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Determining Optimum Coal Bottom Ash Content For Sustainable Concrete Infrastructure

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University of North Dakota

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Thesis

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DETERMINING OPTIMUM COAL BOTTOM ASH CONTENT FOR SUSTAINABLE CONCRETE INFRASTRUCTURE

by

Samrawit Menda

Bachelor of Engineering in Civil Engineering, Brunel University of London, 2016

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December 2022

NOMENCLATURE

AI	Aggregate Industries
BS	Boiler Slag
CBA	Coal Bottom Ash
MOE	Modulus of Elasticity
RCPT	Rapid Chloride Permeability Test
SAM	Super Air Meter
STS	Split Tensile Strength
W/C	Water to Cement Ratio

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DEDICATION

I dedicate this work to my beloved mother, Senait Abebe, who passed away while I was studying and working on this project. Her unconditional love, support, and prayer will always stay with me; she hoped to see me complete this.

ABSTRACT

Concrete usage is increasing rapidly; subsequently, the industry's carbon footprint is increasing. Coal Bottom Ash (CBA)/Boiler Slag Bottom Ash (BS) is a byproduct of coal-burning power plants. This material can replace fine aggregate in concrete to reduce global natural material depletion. Using CBA/BS in the construction industry will reduce the technical and economic problems associated with power plants by reducing solid waste. This project's objective was to determine whether using new sustainable materials, such as CBA/BS, in concrete will reduce natural raw material usage and energy consumption. This study included three projects: comparing increased CBA/BS content to the three-control projects and determining the optimum content based on the compressive strength. The finding of this project indicates that 50% CBA/BS is the optimum content, which reduces fine aggregate usage in a concrete mix by 50% and maintains equivalent to or better concrete strength than the control. The CBA optimum content had a unit weight lower than the controls for all three projects, which makes the CBA lightweight concrete. Increasing CBA content decreases the slump value and the air content, possibly due to the higher water demand of CBA. Therefore, a superplasticizer was used to obtain the desired workability. CBA concrete compressive strength increased over time due to the CBA pozzolanic reaction that occurs later in the hydration reaction. However, using nano clay increased the pozzolanic reaction of CBA content at an early age. It increased CBA optimum content to 80% after 28 days of curing. Therefore, CBA can significantly reduce natural material usage and environmental harm by reducing CBA/BS waste disposal and improving concrete performance.

Chapter 1 Introduction

1.1 General

The world economy is growing, along with the construction industries, leading to high construction and virgin materials consumption. Concrete is the construction industry's primary production. It needs raw materials to supply the continuous need for cement, aggregate, and concrete production, which will aid in maintaining the economy (Ismail et al. 2013).

Concrete use has increased in the last decade, causing an increase in fine aggregate and cement usage and impacting the environment. It is preferable to use reusable waste materials, such as Coal bottom ash (CBA)/ Boiler slag (BS), to reduce the environmental impact and CO_2 emissions caused by the high usage of cement and fine aggregate (Mangi et al. 2018).

CBA/BS is the primary waste from thermal power plants (Kim and Lee 2011). India produces 30 million tons of CBA per year (Singh and Siddique 2014), the USA and Europe produce 14 million and 4 million tons of CBA, respectively (Kim et al. 2021), and Malaysia produces 1.7 million tons (Rafieizonooz et al. 2016); therefore, this waste must be handled properly and used to minimize environmental impacts. CBA can be used as a fine aggregate replacement in concrete to reduce global natural material depletion.

Many authors have concluded that nanoparticle inclusion increases the hydration process, which increases concrete's mechanical properties in only three days (Vera-Agullo et al. 2009). These materials increase the pozzolanic reaction because they have a high surface area acting as a nanofiller to densify the C-S-H (calcium silica hydrate) gel structure (Ji 2005).

Including nanomaterials in concrete mixtures enhances the concrete structure's physical properties, chemical properties, and durability (Vera-Agullo et al. 2009).This research will assess the effects of nanomaterials on the fine aggregate replaced by CBA in Concrete. Considerable research has been conducted on nanomaterial mixed concrete; however, little or almost no research on the optimum CBA content as a fine aggregate replacement with nanomaterials or nano clays.

1.2 Problem Statement

The concrete industry plays a significant role in natural resource consumption. The concrete industries currently consume eight billion tons of natural aggregates (Kumar et al. 2017). Natural aggregate usage has increased in many countries; therefore, finding a replacement for aggregate material is recommended to solve the problem.

CBA/BS disposal in ponds threatens the environment and human health since the hazardous constituents migrate and can contaminate ground or surface water, soil, and living organisms. Therefore, using CBA as a replacement in concrete mixes reduces its effect on the environment and human health (Baig and Varghese 2019). CBA can replace fine aggregate in concrete, aiding in minimizing construction costs and environmental degradation (Ibrahim et al. 2017). Replacing fine aggregate with CBA will positively impact the environment. Therefore, replacing fine aggregate with CBA would help reduce the raw materials harvested to produce concrete mixtures and reduce the carbon footprint of concrete production and the cost of fine aggregate in concrete. This research aimed to test the theory of an optimum CBA content as a fine aggregate replacement and test the CBA concrete performance with and without nanoparticles.

1.3 Project Objectives

This project's objective was to test the hypothesis that there is an optimum CBA/BS content for fine aggregate replacement with and without nanomaterials. Nanomaterials can increase the rate of CBA's hydration reaction at an early age due to their chemical and fineness properties.

The following are the specific objectives of the project:

- Determining the optimum CBA content as a fine aggregate replacement by comparing it to the control based on compressive strength.
- Assessing the optimal CBA content's effects as a fine aggregate replacement on the concrete's fresh, mechanical, and durability properties, compared to the control.
- Evaluate the effect of Nanomaterials on CBA concrete.

1.4 Thesis Organization

Chapter 1 covers natural resource consumption, the environmental impact associated with the construction industry, and how CBA can reduce this problem. Chapter 2 includes a literature review on CBA fresh, mechanical, and durability properties according to different research work.

Chapter 3 consists experimental plan, materials properties, mix design, and testing methods of this project. Chapter 4 discusses the findings, and finally, Chapter 5 makes a conclusion based on the findings, and recommendations, including future works.

Chapter 2 Literature Review

2.1 Concrete

Concrete is a vital construction material; therefore, its consumption increases the demand for Portland cement, which leads to CO_2 emissions and environmental pollution (Ramos et al. 2013). Cement production accounts for 8% of global CO_2 emissions, with a high global carbon footprint (Netherlands Environmental Assessment Agency 2015). In the construction industry, a large amount of fine aggregate is used with cement. Therefore, replacing fine aggregate with sustainable materials is preferable to save our natural resources for the next generation.

2.2 Hydration Process

A chemical reaction begins when water is added to cement and activates its cementing properties. The chemical reaction that occurs between water and cement is called hydration. The reaction is faster in the early stage and continues indefinitely at a reduced rate. The hydration process is complex and continuous in the presence of water, consisting of five stages shown in Figure 2.1.

1. Initial mixing reaction
2. Dormancy
3. Strength acceleration
4. Speed reduction
5. Steady development

In the hydration reaction process, the strength of cement is contributed by the change of silicate to Calcium Silica Hydrate (C-S-H), and Calcium hydroxide in the presence of water and C-S-H contributes to the strength of concrete.

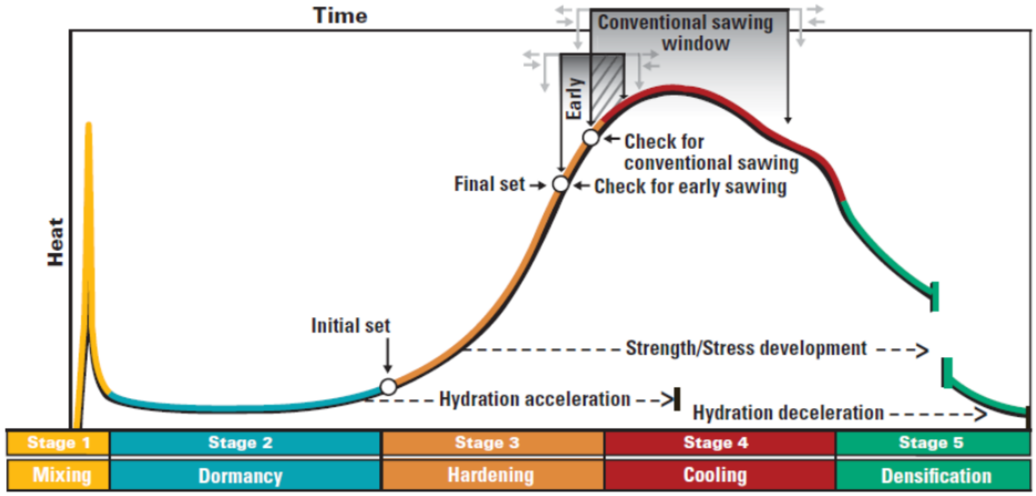

Figure 2.1 Five stages of hydration (Taylor et al. 2007)

2.3 Coal Bottom Ash (CBA) / Boiler Slag (BS)

Coal bottom ash and boiler slag are a byproduct of coal-fired power plants collected from the bottom of coal-burning furnaces, as shown in Figure 2.2. The product of CBA and BS depends on the types of coal-burning furnaces.

A water-filled tanker is used to collect CBA at the bottom of the burning furnace and transfer it to the basin for dewatering using a high-pressure water jet. About 20% of the unburned materials found at the dry bottom boiler are bottom ash. Bottom ash has a particle size similar to fine natural aggregate. However, bottom ash is lightweight and brittle (Babcock and Wilcox 1978). The coal combustion steam generating process and the ash collecting points are shown in Figure 2.2. CBA and BS are collected directly from the boiler/furnace without a separate system.

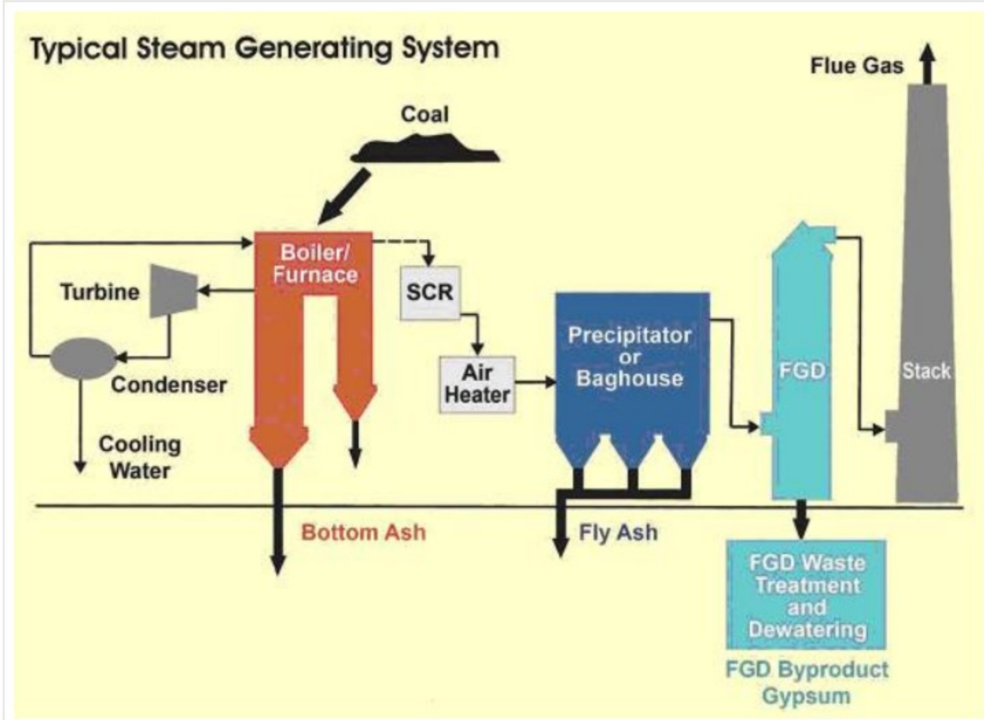

Figure 2.2 Typical CBA production (Abubakar and Baharudin 2012)

When the bottom ash is molten, it gathers at the bottom and is transferred to the ash hopper below in the presence of water. In this process, the molten slag touches the water, then the bottom ash cracks, or breaks, forming boiler slag (BS). BS is a hard, coarse, glassy material often called "black beauty," shown in Figure 2.3 (NETL 2006).

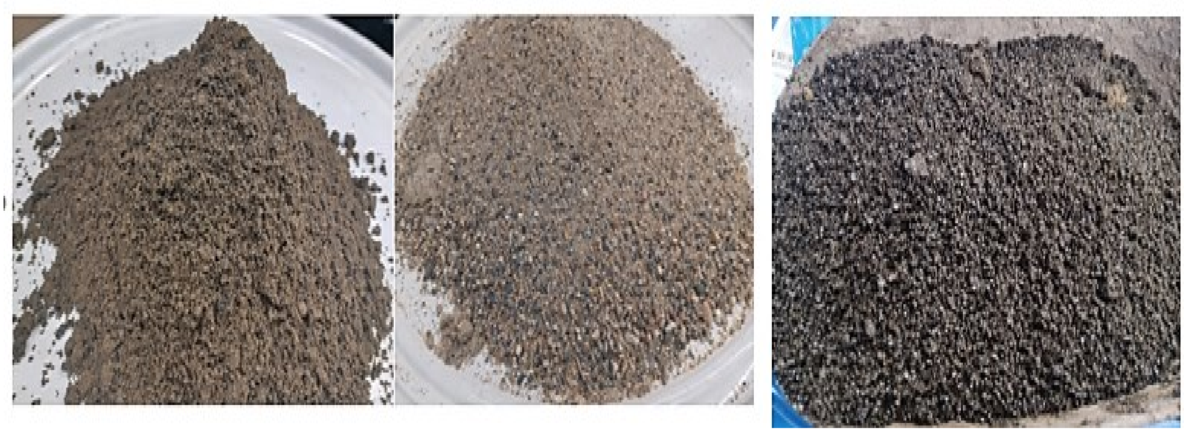

Figure 2.3 CBA (left), Fine aggregate (middle), and BS (right)

CBA/ BS as a Fine Aggregate Replacement

CBA/BS can replace fine aggregate in concrete due to its high shear strength and low compressibility, making it a perfect material for infrastructure design and construction (Amaya 2007).

Design engineers use bottom ash to improve materials due to its porosity and gradation. Therefore, bottom ash is an economical and robust engineering material (Lynn et al. 2016). Using bottom ash helps reduce natural resource consumption and maintain the future construction industry's economy.

Physical and Chemical Properties of CBA/BS

CBA's particle size and appearance resemble river sand shown in Figure 2.3, making it preferable for use as a fine aggregate (Ramzi et al. 2017). Studies indicate that CBA has an angular, irregular, permeable, and rough texture. Its particle size distribution ranges from fine gravel to fine sand. CBA is brittle and lighter than natural sand, and its specific gravity varies from 1.39 to 2.33. Water absorption could be up to 30% (Baig and Varghese 2019).

The primary CBA and boiler slag constituents are silica, alumina, and iron, including a small amount of calcium, magnesium, sulfate, and other compounds. The chemical properties of CBA/BS depend on the origin of the coal. For example, CBA or BS obtained from Sub-bituminous coal has higher calcium content than bituminous coal (Ahady and Gupta 2016).

Pozzolanic Properties of CBA

A test was conducted by Cheriaf et al. (1999) to see the effect of CBA on hydration reaction by comparing a paste with a similar amount of calcium hydroxide and CBA at different curing ages and checking the strength and calcium hydroxide consumption. CBA accelerates the pozzolanic reaction of concrete after 28 days of curing. CBA does not consume calcium hydroxide at an early age of the hydration reaction. CBA can be used in concrete as the measured strength index indicated. The pozzolanic reaction of CBA/BS is shown in Figure 2.4.

