cemconres.2003.09.002.

[37] M.B. Vanjare, S.H. Mahure, Experimental Investigation on Self Compacting Concrete Using Glass Powder, 2 (n.d.) 1488–1492. www.ijera.com.

[38] Y. Wang, B. Lu, X. Hu, J. Liu, Z. Zhang, X. Pan, Z. Xie, J. Chang, T. Zhang, M.L. Nehdi, C. Shi, Effect of CO2 surface treatment on penetrability and microstructure of cement-fly ash–slag ternary concrete, Cem. Concr. Compos. 123 (2021). https://doi.org/10.1016/j.cemconcomp.2021.104194.

[39] M.H. Zhang, J. Islam, Use of nano-silica to reduce setting time and increase early strength of concretes with high volumes of fly ash or slag, Constr. Build. Mater. 29 (2012) 573–580. https://doi.org/10.1016/j.conbuildmat.2011.11.013.

[40] W. Chen, F. Shaikh, Z. Li, W. Ran, H. Hao, Dynamic compressive properties of high volume fly ash (HVFA) concrete with nano silica, Constr. Build. Mater. 301 (2021). https://doi.org/10.1016/j.conbuildmat.2021.124352.

[41] H. El-Chabib, A. Syed, Properties of Self-Consolidating Concrete Made with High Volumes of Supplementary Cementitious Materials, J. Mater. Civ. Eng. 25 (2013) 1579–1586. https://doi.org/10.1061/(asce)mt.1943-5533.0000733.

[42] W. Gong, Q. Chen, J. Miao, Bond behaviors between copper slag concrete and corroded steel bar after exposure to high temperature, J. Build. Eng. 44 (2021) 103312. https://doi.org/10.1016/j.jobe.2021.103312.

[43] A.F. Hashmi, M. Shariq, A. Baqi, An investigation into age-dependent strength, elastic modulus and deflection of low calcium fly ash concrete for sustainable construction, Constr. Build. Mater. 283 (2021). https://doi.org/10.1016/j.conbuildmat.2021.122772.

[44] R. Hay, C.P. Ostertag, New insights into the role of fly ash in mitigating alkali-silica reaction (ASR) in concrete, Cem. Concr. Res. 144 (2021). https://doi.org/10.1016/j.cemconres.2021.106440.

[45] M.U. Hossain, C.S. Poon, I.M.C. Lo, J.C.P. Cheng, Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA, Resour. Conserv. Recycl. 109 (2016) 67–77. https://doi.org/https://doi.org/10.1016/j.resconrec.2016.02.009.

[46] G. Li, Properties of high-volume fly ash concrete incorporating nano-SiO 2, Cem. Concr. Res. 34 (2004) 1043–1049. https://doi.org/10.1016/j.cemconres.2003.11.013.

[47] T. Nochaiya, W. Wongkeo, A. Chaipanich, Utilization of fly ash with silica fume and properties of Portland cement-fly ash-silica fume concrete, Fuel. 89 (2010) 768–774. https://doi.org/10.1016/j.fuel.2009.10.003.

[48] I. Papayianni, E. Anastasiou, Production of high-strength concrete using high volume of industrial by-products, Constr. Build. Mater. 24 (2010) 1412–1417. https://doi.org/10.1016/j.conbuildmat.2010.01.016.

[49] H.O. Shin, J.M. Yang, Y.S. Yoon, D. Mitchell, Mix design of concrete for prestressed concrete sleepers using blast furnace slag and steel fibers, Cem. Concr. Compos. 74 (2016) 39–53. https://doi.org/10.1016/j.cemconcomp.2016.08.007.

[50] I.B. Topçu, A.R. Boğa, Effect of ground granulate blast-furnace slag on corrosion performance of steel embedded in concrete, Mater. Des. 31 (2010) 3358–3365. https://doi.org/10.1016/j.matdes.2010.01.057.

[51] C. Bilim, C.D. Atiş, H. Tanyildizi, O. Karahan, Predicting the compressive strength of ground granulated blast furnace slag concrete using artificial neural network, Adv. Eng. Softw. 40 (2009) 334–340. https://doi.org/10.1016/j.advengsoft.2008.05.005.