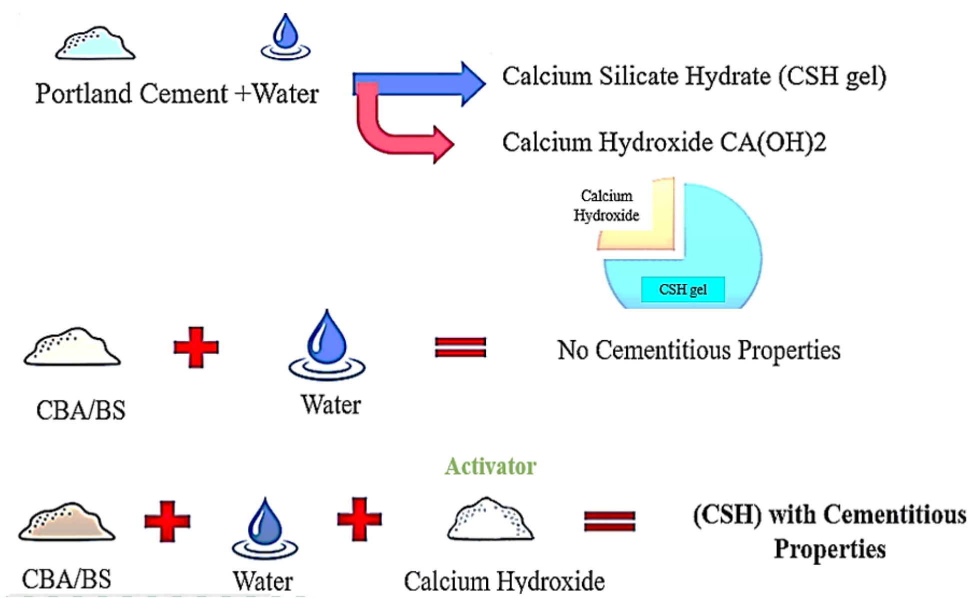

Figure 2.4 Pozzolanic reaction of CBA/BS

Effect of CBA as a Fine Aggregate Replacement on Fresh Property

Determining the fresh properties of a concrete mix includes measuring slump, temperature, air content, and unit weight. Substituting up to 100% of CBA decreases the slump value by up to 100 mm due to the complex shape and rougher surface than the normal aggregate (Kim and Lee 2011). Friction is more significant on a rough surface such as CBA, delaying the flow characteristics of its fresh properties (Lee et al. 2009). CBA's slump value decreases with increasing CBA substitution, from 10% up to 40%; however, replacing CBA by 100% significantly reduces the mix's slump value compared to the control. Therefore, replacing 10% - 40% CBA in concrete allows for better workability (Maliki et al. 2017).

Density and Water Absorption

When substituting fine aggregate with CBA, the unit weight of CBA concrete decreases due to the lower unit weight and higher water absorption capacity of CBA. which leads to the creation of several pores and enormous-sized pores; therefore, the unit weight decreases when the CBA replacement percentage increases (Singh and Siddique 2013).

Effect of CBA as a Fine Aggregate Replacement on Mechanical Property

Compressive Strength

Maliki et al. (2017) substituted fine aggregates with CBA, from 0% as the control to as much as 100% using regular increments of 10%. The results revealed that 60% was the optimum content after 7 and 28 days of curing.

The compressive strength of CBA concrete surpasses the control concrete (Raju et al. 2014). Replacing up to 30% fine aggregate by CBA increases the performance of all the mechanical properties, including split tensile strength and flexural strength, after all, the curing period of up to 90 days; however, CBA concrete compressive strength was not highly affected compared to the modulus of elasticity and flexural strength, which decreased with increased CBA amount (Ramzi et al. 2017). Replacing a durable material with weak materials and the lack of pozzolanic activity by the CBA reduces CBA concrete compressive strength at seven days of curing (Raju et al. 2014).

Flexural Strength

Experiments indicate that the flexural strength of CBA concrete at 28 days of curing does not change; however, after 56 days, the concrete had higher flexural strength than the control sample. These results are not applicable to cement with 25% replacement due to the bottom ash's low activity at an early curing age (Kurama and Kaya 2008).

Split Tensile Strength (STS)

Singh and Siddique (2014) determined that the optimum content of CBA for tensile strength was 50% at 28 days; however, Ramzi et al. (2017) and Maliki et al. (2017) established that the optimal CBA content for tensile strength was 30% and 70% after 7 and 28 days of curing correspondingly.

Modulus of Elasticity (MOE)

Experiments indicate that concrete strength and ductility decrease as CBA content increases in the mix (Lee et al. 2010). Baig and Varghese (2019) established that CBA's low specific gravity compared to sand decreases the MOE. The MOE decreased significantly by substituting 100% fine aggregate with CBA; therefore, using CBA substantially impacts concrete's MOE.

Effect of CBA as a Fine Aggregate Replacement on Durability

Rapid Chloride Penetration Test (RCPT)

Some factors that affect the RCP are the capillary voids' volume and size, the paste's microcracks, the interface between the aggregate, and the pore solution in the concrete. The resistance to CBA's chloride ion penetration after 90 days of curing increases with aging and CBA content in the mix (Singh and Siddique 2014).

CBA concrete has a higher resistance to chloride ion penetration than conventional or regular concrete. An increasing percentage of CBA increases the resistance to chloride ion penetration due to CBA's pozzolanic action and better performance to acid attack compared to regular concrete (Shi-Cong and Chi-Sun 2009).

Nanomaterial and Fly Ash-Based Concrete

Using nanomaterials in a concrete mix accelerates the hydration reaction; therefore, using nanomaterials with fly ash in concrete improves the early age strength problem caused by using fly ash concrete (Reddy et al. 2020).

Fresh and Mechanical Properties of Nanomaterial-Based Concrete

Some of the beneficial effects of nanomaterials include producing high-strength concrete and enhancing the mechanical, durability, and shrinkage properties. The workability of nanoparticle-mixed concrete decreases with a percentage increase in nanoparticle substitution (Vera-Agullo et al. 2009).

Research studies indicate that concrete mixed with nanomaterials, such as concrete mixed with nano silica, has a higher compressive strength than concrete without nano-silica. Activating the hydration reaction and serving as a filler to increase the concrete mix's density leads to a rapid increase in compressive strength in the nano-silica concrete mix (Nasution et al. 2015).

Replacing 1.75% of the cement with nano-TiO_2 particles could allow for obtaining a higher compression and bending strength than conventional cement mortar due to the fast consumption of $Ca(OH)_2$ during the hydration process at an early age of concrete, associated with nano-TiO_2 high reactivity (Salman et al. 2016).

Kumari et al. (2016) demonstrated that a 2% nanoparticle substitution yielded durable concrete in terms of chloride penetration resistance and high pH values. Using nanomaterials in a concrete mix increases the concrete's compressive and split tensile strength. The optimum nanoparticle inclusion is 2%, which creates durable and strong concrete. This percentage is examined in this project with CBA concrete and presented in the results and discussions section.

In this thesis, the effect of nanomaterials on fly ash mixed concrete is included since the effect of nanomaterials on CBA concrete was not available. However, CBA concrete also has a similar early strength problem. Therefore, fly ash mix concrete with nanomaterials can approximate the effect of nanomaterials on CBA concrete, and this project assesses the effect of nanomaterials on CBA concrete strength and performance.

Chapter 3 Methodology

3.1 Introduction

This project replaced fine aggregates with CBA from coal-fired plants and analyzed the CBA content, nanoclay content, and curing periods for optimal use by comparing the compressive strength to the control. After obtaining the optimum CBA content, fresh properties, mechanical properties, and durability test results were compared to the control. Three samples were tested in each testing parameters category to ensure sufficient data were obtained for analysis.

3.2 Experimental Plan

The experimental plan includes the preparation and testing of three broad concrete test categories: (1) Ordinary Portland cement-based concrete as the control, (2) CBA and BS-based Concrete, and (3) CBA and nanoclay-based concrete. CBA/BS content has increased at a 10% rate to reach the optimum threshold. The nanoclay content, measured as a percentage by weight of cement, was tested from the 0.5% initial value by increasing 0.5% until the optimal content was reached, equivalent to or better than the control value obtained. The experimental plan is shown in Figure 3.1.

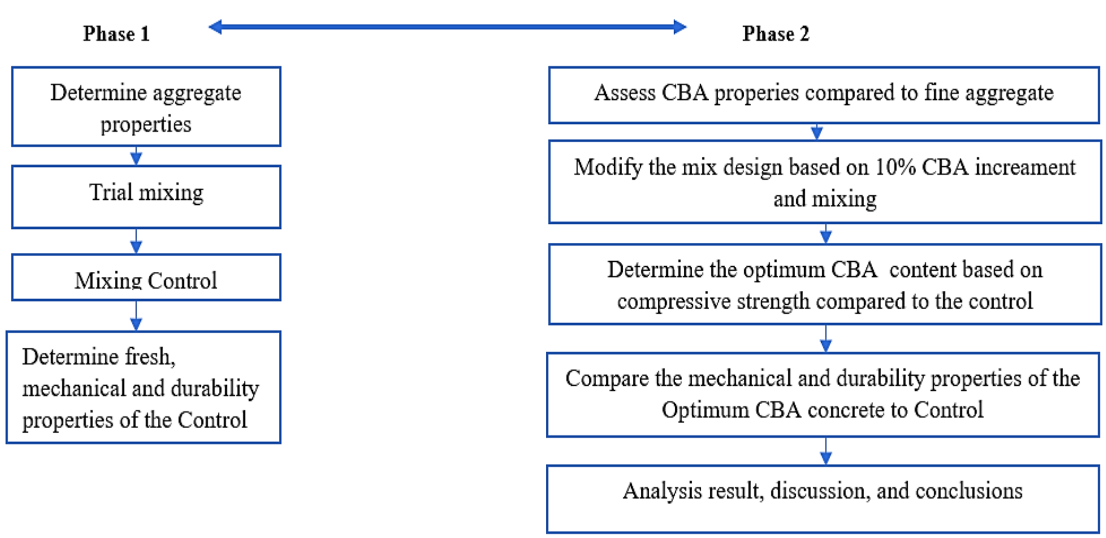

Figure 3.1 Project experimental plan

3.3 Material Source and Properties

The fine and coarse aggregates used in this research were donated by Strata Corporation, Aggregate Industries (AI), and Kost in Grand Forks, North Dakota. Therefore, the research was conducted on three projects: Strata aggregate, Aggregate Industries (AI), and Kost aggregate. The suppliers and the research team determined the aggregate properties for comparison before batching. Ingredient properties were determined based on AASHTO and ASTM standards listed in Table 3.1. Table 3.2 shows no significant difference between the results of the supplier and the research team.

Table 3.1 Standards used to determine aggregate properties

Aggregate properties	Standard
Sieve analysis of Coarse and fine aggregate	AASHTO T 27-20
Specific gravity and absorption of fine aggregate	AASHTO T 84-13 (2017)
Specific gravity and absorption of coarse aggregate	AASHTO T 85-14(2018)
Moisture content	AASHTO T 255
Fineness modulus of aggregate	ASTM C136
Bulks density (unit weight) and void in aggregate	AASHTO T19 M/19

Table 3.2 Comparison of the experimental and suppliers' aggregate properties

Aggregate properties (Strata)	Coarse Aggregates		Fine Aggregates	
	Lab	Strata	Lab	Strata
Bulk Oven Dry	2.60	2.66	2.62	2.66
Surface saturated dry	2.63	2.69	2.64	2.67
Absorption %	0.91	0.91	0.36	0.36
Fineness Modulus	N/A	N/A	2.85	2.86
Aggregate properties (Kost)	Coarse Aggregates		Fine Aggregates	
	Lab	Kost	Lab	Kost
Bulk oven dry	2.64	2.69	2.64	2.67

Surface saturated dry	2.67	2.71	2.65	2.68
Absorption %	0.86	0.86	0.38	0.36
Fineness Modulus	N/A	N/A	2.74	2.86
Aggregate Properties (AI)	Coarse Aggregate		Fine Aggregate	
	Lab	AI	Lab	AI
Bulk oven dry	2.63	2.69	2.64	2.66
Surface saturated dry	2.66	2.76	2.66	2.67
Absorption %	0.86	0.86	0.54	0.56
Fineness Modulus	N/A	N/A	2.90	2.5

CBA/BS

CBA/BS was supplied by Leland Olds power plant (Basin Electric), Milton R. Young power plant (Minnkota), Coal Creek station (Great River Energy), and Coyote station (Ottertail). Therefore, four suppliers have provided two types of CBA, from Great River and Leland, and the other two, BS from Minnkota and Ottertail. From those four, two (Great River (CBA) & Minnkota (BS) were assessed with three control projects and presented in this thesis.

CBA, BS, and fine aggregate properties were tested and presented in Table 3.3 for comparison. The CBA's fineness modulus value was closer to the fine aggregate; however, the CBA's absorption capacity was higher than the fine aggregate and BS. The mix design considered moisture correction calculations while substituting fine aggregate with CBA and BS. The specific gravity of CBA was lower than fine aggregate and BS.

Strata and Kost has both the same fine aggregate, as shown in Table 3.3 but different coarse aggregate.

Table 3.3 Comparison of CBA, BS, and fine aggregate properties

Specific gravity (AASHTO T84)	CBA (GRE)	BS (Minnkota)	BS (Ottertail)	CBA (Leland)	Fine aggregate (Strata and Kost)	Fine aggregate (AI)
Bulk oven dry	2.23	2.68	2.89	2.11	2.66	2.65
Surface saturated dry	2.26	2.70	2.88	2.17	2.67	2.67
Absorption %	2.31	0.18	0.68	5.53	0.36	0.56
Fineness modulus	2.75	2.52	2.65	2.91	2.86	2.5

Chemical Properties of CBA and BS

The primary constituents of both CBA and BS are silica, alumina, and iron, including a small amount of calcium, magnesium, sulfate, and other compounds shown in Table 3.4. Both CBA and BS have almost similar chemical properties. Silica, alumina, and iron are the same chemical properties in cement clinker. Therefore, the silicates in the CBA react with calcium hydroxide and form C-S-H, the main strength-gaining component in concrete. The more the C-S-H, the more the concrete gain strength over time.

Table 3.4 Chemical properties of CBA and BS

Constituents Percentage by weight (%)	CBA (GRE)	BS (Minnkota)	BS (Ottertail)	CBA (Leland)
SiO2	51.87	47.9	35.96	36.61
Al2O3	13.98	14.87	13.97	13.34
Fe2O3	7.20	12.55	15.01	14.54
Sum of Oxides	**73.06**	**75.32**	**64.95**	**64.5**
TiO2	0.62	0.62	0.6	0.58
Cao	15.05	12.34	18.80	20.06
MgO	4.63	4.48	5.35	6.26
SO3	0.66	0.21	0.31	2.66

Na2o	1.83	3.33	5.67	2.09
K2O	1.7	1.71	0.61	0.85
P2O5	0.2	0.09	0.17	0.27
Tio2	0.62	0.62	0.6	0.58
Total	97.73	98.09	96.47	97.26
SrO	0.31	0.29	0.58	0.46
Bao	0.39	0.53	1.28	0.97
Sum	98.43	98.91	98.32	98.69

Gradation of Coarse Aggregate, Fine Aggregate, and CBA/BS

The other aggregate property that was determined using AASHTO T27-20 was gradation. The results of the gradation of the fine aggregate versus CBA/ BS and coarse aggregate were presented in Figure 3.2 and Figure 3.3.

Both fine aggregate and CBA/BS were oven dried for 24 hrs. and cooled down before use in the concrete mix. CBA was sieved through a 4.75mm sieve to remove coarser particles throughout the project. The fine aggregates, CBA, and BS gradation crosses one another, as shown in Figure3.2. The coarse aggregate gradation is shown in Figure 3.3. Both fine and coarse aggregates are well-graded.

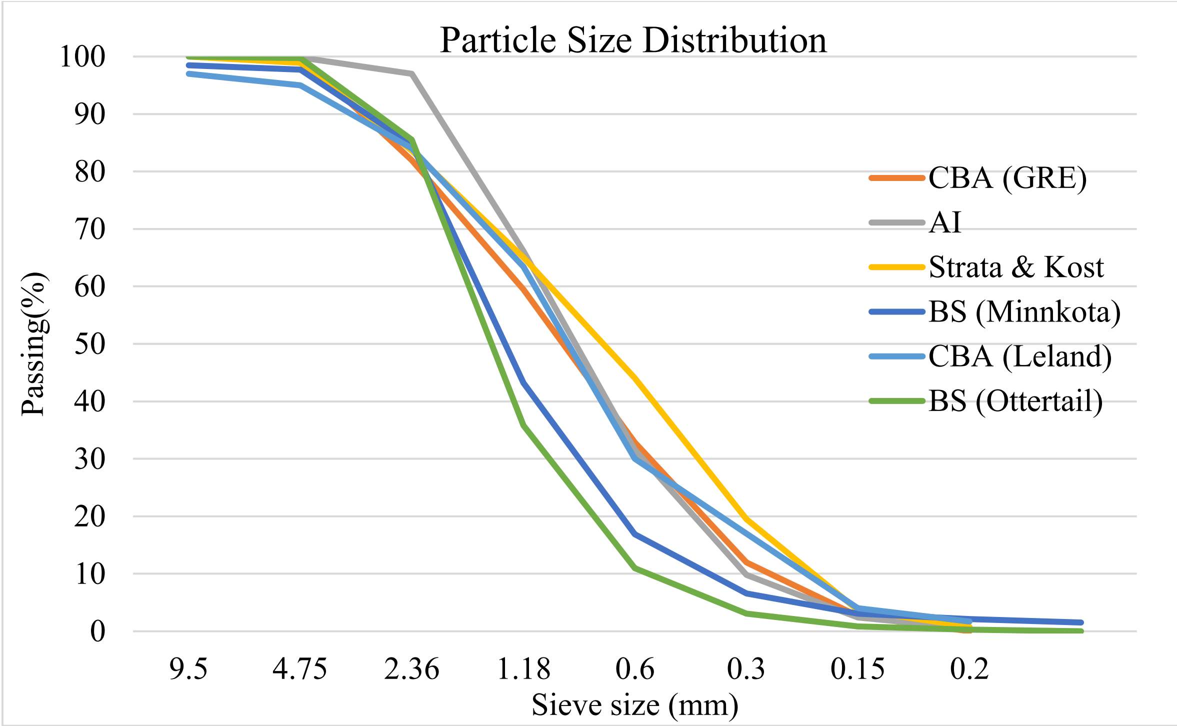

Figure 3.2 Fine aggregates vs. CBA/ BS particle size distribution

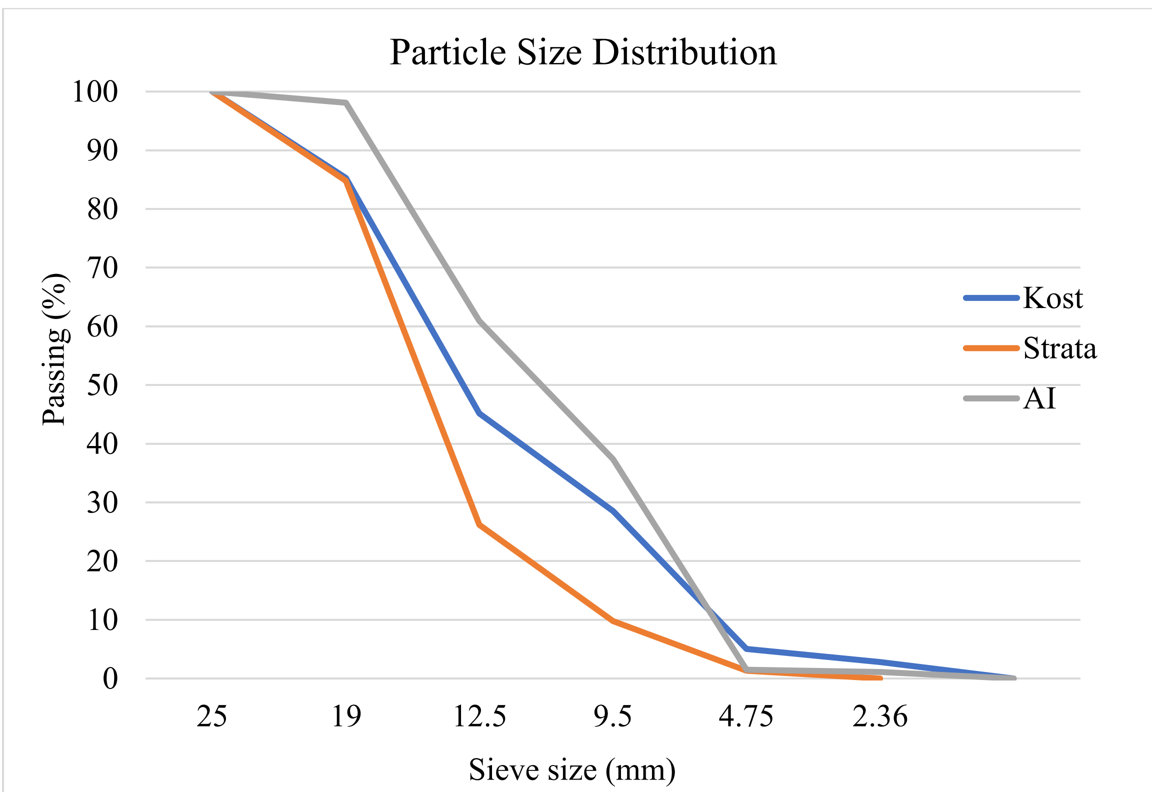

Figure 3.3 Strata, Kost, and AI coarse aggregate particle size distribution

Nanoclay

Nanoclay is primarily composed of Cao (20–30 wt.%), SiO_2 (30–40 wt.%), and Al_2O_3 (10–15 wt.%) with traces of other compounds like Fe_2O_3. Nanoclay enhances the concrete's mechanical properties at an early age by activating the hydration reaction and serving as a filler to increase the concrete mix's density, leading to a rapid increase in compressive strength (Saloma et al. 2015). The same analogy might help CBA concrete initiate early strength as CBA pozzolanic properties start reacting later. Therefore, in this project, nanoclay was used to analyze the concrete's performance after finding the optimum value of the replaced CBA in Concrete.

Air Entraining

The air content was measured using the Super Air Meter (SAM) method immediately after concrete mix completion. Entrained air significantly increases the concrete's durability; however, strength decreases as air content increases. Therefore, it is preferable to adjust the entrained content to obtain the desired air content. The desired air content was 5% to 7%, which increased durability without sacrificing strength, and AEA-92 air entrained was used in this project to achieve the desired air content.

Water Reducer and High Range Water Reducer (Superplasticizer)

Concrete workability is very important during the mixing and placing of concrete. This project used a water reducer and high-range plasticizer to maintain the desired slump value of 3 to 4 inches. Water reducer EUCON WR-91 was supplied by AI and used to increase the workability of the CBA mix. However, the increasing workability of this water reducer was insufficient due to CBA's high water absorption capacity. Therefore, the research team decided to use high range water reduce/ superplasticizer EUCON SPJ that enables concrete to be produced with very low water-to-cement ratios and obtain up to 45% water reduction that was needed for CBA.

3.4 Mix Design and Proportions

The mix design for this project was obtained from Strata and Aggregate Industries (AI), and the research team prepared the third mix for the Kost project. The control mix proportion is listed in Table 3.5, Table 3.6 and Table 3.7. The proportion was modified based on various mix types. For example, CBA replaced a percentage of fine aggregate, and nanoclay replaced a percentage of cement in the mix. The designed mix had a compressive strength of 4,000 psi and a W/C of 0.45 for both Strata and AI. The project design mix Kost had a compressive strength of 3,000 psi with a W/C of 0.42.

The expected slump values ranged from 3" to 4" based on the mix design. All aggregate and CBA used in the experiment were oven-dried or had the least moisture content to keep constant material properties. A moisture correction method was used in the mix design to consider the amount of water loss in the aggregate, including the equivalent volume method for the CBA weight-obtaining method.

The mix design's air-entrained value was 6% for the control mixes Strata and AI; however, after many trial batches, the content of the air-entrained value was extremely high, up to 12 %. Consequently, the project team decided to reduce the amount of air entrained to 3.25 ml/ft^3 to obtain a desirable air-entrained value of 5%-7% for both Strata and AI projects. This is because the supplier's design mix was based on fly ash, and fly ash was not used in this project. This discrepancy made it difficult to maintain an air content and slump value. However, the Kost project's air content was in the range of 6%-8% without any air entraining reduction, as the project team designed it.

Table 3.5 Strata control and % CBA concrete mix design proportion

Strata Mix design								
	Control	10% CBA	20% CBA	30% CBA	40% CBA	50% CBA	60% CBA	70%CBA
Material	Weight lbs /CY	Weight lbs /CY	Weight lbs /CY	Weight lbs /CY	Weight lbs /CY	Weight lbs /CY	Weight lbs /CY	Weight lbs /CY
Cement	564	564	564	564	564	564	564	564
Coarse aggregate # 1	1,640	1,640	1,640	1,640	1,640	1,640	1,640	1640
Coarse aggregate # 2	125	125	125	125	125	125	125	125
Fine aggregate	1,380	1,242	1,104	966	828	690	552	414
CBA (GRE)	-	114.00	228.00	342.00	456.00	570.00	684.00	798.00
CBS (Minnkota)	-	138.72	277.45	416.17	554.90	693.62	832.34	971.07
CBA (LeLand)	-	109.50	219.00	328.50	438.00	547.50	657.00	766.50
CBS (Ottertail)	-	149.22	298.45	447.67	596.90	746.12	895.34	1044.57
Water	237.4	237.4	237.4	237.4	237.4	237.4	237.4	237.4
Air content(ml/ft3)	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25
Expected Air content (%)	5-7	5-7	5-7	5-7	5-7	5-7	5-7	5-7
W/C	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45

Table 3.6 AI Control and % CBA concrete mix design proportion

AI Mix design								
	Control	10% CBA	20% CBA	30% CBA	40% CBA	50% CBA	60% CBA	70% CBA
Material	Weight lbs /CY	Weight lbs /CY	Weight lbs /CY	Weight lbs /CY	Weight lbs /CY	Weight lbs /CY	Weight lbs /CY	Weight lbs /CY
Cement	564	564	564	564	564	564	564	564
Coarse aggregate	1767	1767	1767	1767	1767	1767	1767	1767
Fine aggregate	1338.00	1204.20	1070.40	936.60	802.80	669.00	535.20	401.40
CBA (GRE)	-	111.02	222.04	333.06	444.08	555.11	666.13	777.15
CBS (Minnkota)	-	135.16	270.32	405.48	540.64	675.80	810.96	946.12
CBA (LeLand)	-	106.69	213.37	320.06	426.75	533.44	640.12	746.81
CBS (Ottertail)	-	145.39	290.78	436.17	581.56	726.95	872.35	1017.74
Water	254	254	254	254	254	254	254	254
Air content(ml/ft3)	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Water Reducer(ml/ft3)	18.53	18.53	18.53	18.53	18.53	18.53	18.53	18.53
Expected Air content (%)	6-8	6-8	6-8	6-8	6-8	6-8	6-8	6-8
W/C	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45

Table 3.7 Kost Control and % CBA concrete mix design proportion

Kost Mix design								
	Control	10% CBA	20% CBA	30% CBA	40% CBA	50% CBA	60% CBA	70% CBA
Material	Weight lbs /CY	Weight lbs /CY	Weight lbs /CY	Weight lbs /CY	Weight lbs /CY	Weight lbs /CY	Weight lbs /CY	Weight lbs /CY
Cement	619.04	619.04	619.04	619.04	619.04	619.04	619.04	619.04
Coarse aggregate	1909.44	1909.44	1909.44	1909.44	1909.44	1909.44	1909.44	1909.44
Fine aggregate	982.25	884.03	785.80	687.58	589.35	491.13	392.90	294.68
CBA (GRE)	-	81.11	162.21	243.32	324.42	405.53	486.63	567.74
CBS (Minnkota)	-	98.74	197.48	296.22	394.96	493.70	592.44	691.18
CBA (LeLand)	-	77.94	155.88	233.82	311.76	389.70	467.64	545.58
CBS (Ottertail)	-	106.21	212.43	318.64	424.86	531.07	637.28	743.50
Water	260	260	260	260	260	260	260	260
Air content(ml/ft3)	6.78	6.78	6.78	6.78	6.78	6.78	6.78	6.78
Expected Air content (%)	6-8	6-8	6-8	6-8	6-8	6-8	6-8	6-8
W/C	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42

3.5 Testing Procedures

Fresh Properties

The fresh properties were measured immediately after mixing, including air content, slump value, and unit weight shown in Figure 3.4. An air-entraining admixture was used to obtain the desired air content for the concrete's freeze-thaw resistance. The Super Air Meter (SAM) pressure method was used to measure the mix's air content following AASHTO TP 118-17. The slump was measured according to AASHTO T 119M, and the fresh concrete's density was measured and calculated following AASHTO T 121M.

The SAM number correlates with the ASTM C 457 spacing factor. A SAM Number of 0.2 psi and lower correlated best with a spacing factor of 0.008 inches and lower. Based on ACI 201 recommendation, a SAM number of 0.2 psi or below indicates satisfactory air void size distribution in the concrete mix in this research.

Figure 3.4 SAM number and air content (left), slump value (middle), and unit weight (right)

Mechanical Properties

Compressive Strength

The compressive strength of concrete is the ability to withstand the applied load that tends to crash or compress it. A 4 inches diameter by 12 inches height cylinder was used to test the compressive strength of the concrete following the AASHTO T-22 standard using the

Universal Testing Machine, as shown in Figure 3.5. The compressive strength was the main parameter used to determine the optimum content of CBA in this project.

Figure 3.5 Compressive strength test

Split Tensile Strength

The concrete's tensile strength is approximately 10-12% of its compressive strength. Tensile strength allows greater bending before breaking and can minimize the concrete's cracking potential. The average split tensile strength of the project control mix was determined using AASHTO T 198-15, as shown in Figure 3.6. An average of three tests per sample were taken.

Figure 3.6 Split tensile strength

Flexural Strength

Flexural strength is important to measure a material's brittleness and bending resistance, especially concrete pavement. It is determined using a third-point loading beam sample. The findings are calculated and reported as modulus of rupture in psi. The test was conducted following AASHTO T 97-8 standards using the universal testing machine illustrated in Figure 3.7.

Figure 3.7 Flexural strength test

Measuring the Specimen and Calculating the Modulus of Rupture

Steps to calculate the modulus of rupture include: measuring the width and depth of the specimen as it is oriented for testing, taking one measurement at each edge and one at the center of the beam, determining the average width and depth, and calculating the modulus of rupture based on Equation 1.

$$R = \frac{PL}{bd^2} \qquad (1)$$

where:

R = modulus of rupture (psi)

P = maximum applied load indicated by the testing machine (lb)

L = span length (in.)

b = average width of specimen at the fracture (in.)

d = average depth of specimen at the fracture (in.)

Modulus of Elasticity (MOE)

One of the most important characteristics of concrete is MOE because it indicates the ability of the materials to resist deformation under applied load. The MOE was obtained using the universal testing machine according to ASTM C469, as shown in Figure 3.8.

Figure 3.8 Modulus of elasticity test

Concrete Durability

Rapid Chloride Permeability Test (RCPT)

The RCPT was used to examine the influence of internal curing agents on the concrete's chloride-permeability characteristics, measure the concrete samples' electrical conductivity, and reveal the resistance to chloride ion penetration. A four-inch diameter cylinder was cut to a length of two inches after 28 and 56 days of curing, then kept in a vacuum chamber for three hours to remove air from the concrete, followed by submersion in water for one hour in the vacuum chamber. The sample was immersed in water for another 18 hours before testing, according to ASTM C1202. The two-inch concrete was placed between two test cells filled with 3% NaCl and 0.3M NaOH, clamped with bolts to avoid leakage, as shown in Figure 3.9. The test ran for six hours before measuring the electric charge passing across the concrete in Coulombs. The passing charge has five levels, as shown in Table 3.8.