[52] Z.T. Chang, X.J. Song, R. Munn, M. Marosszeky, Using limestone aggregates and different cements for enhancing resistance of concrete to sulphuric acid attack, Cem. Concr. Res. 35 (2005) 1486–1494. https://doi.org/10.1016/j.cemconres.2005.03.006.

[53] M.U. Hossain, C.S. Poon, Y.H. Dong, D. Xuan, Evaluation of environmental impact distribution methods for supplementary cementitious materials, Renew. Sustain. Energy Rev. 82 (2018) 597–608. https://doi.org/10.1016/j.rser.2017.09.048.

[54] L. Jiang, C. Li, C. Wang, N. Xu, H. Chu, Utilization of flue gas desulfurization gypsum as an activation agent for high-volume slag concrete, J. Clean. Prod. 205 (2018) 589–598. https://doi.org/10.1016/j.jclepro.2018.09.145.

[55] R.P. Khatri, V. Sirivivatnanon, W. Gross, EFFECT OF DIFFERENT SUPPLEMENTARY CEMENTITIOUS MATERIALS ON MECHANICAL PROPERTIES OF HIGH PERFORMANCE CONCRETE, 25 (1995) 209–220.

[56] Y. Kim, A. Hanif, M. Usman, M.J. Munir, S.M.S. Kazmi, S. Kim, Slag waste incorporation in high early strength concrete as cement replacement: Environmental impact and influence on hydration & durability attributes, J. Clean. Prod. 172 (2018) 3056–3065. https://doi.org/10.1016/j.jclepro.2017.11.105.

[57] D.W. Law, A.A. Adam, T.K. Molyneaux, I. Patnaikuni, Durability assessment of alkali activated slag (AAS) concrete, Mater. Struct. Constr. 45 (2012) 1425–1437. https://doi.org/10.1617/s11527-012-9842-1.

[58] C. Li, L. Jiang, Utilization of limestone powder as an activator for early-age strength improvement of slag concrete, Constr. Build. Mater. 253 (2020). https://doi.org/10.1016/j.conbuildmat.2020.119257.

[59] K.L. Jain, G. Sancheti, L.K. Gupta, Durability performance of waste granite and glass powder added concrete, Constr. Build. Mater. 252 (2020). https://doi.org/10.1016/j.conbuildmat.2020.119075.

[60] A.S. Raju, K.B. Anand, P. Rakesh, Partial replacement of Ordinary Portland cement by LCD glass powder in concrete, in: Mater. Today Proc., Elsevier Ltd, 2019: pp. 5131–5137. https://doi.org/10.1016/j.matpr.2020.10.661.

[61] Y. Shao, T. Lefort, S. Moras, D. Rodriguez, Studies on concrete containing ground waste glass, Cem. Concr. Res. 30 (2000) 91–100.

[62] A. Zidol, M.T. Tognonvi, A. Tagnit-Hamou, Effect of Glass Powder on Concrete Sustainability, New J. Glas. Ceram. 07 (2017) 34–47. https://doi.org/10.4236/njgc.2017.72004.

[63] A.A. Aliabdo, A.E.M.A. Elmoaty, A.Y. Aboshama, Utilization of waste glass powder in the production of cement and concrete, Constr. Build. Mater. 124 (2016) 866–877. https://doi.org/10.1016/j.conbuildmat.2016.08.016.

[64] H. Du, K.H. Tan, Waste glass powder as cement replacement in concrete, J. Adv. Concr. Technol. 12 (2014) 468–477. https://doi.org/10.3151/jact.12.468.

[65] H. Du, K.H. Tan, Properties of high volume glass powder concrete, Cem. Concr. Compos. 75 (2017) 22–29. https://doi.org/10.1016/j.cemconcomp.2016.10.010.

[66] H.A. Elaqra, M.A.A. Haloub, R.N. Rustom, Effect of new mixing method of glass powder as cement replacement on mechanical behavior of concrete, Constr. Build. Mater. 203 (2019) 75–82. https://doi.org/10.1016/j.conbuildmat.2019.01.077.

[67] Z. hai He, P. min Zhan, S. gui Du, B. ju Liu, W. bin Yuan, Creep behavior of concrete containing glass powder, Compos. Part B Eng. 166 (2019) 13–20. https://doi.org/10.1016/j.compositesb.2018.11.133.