Figure 3.9 Rapid chloride penetration testing

Table 3.8 Chloride iron penetration based on charge passing

Charge passed Coulombs (C)	Chloride ion Penetration
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very low
<100	Negligible

Summary

The project team has investigated the control mix mechanical and durability properties and compared it to the bottom ash replaced at 10%, 20%, 30%, 40%, 50%, 60%, 70%, and 80%. The tested mechanical properties include compressive strength, flexural strength, modulus of elasticity, and splitting tensile tests. Cylindrical and beam specimens were created and tested according to their respective AASHTO and ASTM methods after determining the ingredient properties and mixing the design. The project's next steps were mixing, compacting, curing, and testing the concert based on the standards listed in Table 3.9 and Table 3.10 to establish fresh properties, mechanical properties, and concrete durability and compare to control and discuss the findings in chapter 4.

Table 3.9 Concrete mixing, curing, and compacting standards

Concrete Mixing, Curing, and Compacting	Standards
Mixing concrete	ASTM C-192-7
Concrete consolidation	ASTM C138
Molding for forming test cylinder	AASHTO M205M
Capping cylindrical specimens	AASHTO T 231
Concrete making and curing in the Lab.	AASHTO R 39

Table 3.10 Properties, curing period, equipment, and standards for concrete testing

Property		Curing Period (days)	Equipment	Standards
Fresh Properties	Slump	0	Slump content	AASHTO T 119M/T
	Unit weight		Super air meter	AASHTO T 121M
	Air content			AASHTO TP 118-17
Mechanical Properties	Compressive strength	7, 28, 56, 90	Universal testing machine	AASHTO T 22MT
	Flexural strength			AASHTO T 97-8
	Splitting tensile strength			AASHTO T 198
	Modulus of elasticity			ASTM C469
Durability	Chloride penetration		Rapid chloride penetration	ASTM C1202

Table 3.11 shows the overall summary of tests. The three projects' Strata, Kost, and AI mixed with CBA (Great River), including three optimum content mechanical and durability properties,

are included in the summary. Conversely, BS was mixed with both Kost and Strata projects. Its optimum content was determined, including its effects on the mechanical and durability properties of the Kost project BS optimum content.

Table 3.11 Overall summary of tests

Control	CBA/BS	Determined Optimum content	Mechanical properties	Durability test
Strata	Great river (CBA)	✓	✓	✓
	Minnkota (BS)	✓		
Kost	Great river (CBA)	✓	✓	✓
	Minnkota (BS)	✓	✓	✓
AI	Great river (CBA)	✓	✓	✓
	Nano clay (CBA)	✓		

Chapter 4 Results and Discussions

4.1 Introduction

This chapter covers the relationship between the control, Strata, Kost, and AI with respect to CBA and BS compressive strength to determine the optimum CBA/BS content. After obtaining the optimum CBA content, the mechanical and durability properties of the CBA concrete were compared to the control concrete.

4.2 Strata Project

Fresh Properties

Concrete's fresh properties are slump, air content, and unit weight. The desired slump and air content are the two controlled variables chosen for the mix design. However, it was difficult to maintain the same slump and air content in CBA concrete.

Slump

Concrete slump depends on mixer size, air entrainment, and material moisture content. An acceptable slump value range is 3 to 4.5 inches for this project but based on the substituted CBA, and there was a variable slump value due to the higher water demand of CBA. CBA is porous and has a high-water absorption capacity. The workability of the CBA-based concrete mix decreased as CBA content increased. For example, the slump value of the concrete mix decreased with an increased CBA content from 10% to 50%. A slump value of 0.75 inches for 30% CBA concrete mix significantly decreased the mix's workability and further increased CBA content, yielding a 0-inch slump value. Therefore, the research team used a water reducer to increase the mix's workability as the CBA content increased 20ml/ft^3, 35 ml/ft^3, and 60 ml/ ft^3 of the water reducer was used to obtain 0.7-inch, 2.5-inch, and 2-inch slump values for the 40%, 50%, and 60% CBA replacement values, respectively. However, further increasing to 70%CBA concrete with 75ml/ft^3

leads to a zero-slump value, which is unacceptable. Therefore, the research team has decided to use a high-range water reducer to obtain the desired workability and air contents.

The slump value decreased with increased %CBA until it reached the optimum content 50%CBA, possibly due to CBA's high-water demand (Figure 4.1**)**.

Air Content

The air content decreased with increased CBA content compared to the control and increased compressive strength until the optimum content of 50% CBA was achieved. The increased air content decreased compressive strength after 50%CBA. The air content and the slump value have a trend shown in Figure 4.1. When the air content decreases, the slump decreases up to 40% CBA replacement, leading to higher air content and slump value for the optimum content of 50% CBA. This might be due to the high-water absorption capacity of CBA and the water reducer used to increase workability, which led to increasing unit weight, decreasing slump value, and air content.

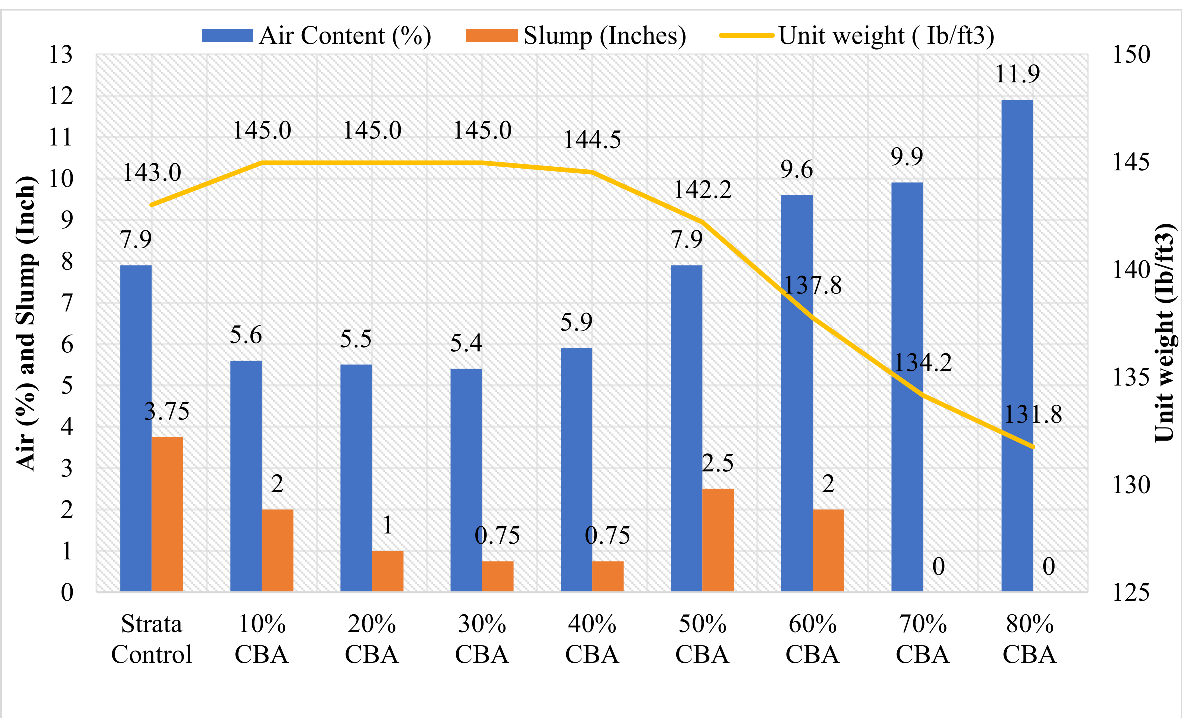

Figure 4.1 Air content, slump, and unit weight of Strata CBA concrete

SAM (Super Air Meter) Number

The SAM number for the % CBA mix was higher than the control, possibly due to CBA's porous behavior as the amount was increased. The air content of % CBA concrete decreased with an increase in CBA content up to 40% (Table 4.1), which may have been caused by the spacing factor of the voids in the mix and CBA's porous behavior.

Table 4.1 Fresh properties of Strata control and % CBA concrete

Fresh properties	Strata Control	10 % CBA	20 % CBA	30% CBA	40% CBA	50% CBA	60% CBA	70% CBA	80% CBA
SAM Number (psi)	0.21	0.37	0.48	0.42	0.5	0.39	0.42	0.63	N/A
Measured slump (inch)	3.75	2	1	0.75	0.75	2.5	2	0	0
Measured Air Content (%)	7.4	5.6	5.5	5.4	5.9	7.9	9.6	9.9	11.9
Unit Weight (lb /ft^3)	143	144.9	144.9	144.9	144.5	142.6	137.8	134.2	131.7
Water reducer (ml/ft^3)	N/A	N/A	N/A	N/A	20	35	60	75	90

Note: N/A-not applicable

Unit Weight

The 50% CBA replacement had a slightly lower unit weight than the Strata control. However, the rest of the CBA-containing concrete had a higher unit weight than the control, up to 40%, possibly due to CBA's fineness properties. Increasing the % of CBA decreased the unit weight of the concrete, possibly due to CBA's higher water demand, which led to pore formation and larger pore sizes. 50% CBA has a slightly lower unit weight than the control, which is lightweight concrete compared to concrete without CBA (Figure 4.2**).**

The unit weight and the compressive strength of the CBA concrete started declining after 40% CBA replacement, as shown in Figure 4.2**.** This might be due to CBA's higher water demand, which led to larger pore size formation and weaker concrete.

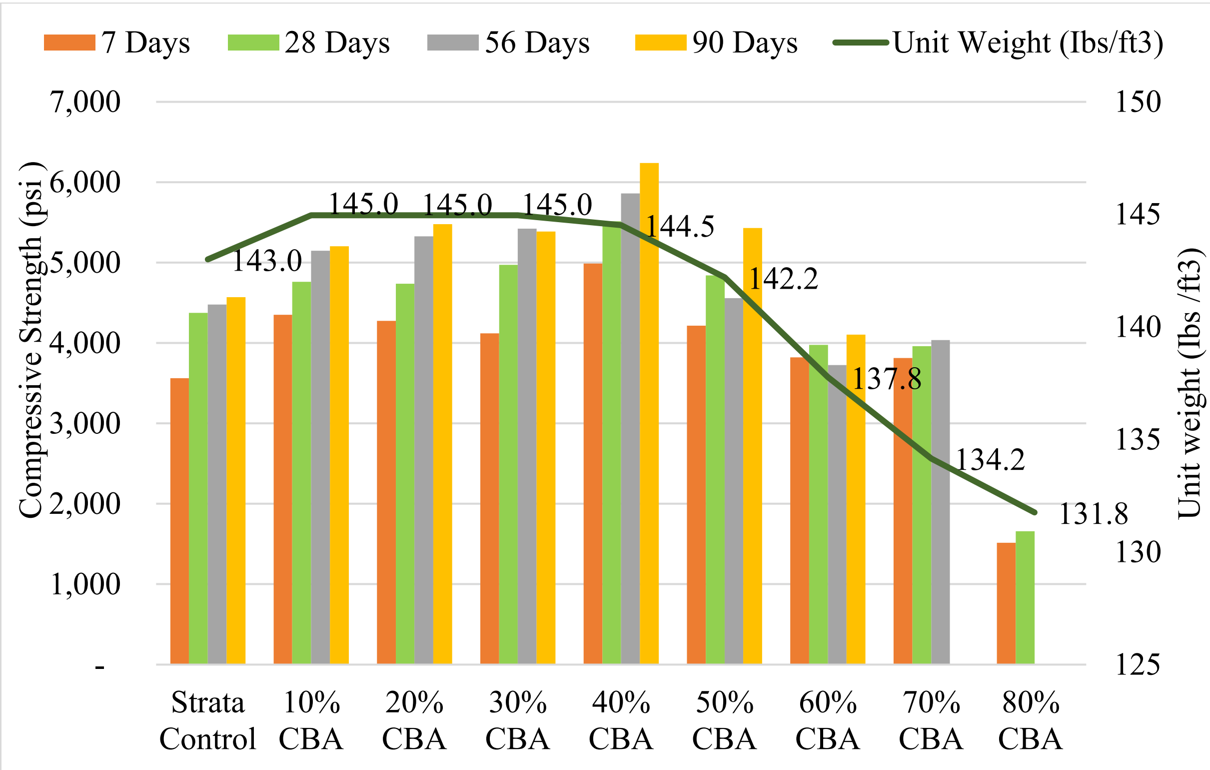

Figure 4.2 Compressive strength of Strata project control and %CBA vs. unit weight

Mechanical Properties

Compressive Strength

This study aimed to obtain the optimal amount of CBA that could replace fine aggregate by comparing compressive strength to the control (without CBA). Compressive strength was selected since it is the most widely used strength to determine the quality of concrete.

The compressive strength of the Strata mix design was 4,000psi. The compressive strengths were 3,600 psi after seven days, 4,374 psi after 28 days, 4,736 psi after 56 days, and 4,571 psi after 90 days for the control, as shown in Table 4.2. The numbers are an average of three tests per curing time. The optimum CBA content for the Strata project after 90 days of curing is 50% CBA, as shown in Table 4.2.

Table 4.2 Compressive strength (psi) of Strata control and %CBA concrete

Curing time	Strata Control	10 % CBA	20 % CBA	30% CBA	40% CBA	50% CBA	60% CBA	70% CBA	80% CBA
7 Days	3,600	4,351	4,276	4,119	4,988	4,216	3,823	3,815	1,517
28 Days	4,374	4,763	4,736	4,971	5,514	4,842	3,979	3,961	1,660
56 Days	4,477	5,148	5,328	5,423	5,859	4,560	3,726	4,036	
90 Days	4,570	5,205	5,477	5,388	6,241	5,431	4,645		

The CBA concrete gains strength after 28 days of curing due to its pozzolanic reaction that occurs at a later age. Therefore, Table 4.2 shows that almost all CBA % concrete gains strength over time up to the optimum content, but CBA concrete after the optimum content, especially at 80% CBA replacement, does not set properly.

The 10% CBA replacement values after seven days of curing were similar to the control's strength after 28 days. The compressive strength started decreasing slightly when the CBA replacement was increased from 10% to 30%. However, it still has higher compressive strength than the control after ninety days of curing. The slump and the air content decreased and increased with the same pattern with increased compressive strength due to CBA's high-water demand (Figure 4.3).

The research team used a water reducer after 30% CBA replacement to achieve the desired workability. The compressive strength decreased from 40%, and 50 % of CBA replacements reached an optimum content of 50% at all curing periods (Figure 4.3). The increasing compressive strength from 30% to 40% and 50% is possibly due to adding water reducer effect. The research team created another mix of 30% CBA without a water reducer to determine the water reducer's effect on the CBA concrete's compressive strength. The results indicated that 30% CBA concrete with a water reducer had a compressive strength of 4,521 psi compared to 30% CBA without a water reducer at 4,119 psi. These results must be researched further to conclude if CBA with a water reducer yields a higher compressive strength.

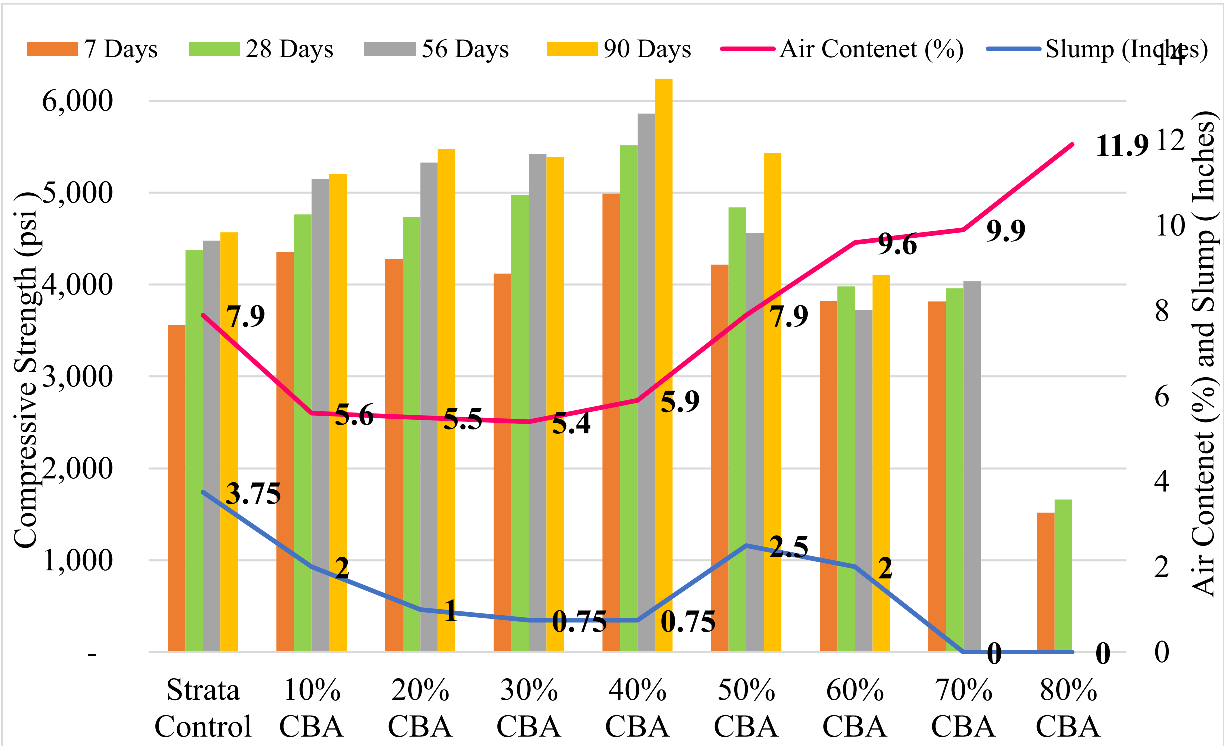

Figure 4.3 Compressive strength of Strata project control and %CBA vs. slump and air content

Comparisons of the compressive strength of the control to the CBA concrete after 28 days revealed that increasing the CBA percentage in the mix yields an increase in concrete strength up to 40% CBA concrete. Then, the values began to decline after 50%, as shown in Figure 4.3. The 40% CBA and 50% replaced mix yielded a 20.6% and 12.3 % increase in compressive strength, respectively, after 28 days of curing. The 30% CBA concrete mix's performance surpassed the control by 697 psi after 56 days, or an increase of 12.86%, indicating that the CBA concrete mix's strength increases with time due to its pozzolanic property.

The compressive strength of the CBA concrete was higher than that of Strata control concrete at all curing periods, 7, 28, 56, and 90 days. The result indicates that this replacement technique yielded acceptable results, and the mix exhibited better performance, as shown in Figure 4.3.

Splitting Tensile Strength of Strata Project at Optimum CBA Content

The tensile strength of the concrete was roughly 10-12% of the compressive strength of normal-weight concrete. The strata project's average split tensile strength was 211 psi, 443 psi, 456 psi, and 430 psi for 7, 28, 56, and 90 days of curing, respectively. At 7 days, the result was lower than the average range, which should be 10% of the compressive strength or 360 psi. However, afterward, it became in the range of 10-12% of the compressive strength of the control Strata control. Figure 4.4 shows the stated results, including the optimum content of 50% CBA split tensile strength for comparison. The optimum content CBA has higher split tensile strength than the Strata control after 7 days of curing. Nevertheless, lower tensile strength was obtained after 28 days, as shown in Figure 4.4. The tensile strength of CBA concrete is expected to be higher than the control after 28 days of curing due to the pozzolanic properties of CBA that increase the quality of the paste, which increases the split tensile strength of CBA concrete.

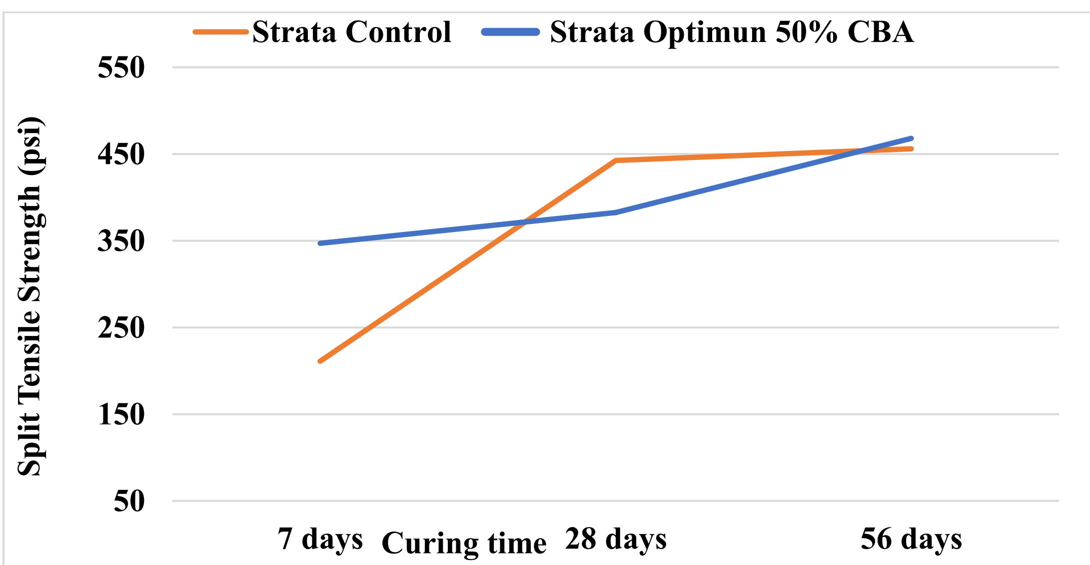

Figure 4.4 Tensile strength of Strata project at optimum CBA content vs. Strata control

Flexural Strength of Strata Project at Optimum CBA Content

The control flexural strength is 581 psi, 792 psi, 754 psi, and 691 psi for 7 days, 28 days, 56 days, and 90 days of curing, respectively. As expected, these results range from 10-20% of the concrete's compressive strength. The optimum content of 50% CBA concrete has a higher flexural strength than the Strata control. The result is favorable regarding the bending resistance of concrete using CBA after 28 days of curing (Figure 4.5).

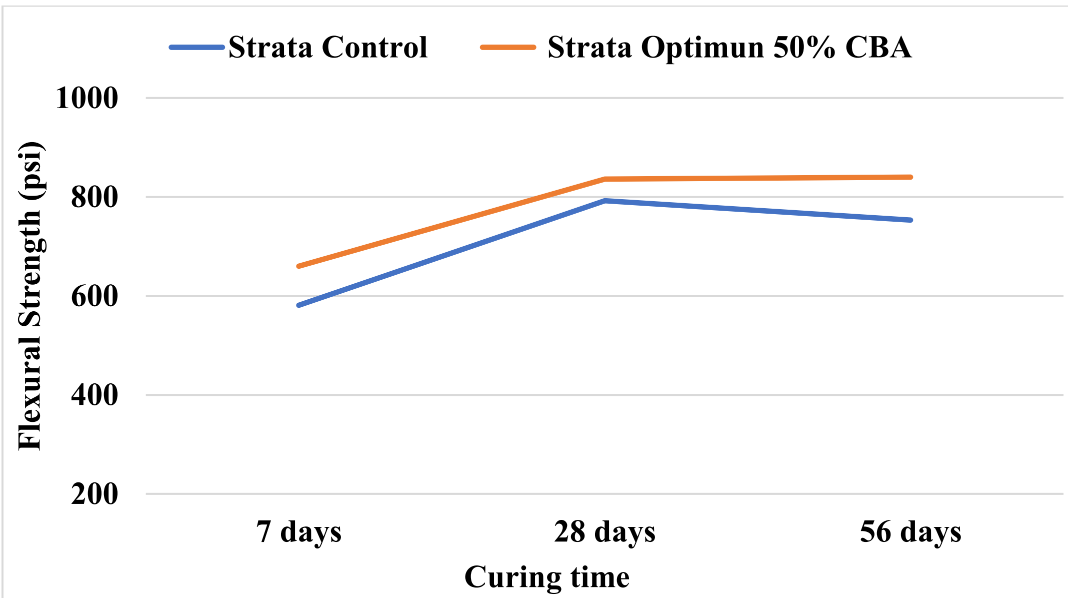

Figure 4.5 Flexural strength of Strata project at optimum CBA content vs. Strata control

Modulus of Elasticity (MOE) of Strata Project at Optimum CBA Content

The MOE obtained for the strata control mix was 4,185ksi, 4,732 ksi, 4,691 ksi, and 4,784 ksi for 7, 28, 56, and 90 days of curing, respectively, as shown in Figure 4.6 based on ASTM C469. The results were within the MOE expected range. The MOE of Strata optimum CBA concrete is higher than the Strata control, as shown in Figure 4.6, after 28 days of curing. This indicates that CBA concrete had a higher ability to resist deformation than conventional concrete.

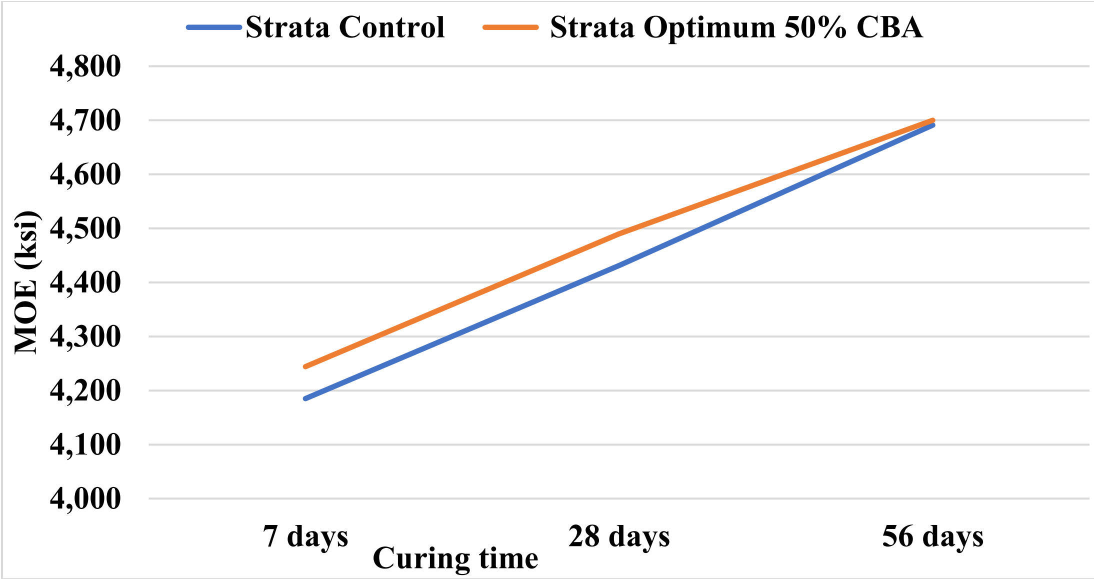

Figure 4.6 MOE of Strata project at optimum CBA content vs. Strata control

CBA particles are denser and less stiff than fine aggregate. Replacing fine aggregate with CBA results in a weak and porous paste that decreases the MOE of CBA concrete. Applying chemical admixtures improves the concrete's MOE because of the lower water-to-cement ratio, which might be why the optimum content has a relatively higher MOE than the control due to the superplasticizer.

Durability of Concrete

Rapid Chloride Permeability of Strata Project at Optimum CBA Content

The average value obtained for Strata control was 4,569 C after 28 days and 3,405 C after 56 days, and 1927 C after 90 days of curing, considering that 4,000 C and above is a higher chloride permeability value for concrete. The results show decreasing permeability over time, probably due to the strength gain of concrete through time, and it becomes less permeable. CBA concrete has low chloride permeability compared to the control after 28 days of curing or 55 % lower than the control chloride permeability, as shown in Figure 4.7. CBA is less permeable than conventional concrete and has less chloride ion penetration, possibly due to the bonding between the aggregate and the pozzolanic property of CBA.

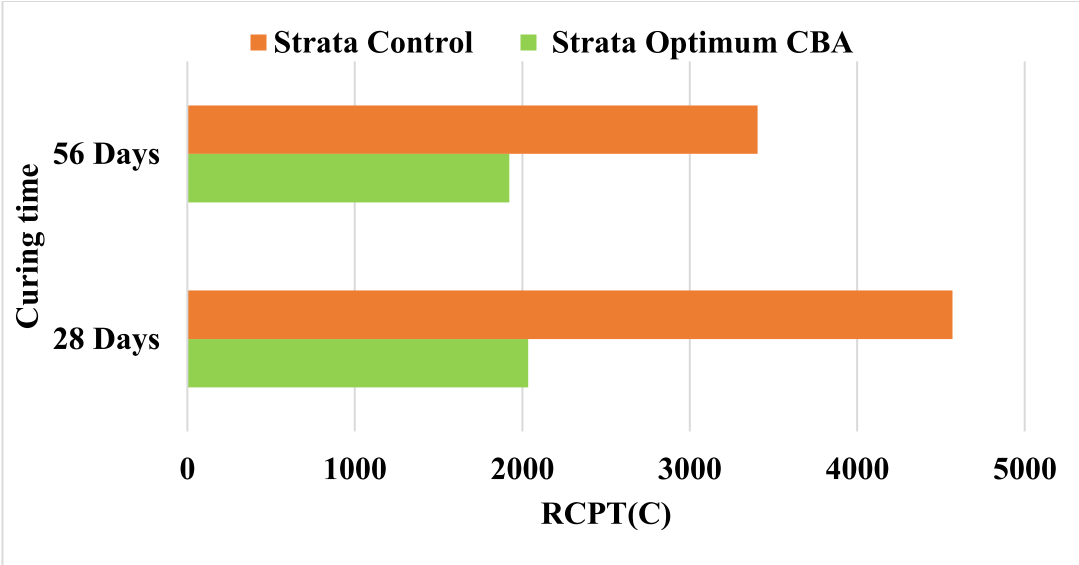

Figure 4.7 RCPT of Strata project at optimum CBA content vs. Strata control

4.3 Strata Project at Optimum BS Content

Boiler slag and bottom ash are by-products of power plant stations with different steps and similar properties, as explained in the literature review part of this thesis and materials properties sections. A test was conducted to see if CBA and BS had significant differences in strength. The result showed that after 28 days of curing, 50% is the optimum BS content, as shown in Table 4.3. The compressive strength of BS after 28 days of curing is higher than the Strata control after 56 days of curing or 11.9 % higher than the control. Therefore, both BS and CBA can replace 50% of fine aggregate in concrete. However, BS Minnkota has crystalline or glassy properties and has a unit weight higher than CBA. Nevertheless, the result shows it can replace 50% of fine aggregate in a concrete mix.

Table 4.3 Strata project at optimum Minnkota BS content

	Strata control	BS Strata Minnkota	
BA	0%BS	50%BS	60%BS
Slump (inch)	3.75	0.75	2.5
Air content (%)	7.4	4.6	7.7
SAM	0.21	0.58	0.22
Unit weight (lb./ft^3)	143	148	142.8
Plasticizer (ml/ft^3)	-	-	10
7 days	3600	4003	3639
28 days	4374	5013	3830
56 days	4477		

4.4 Aggregate Industry (AI) Project

Fresh Properties

Slump

The workability of the CBA mixes decreased as the % CBA increased, similar to the observations for the Strata mix, possibly due to CBA's higher water demand. Compressive strength increased with decreased slump and CBA content up to 50% CBA. The slump value has increased from 0.5 to 1.25 inches as CBA increased from 50% to 60%, and the compressive strength has decreased from 6,132 psi to 4,898 psi, respectively (Figure 4.8). The two projects had the same result; when the slump value increases, the compressive strength decreases and vice versa.