[68] H. Guo, C. Shi, X. Guan, J. Zhu, Y. Ding, T.-C. Ling, H. Zhang, Y. Wang, Durability of recycled aggregate concrete – A review, Cem. Concr. Compos. 89 (2018) 251–259. https://doi.org/https://doi.org/10.1016/j.cemconcomp.2018.03.008.

[69] ASTM C33/C33M-18, Standard Specification for Concrete Aggregates, ASTM Int. (2020).

[70] ASTM C1170/C1170M-20, Standard Test Method for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table, West Conshohocken, PA, 2020.

[71] W. Toufar, Beitrag zur Optimierung der Packungsdichte polydisperser körniger Systeme, Freib. Forschungsh. . 558 (1976) 29–44.

[72] M. Mohamadreza, S. Konstantin, F.-V. Ismael, A. Adil, M. Moini, K. Sobolev, I. Flores-Vivian, A. Amirjanov, Modeling and Experimental Evaluation of Aggregate Packing for Effective Application in Concrete, J. Mater. Civ. Eng. 31 (2019) 4019001. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002628.

[73] R.B.B. Aim, P. Le Goff, Effet de paroi dans les empilements désordonnés de sphères et application à la porosité de mélanges binaires, Powder Technol. 1 (1968) 281–290.

[74] C.C. Furnas, Grading Aggregates - Mathematical relations for beds of broken solids of maximum density, Ind. Eng. Chem. 23 (1931) 1052–1058.

[75] P. Goltermann, V. Johansen, L. Palbøl, V.J. Per Goltermann and Lars Palbøl, Packing of Aggregates: An Alternative Tool to Determine the Optimal Aggregate Mix, ACI Mater. J. 94 (n.d.). https://doi.org/10.14359/328.

[76] K. Sobolev, A. Amirjanov, The development of a simulation model of the dense packing of large particulate assemblies, Powder Technol. 141 (2004) 155–160. https://doi.org/10.1016/j.powtec.2004.02.013.

[77] M. Moini, I. Flores-Vivian, A. Amirjanov, K. Sobolev, The optimization of aggregate blends for sustainable low cement concrete, Constr. Build. Mater. 93 (2015) 627–634. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2015.06.019.

[78] M. Marceau, M.A. Nisbet, M.G. Van Geem, Life cycle inventory of portland cement concrete, Skokie, IL, 2007.

[79] A. Sorensen, R. Thomas, M. Maguire, I. Quezada, Calcium Sulfoaluminate (CSA) CementL Benefits and Applications, Concr. Int. 40 (2018).

[80] T. Hanein, J.-L. Galvez-Martos, M.N. Bannerman, Carbon footprint of calcium sulfoaluminate clinker production, J. Clean. Prod. 172 (2018) 2278–2287. https://doi.org/https://doi.org/10.1016/j.jclepro.2017.11.183.

[81] (DOE); U.S. Department of Energy, Executive summary for the environment baseline, Volume 1: Greenhouse gas emissions from the U.S. Power Sector, 2016.

[82] C. Chen, G. Habert, Y. Bouzidi, A. Jullien, A. Ventura, LCA Allocation procedure used as an incitative method for waste recycling: An application to mineral additions in concrete, Resour. Conserv. Recycl. 54 (2010).

[83] C.U. Technologies;, Carbon Upcycling Technologies, Technology. (2021).

[84] V. Minerals;, EPD for ground glass pozzolan, 2020.

[85] C. Earth, Ground glass pozzolan EPD - Pozzotive Screening LCA-Pre-Production, 2020.

[86] ASTM EPD 195 for portland cement, West Conshohocken, PA, 2021.

[87] ASTM EPD 196 for portland limestone cement, West Conshohocken, PA, 2021.

[88] A. EPD-063, Environmental Product Declaration - Martin Marietta, 2017.

[89] A. Yazdanbakhsh, L.C. Bank, T. Baez, I. Wernick, Comparative LCA of concrete with natural and recycled coarse aggregate in the New York City area, Int. J. Life Cycled Assess. 23 (2018).

[90] S. Monkman, Utilization of CO2 in Ready Mixed Concrete Production: A Case Study, in: Proc. Concr. 2021, Concrete Institute of Australia, Perth, Australia, 2021.