Air Content

Air content and slump value decreased with increased CBA from control to 50% CBA. They increased from 50% to 60% CBA, possibly due to the increased water reducer dose from 20ml/ft^3 to 40ml/ft^3 to obtain the desired workability (Figure 4.8**).** However, the slump value has only increased from 0.5 to 1.25 inches.

The compressive strength decreased from 50% to 60% CBA with increased air content and slump value which is expected when air content and slump value increase, strength decreases.

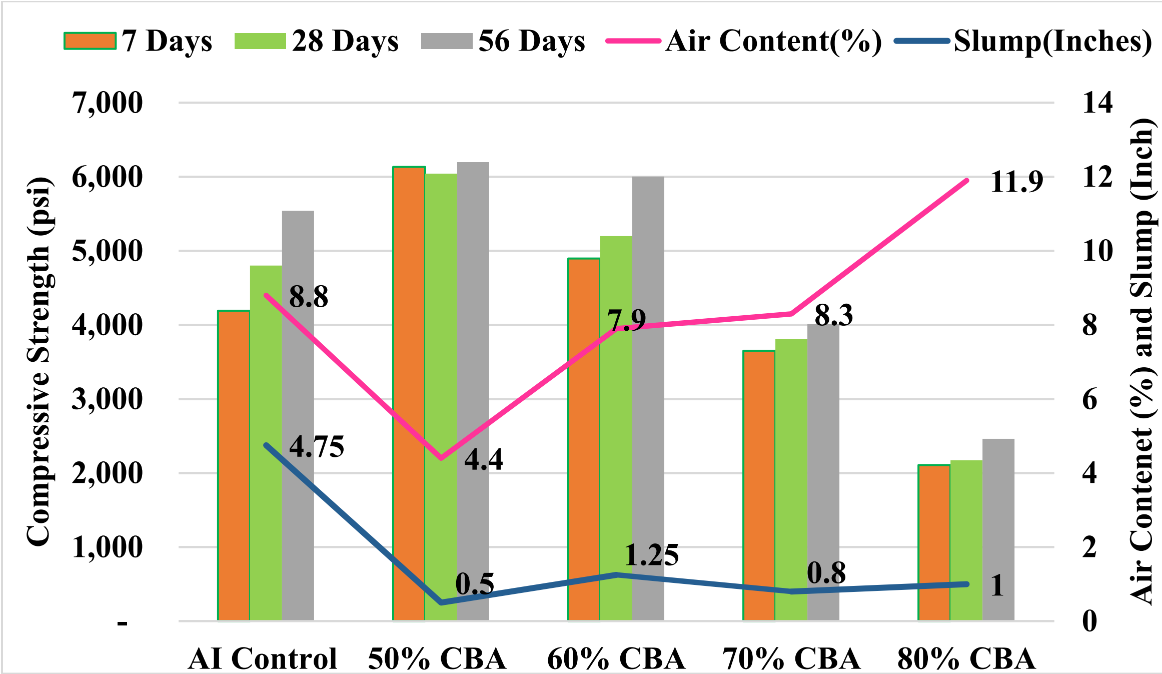

Figure 4.8 Compressive strength of AI project control and %CBA vs. slump and air content

SAM number

The SAM number increased with increased % CBA, which may have been caused by the spacing factor of the voids in the mix and CBA's porous behavior, as shown in Table 4.4. The slump and air content had decreased from control to 50% CBA concrete, and the SAM number has increased, possibly due to the porous property of CBA.

Table 4.4 AI control and % CBA fresh properties

		AI % CBA concrete			
	AI Control	50% CBA	60% CBA	70% CBA	80% CBA
Slump (inches)	4	0.5	1.25	0.8	1
Air (%)	8.8	4.4	7.9	8.3	11.9
SAM (psi)	0.07	0.77	0.44	0.15	N/A
Unit weight (lb. / ft^3)	142.1	141.9	140.96	140	134.96
Water reducer (ml/ ft^3)	18.6	20	40	60	70

Note: N/A-SAM did not provide any reading

Unit Weight

The unit weight of the 50% CBA was comparable to the control, which was the same as the Strata project. The unit weight decreased with increases in %CBA and slump value (Table 4.4), possibly due to CBA's higher water demand, which leads to pore formation and larger pore sizes.

Mechanical Properties

Compressive Strength

The compressive strength of the control and CBA-based concrete is shown in Table 4.5. The optimum CBA content was 60% at 56 days of curing. The results for the mix with 70% and 80% replacement were not comparable to the control; therefore, only the 50% and 60% mixes at 56 days of curing were considered.

Table 4.5 AI control and CBA% compressive strength

	Compressive strength (psi)				
Curing time	AI Control	50%CBA	60%CBA	70% CBA	80% CBA
7 days	4192	6132	4898	3650	2107
28 days	4802	6043	5200	3813	2250
56 days	5540	6250	6005	4010	2461

The 50% CBA has 25.8% higher compressive strength than the control after 28 days of curing. The optimum content is 60% because 70% and 80% CBA concrete had lower compressive strength than the control. The optimum content of 60% has 8.4% higher compressive strength than the control concrete after 56 days Table 4.5. Therefore, CBA enhances the compressive strength of concrete, as the two projects confirm the same results.

The unit weight decreased from 147.9 lbs. /ft^3 to 141 lbs. /ft^3 as CBA content increased to 50% CBA and 60% CBA concrete, respectively, possibly due to porous properties (Figure 4.9). Therefore, the optimum content of 60% CBA has a lower unit weight than the control, similar to

Strata's results. So far, the two projects have had the same fresh and compressive strength properties, which confirms the results.

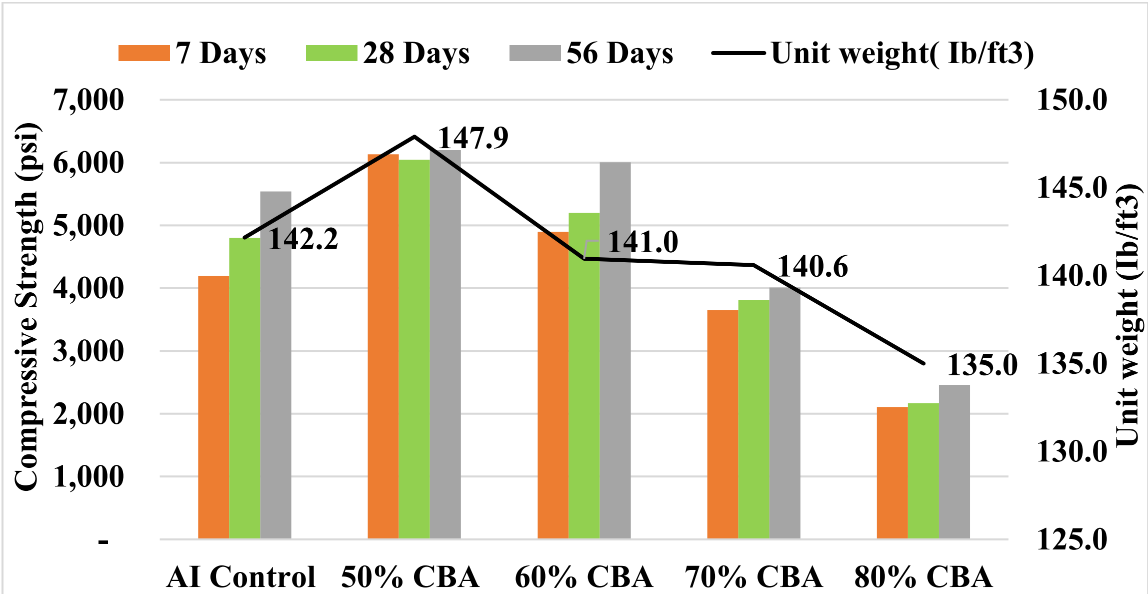

Figure 4.9 Compressive strength of AI project control and %CBA vs. unit weight

For the Strata project, the increasing CBA content led to decreasing workability. A water reducer was used to increase the workability. However, the increasing water reducer at an increment of 10% CBA in the mix has caused to increase in the air content in the mix due to the formation of bubbles. The higher percentage of air content in the concrete mix, the lower durability of the concrete performance. Therefore, to avoid this and obtain the desired workability, the research team has decided to use a high-range water reducer or superplasticizer to mix with the optimum AI content, 60% CBA concrete.

Spilt Tensile Strength of AI Project at Optimum CBA Content

The average splitting tensile strength of the AI control mix was 291 psi at 7 days of curing, as low as the first control mix (Strata) at 7 days of curing but at 28 days and 56 days are in the range of 10-12% of the compressive strength of the AI control mix as expected. The tensile strength of the optimum content of 60% CBA concrete was higher than the control, as shown in Figure 4.10.

CBA pozzolanic reaction enhances the quality of cement past and the interfacial transition zones, enhancing the split tensile strength.

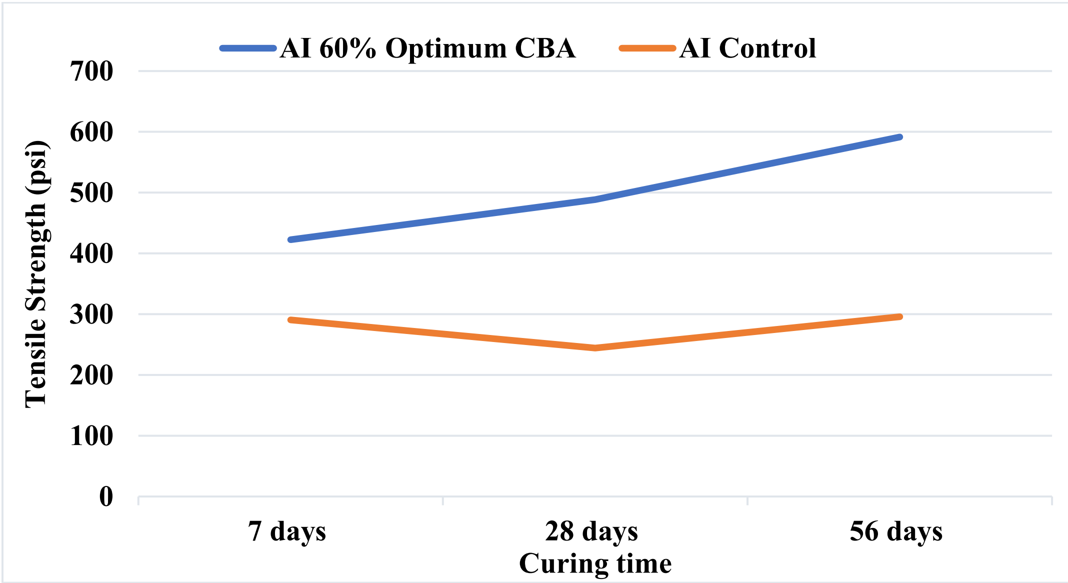

Figure 4.10 Tensile strength of AI project at optimum CBA content vs. Strata control

The effect of using a superplasticizer is highly remarkable; for example, the AI optimum content of 60% CBA has an air content of 7.9% and a slump of 1.2 inches after using a 40 ml/ ft^3 water reducer. However, in Table 4.6, the slump value has increased from 1.2 inches to 3 inches. The air content has decreased from 7.9 % to 6.5 % for using the same 40ml/ ft^3 superplasticizer. Therefore, it is recommended to use a high-range water reducer or superplasticizer while replacing fine aggregate with CBA to avoid the increasing air content in CBA concrete due to its higher water demand.

Table 4.6 Fresh properties of IA control and optimum content CBA

	AI Control	AI Optimum content 60% CBA
SAM number (psi)	0.07	0.18
Measured slump (inch)	4.75	3
Measured air Content (%)	8.8	6.5
Measured unit weight (lbs./ft^3)	142.2	142
Superplasticizer (ml/ft^3)	-	40

Flexural Strength of AI project at Optimum CBA Content

Flexural strength of 642 psi, 1070 psi, 975 psi, and 662 psi were obtained after 7 days, 28 days, 56 days, and 90 days of curing for the AI control mix. These results were within the acceptable range of 10% to 20 % of the concrete's compressive strength for all curing periods, as shown in Figure 4.11. The optimum content flexural strength is higher than the control after 7 days. However, after 28 days and 56 days of curing, the flexural strength has decreased, and this might be due brittleness property of CBA. The same finding was obtained by Raju et al. (2014)

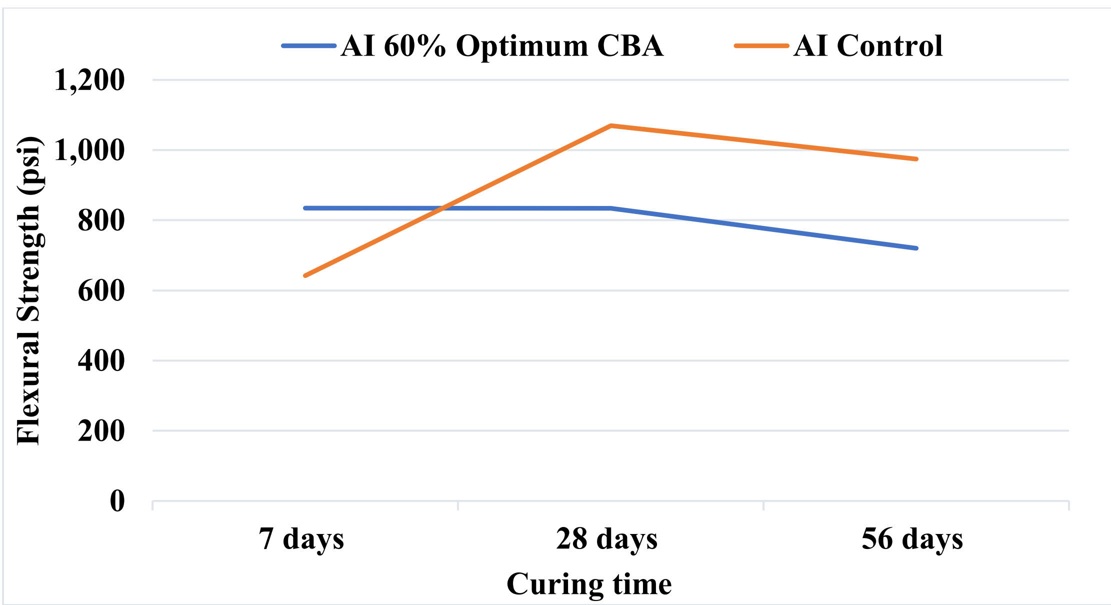

Figure 4.11 Flexural Strength of AI project at optimum CBA content vs. AI control

Modulus of Elasticity (MOE) of AI Project at Optimum CBA Content

The MOE of the AI control mix was 4,740 ksi at 7 days of curing, which is higher than the Strata control mix. It is still within the acceptable range because the compressive strength was also higher: 4,192 psi compared to the Strata control result of 3,600 psi after 7 days of curing.

However, the optimum content of 60% CBA concrete has a lower MOE than the AI control only after 7 days of curing, as shown in Figure 4.12. The result is due to the pozzolanic reaction of

CBA that occurs after 28 days in most cases but not at an early age of the hydration process. Therefore, CBA concrete gains strength with time.

The other possibility for the lower MOE at 7 days of curing compared to the control might be due to the low specific gravity of CBA that caused lower MOE of CBA concrete.

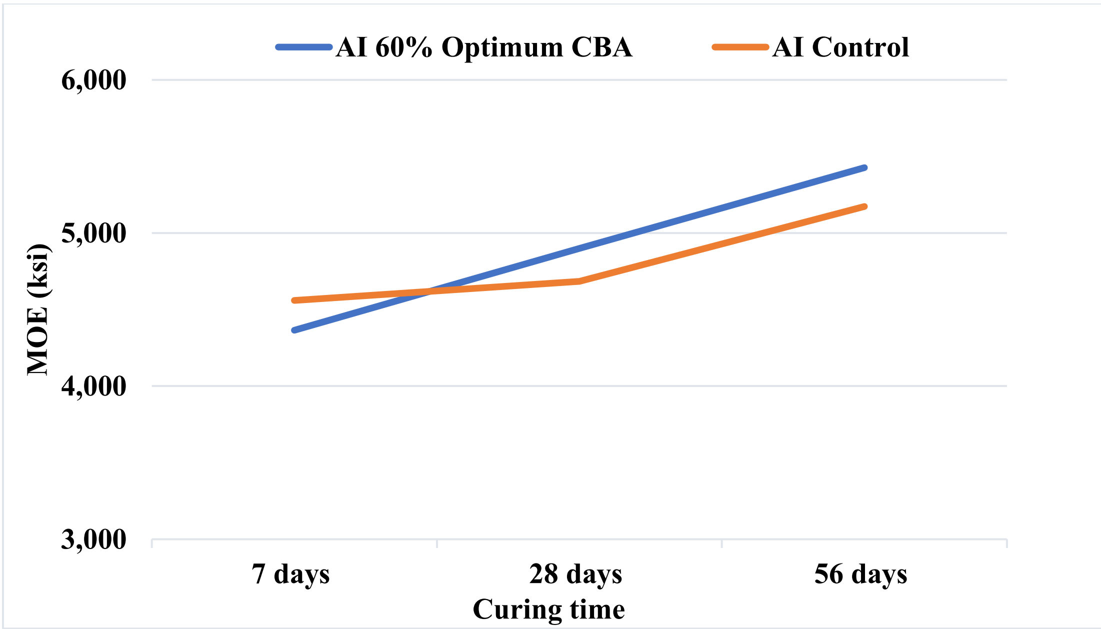

Figure 4.12 MOE of AI project at optimum CBA content vs. AI control

Durability of Concrete

Rapid Chloride Permeability AI project at Optimum CBA Content

The chloride permeability of AI control was 3165 C after 28 days and 2516 C after 56 days of curing, considering that 4,000 C and above is a higher chloride permeability value for concrete. The results show decreases in permeability over time, possibly due to increased strength and void-filled or fewer void spacing.

CBA has a higher resistance to chloride ion penetration, as shown in Figure 4.13, compared to the control. The optimum content has low chloride permeability, which means a lower chloride diffusion than the conventional concrete or control, which is the same finding with the Strata project. Therefore, CBA has lower permeability for chloride penetration and is more durable than the control.

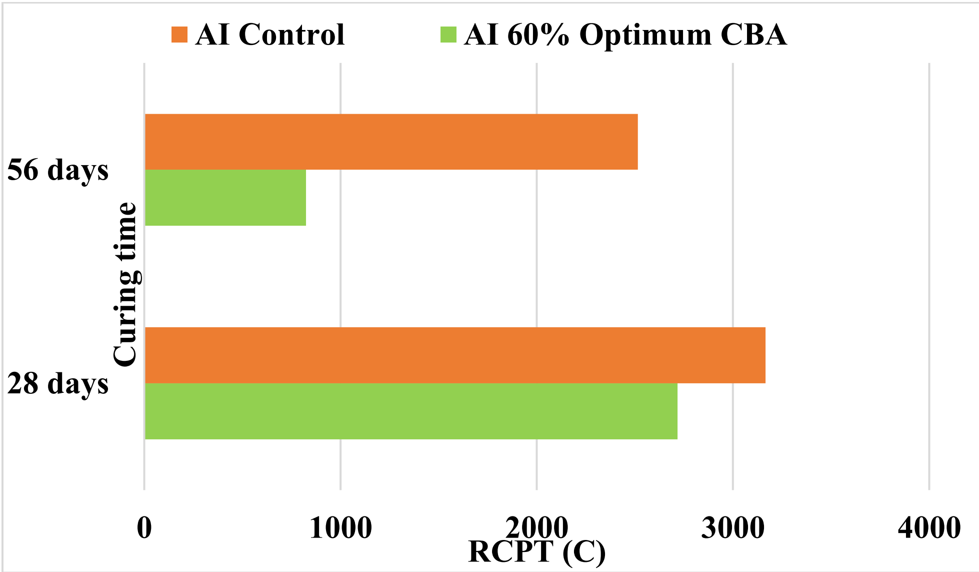

Figure 4.13 RCPT of AI project at optimum CBA Content vs. AI control

4.5 Kost Project

Fresh Properties

The third project, Kost, confirms the results of the other two projects, as shown in Figure 4.7. The optimum content is 60%, and all the fresh properties for 50% CBA and 60 % CBA had similar trends. For Kost and AI project, the research team tested the sample only for 50% CBA, 60% CBA, and 70%CBA since it has been found that the optimum content is 50% for Strata and 60% for AI projects. It was decided to confirm those findings rather than starting from a 10% CBA mix.

Air Content and Slump

The slump value has decreased from 50% CBA to 60% CBA, and the air content has increased from 50%CBA to 60% CBA, indicating that 60% is the optimum content for the Kost project. This trend is similar to the Strata and AI projects shown in Table 4.7.

Table 4.7 Kost control and % CBA concrete

Kost control Vs. % CBA				
CBA	Control	50% CBA	60% CBA	70% CBA
Slump (Inches)	4.75	3	2.5	6
Air Content (%)	8.1	6.2	6.3	13.1
SAM Number	0.09	0.42	0.54	0.07
Unit weight (Ib/ ft^3)	142.4	143.8	142.2	131.2
Curing time	Compressive strength (psi)			
7 Days	2990	4274	3444	1944
28 Days	3389	5592	4878	
56 Days	3577	5866	5083	
90 Days	4457	6403	4874	

Unit Weight

The unit weight decreased with an increase in CBA content from 143.8 lb./ft^3 to 142.2 lb./ft^3 for 50% CBA and 60% CBA concrete, respectively, possibly due to CBA's higher water demand leading to pore formation and larger pore sizes (Figure 4.14**).** However, the optimum content of 60% CBA has almost a similar unit weight to the control. The other two projects' optimum CBA concrete have similar findings, either equivalent or lower unit weight than the control.

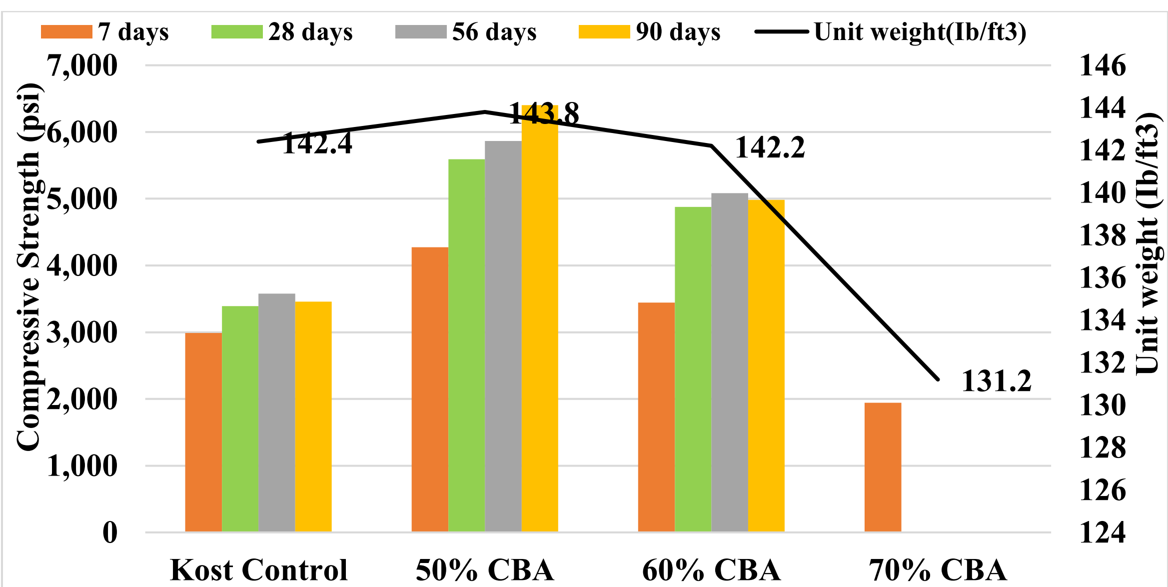

Figure 4.14 Compressive strength of Kost project control and %CBA vs. unit weight

Mechanical Properties

Compressive Strength

Kost did not provide a mix design; therefore, the research team designed the concrete mix. The Kost project findings confirm the finding of the AI project; the compressive strength decreases after 60% CBA, the air content increases afterward, and the optimum CBA content is 60% (Figure 4.15). The optimum content of 60% CBA concrete has 15%, 43%, and 42 % higher compressive strength than the control after 7 days, 28 days, and 56 days, respectively (Figure 4.15). Increasing compressive strength over time is similar to Strata and AI projects, possibly due to CBA's pozzolanic properties. Therefore, it can be concluded that CBA increases the compressive strength of concrete over time.

This project work has confirmed the finding of Maliki et al. (2017), which confirms the findings of the other two projects.

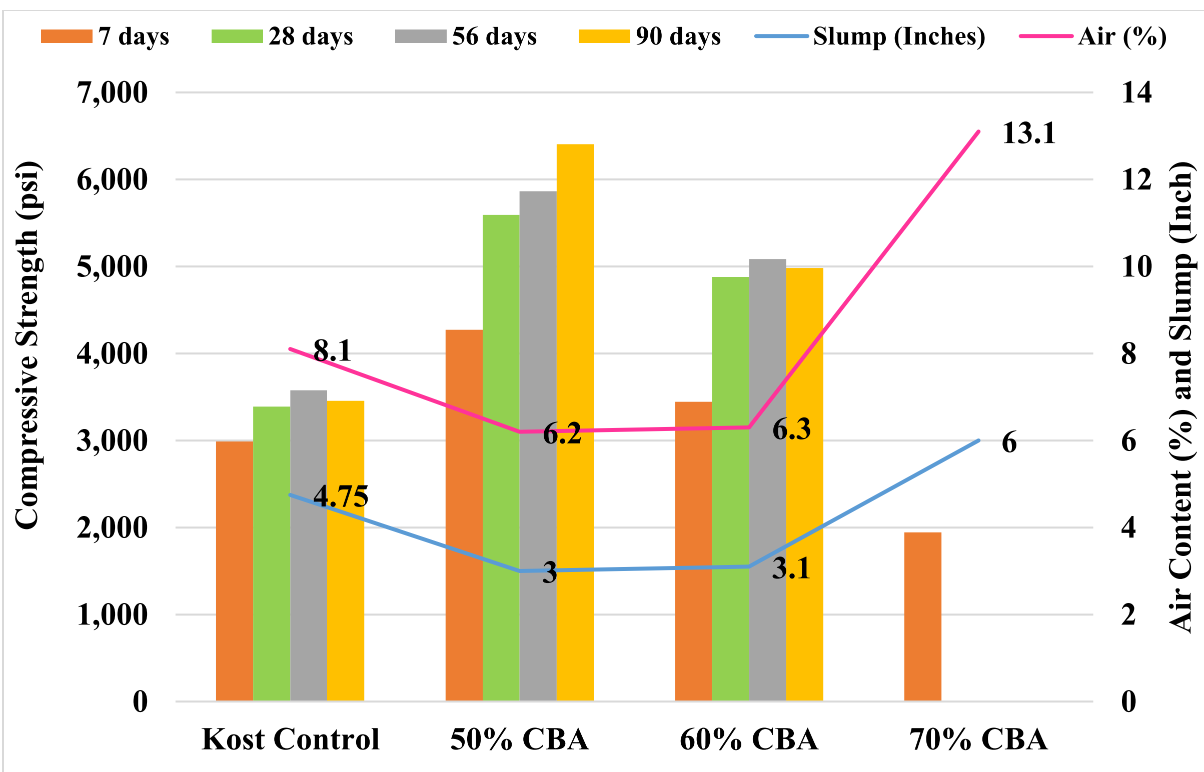

Figure 4.15 Compressive strength of Kost project control and %CBA vs. slump and air content

Split Tensile Strength of Kost Project at Optimum CBA Concrete

The obtained Kost optimum tensile strength has similarities with Strata and AI projects. The tensile strength of the optimum content is higher than the control after 7- and 28-day curing, as shown in Figure 4.16.

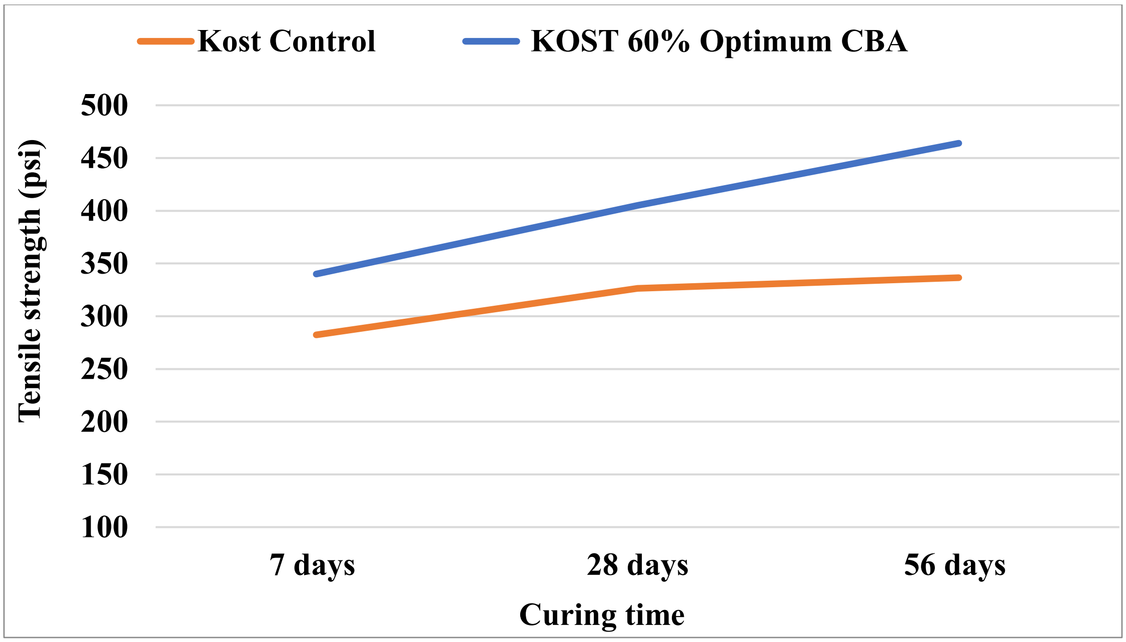

Figure 4.16 Tensile strength of Kost project at optimum CBA content vs. Kost control

Flexural Strength of Kost Project at Optimum CBA Content

The flexural strength of the optimum 60% CBA concrete was higher than the Kost control after 7 days of curing. However, 28 days had a slightly lower value as the flexural strength of CBA is lower than the conventional control due to its brittle and porous properties, as shown in Figure 4.17.

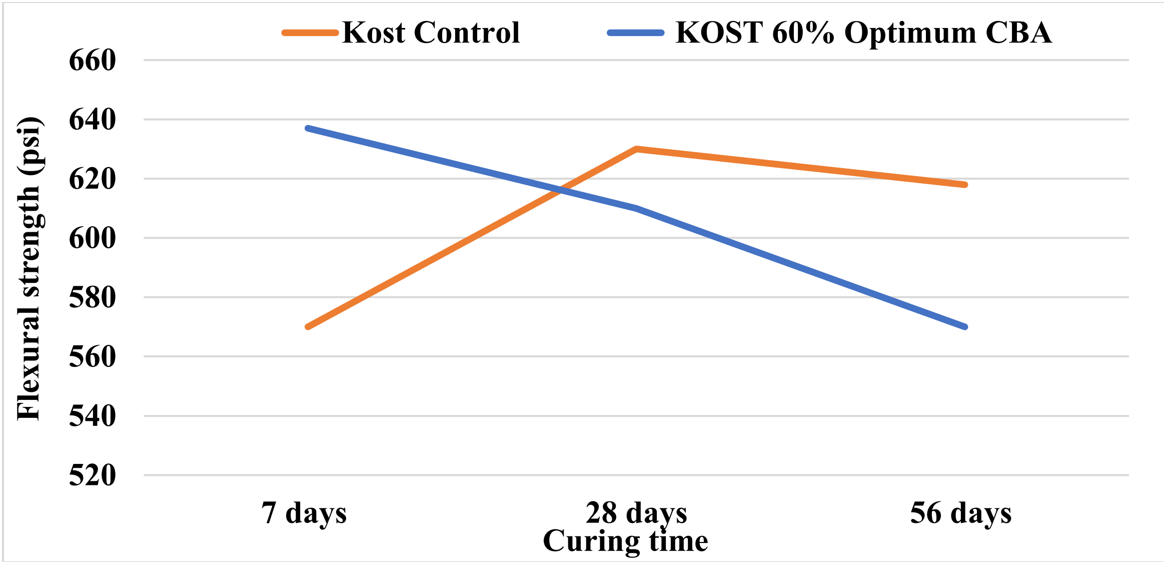

Figure 4.17 Flexural strength of Kost project at optimum CBA content vs. Kost control

Modulus of Elasticity (MOE) of Kost Project at Optimum CBA Content

The Kost project optimum content MOE is higher than the control after 28 days, as shown in Figure 18. It confirms the other two projects' findings. All three projects' optimum content concrete mixes have higher MOE than the controls, at least after 28 days of curing.

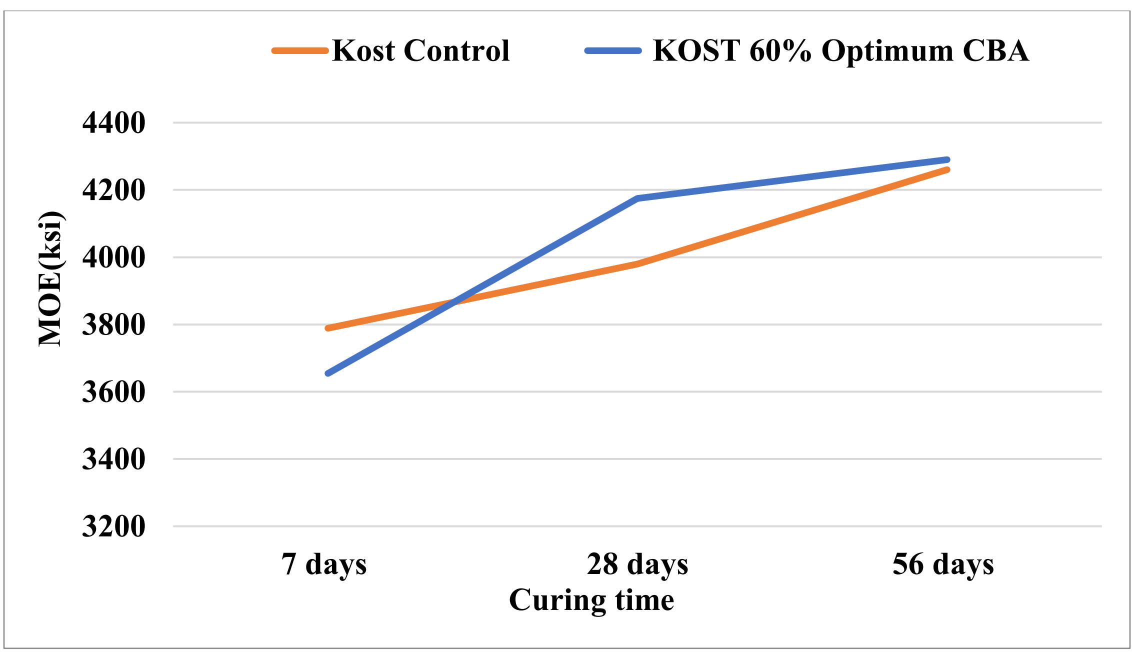

Figure 4.18 MOE of Kost project at optimum CBA content vs. Kost control

Durability of Concrete

Rapid Chloride Permeability Kost Project at Optimum CBA Content

The chloride permeability test in Figure 4.19 shows a lower value than the control value. The other two projects have similar findings; CBA concrete showed better chloride penetration resistance than the control.

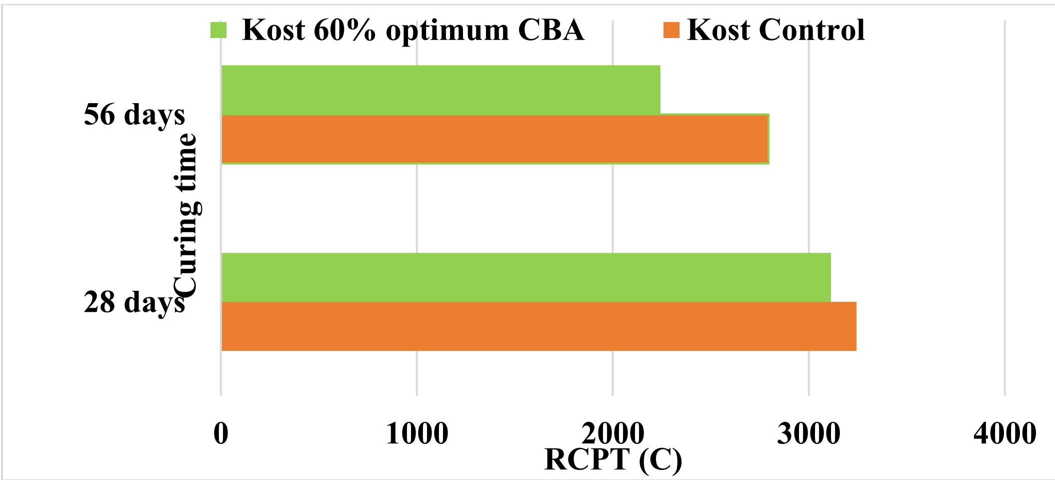

Figure 4.19 RCPT of Kost project at optimum CBA content vs. Kost control

4.6 BS/CBA and Kost Control

The Kost control was compared to both BS and CBA to see the effect of BS and CBA concrete. Furthermore, the compressive strength of Leland 50%CBA concrete was higher than the BS Minnkota. It shows that CBA concrete yields higher compressive strength than BS, as shown in Table 4.8. It might be due to the glassy property of BS.

From Table 4.8, the optimum Minnkota BS content is 50% after 56 days of curing, confirming the finding for CBA and BS optimum content in the previous section, which means both CBA and BS have similar fine aggregate replacing capacities. However, BS has less absorption capacity and less coarse and glassy properties. The increasing compressive strength is not similar to CBA; CBA compressive strength increases over time and has a higher value than the control due to the pozzolanic properties of CBA. Leland CBA's 50% compressive strength was 93.3%

higher than the Kost control after 56 days of curing, and the optimum content is 50% for Leland CBA. On the other side, BS Kost Ottertail 50% has 19.3% higher compressive strength than the control after 90 days of curing.

Preliminary results of mechanical properties of optimum content of Kost Minnkota 50% are discussed in this section.

Table 4.8 %BS, %CBA, and Kost control

	Kost Control	Minnkota BS Kost		Leland CBA Kost		Ottertail BS Kost	
BA	0%CBA	50%	60%	50%	60%	50%	60%
Slump (Inch)	4.75	3.25	3.1	0.25	3.75	2.75	2.5
Air (%)	8.1	7.8	7.5	2.2	10	8	5.4
SAM (psi)	0.09	0.1	0.33	0.29	0.6	0.31	0.18
Unit weight (lb/ ft^3)	142.4	144	144.4	149.6	135.2	144.4	139.2
Plasticizer (ml/ft^3)		-	-	-	25	-	-
7 days	2990	3105	2662	5427	2740	3226	3470
28 days	3389	3648	3099	6390		3847	
56 days	3577	3684	3299	6917		4052	
90 days	3455	4097		7264		4137	

Fresh Properties of Kost Project at Optimum Minnkota BS Content

The optimum Minnkota BS has a slightly lower air content than the control mix, which is a favorable result because higher air content significantly affects the durability of concrete and the slump value was in the range as shown in Table 4.9. However, the unit weight was higher than the Kost control, similar to the Strata Minnkota BS finding in section 4.3. The results confirm that Strata Minnkota BS and Kost Minnkota BS have an optimum value of 50% and a unit weight higher than the control. This finding shows that CBA and BS are affected by unit weight. CBA is lighter weight than BS, which might be due to the nature of their processing method and the higher specific gravity of Minnkota BS.

Table 4.9 Fresh properties of Kost at optimum Minnkota BS content and Kost control

	Kost Control	Kost project at optimum Minnkota BS
Slump (Inches)	4.75	3.3
Air content (%)	8.1	7.8
SAM (psi)	0.09	0.1
Unit weight (Ibs. /ft^3)	142.4	144.0

Mechanical Properties of Kost Project at Optimum Minnkota BS Content

The optimum content Kost Minnkata BS had slightly higher compressive, tensile strength, and MOE than the Kost control after 56 days of curing, as illustrated in Figure 4.20. The flexural strength of Kost optimum Minnkota BS was lower than that of the control, which is the same finding as the Kost and Strata project optimum content CBA. This finding has similarities with the other projects, Strata, Kost, and AI with CBA.

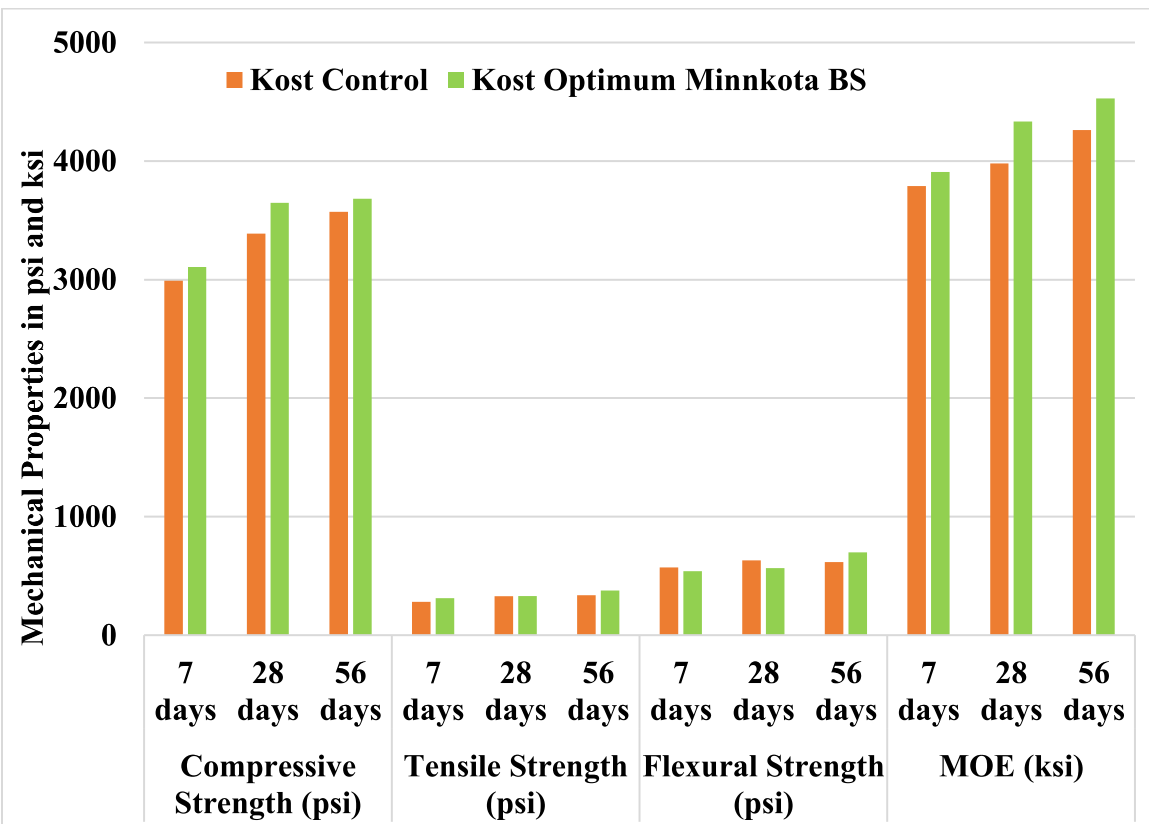

Figure 4.20 Kost at optimum Minnkota BS content mechanical properties

Durability of Concrete

Rapid Chloride Permeability of Kost Project at Optimum Minnkota BS Content

The durability test is similar to the other three projects. Kost optimum BS has better resistance to chloride ion penetration, as shown in Figure 4.21.

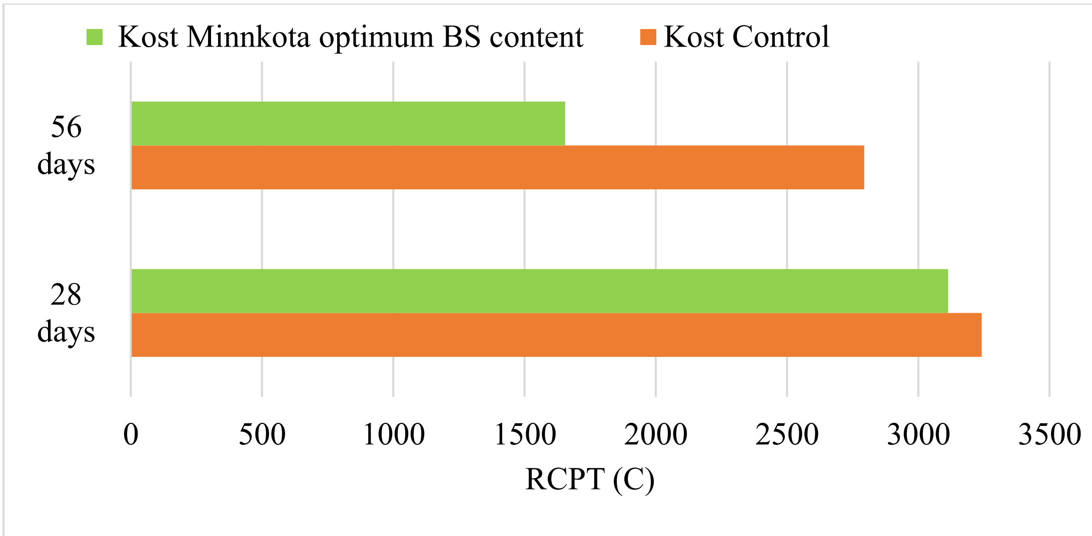

Figure 4.21 RCPT of Kost at optimum Minnkota BS content and Kost control

4.7 Effect of Nanoclay on CBA-Based Concrete

The effect of 2.5% nanoclay by weight of cement on CBA-based concrete was investigated.

Fresh Properties

The air value decreases when the slump value decreases, similar to the other findings. However, the unit weight had increased compared to the control, from 70% to 80 %, as shown in Table 4.10, which might be due to the fineness properties of nanoclay that filled the void in the cement matrix and the high-water absorption properties of CBA.

Compressive Strength

The compressive strength of 80% CBA was higher than the control after 28 days of curing. This result advanced the finding of this paper from 50% optimum CBA content to 80% CBA with nano clay, as shown in Table 4.10. Nanoclay enhances the performance of concrete by consuming Ca $(OH)_2$ in hydration reaction at an early age, and CBA does this at a later age. Therefore, this combination provided a better performance concrete with 70% CBA up to 80% or even more percentage of CBA replacing fine aggregate.

80% CBA nanoclay mixed concrete had 4.8% higher compressive strength after 7 days of curing than the AI control after 56 days.70% CBA nano clay mix concrete had 5.2% higher compressive strength than the control after 28 days of curing.

The 80% CBA with nanoclay mixed concrete had 20% higher compressive strength after 28 days than the control for the AI project after 56 days. This result indicates that nanoclay initiates the hydration reaction at an early age and increases strength earlier than CBA at a later age. The combination of the two materials provided a better-performing concrete and increased the optimum CBA content to 70% and possibly 80%. Replacing fine aggregate by 90% and 100% CBA samples testing is undergoing.

Table 4.10 AI control and 2.5 % nanoclay CBA concrete

	Control	Nanoclay AI 2.5 %	
BA	AI Control	70%CBA	80%CBA
Slump (inch)	4.75	3	1
Air (%)	8.8	5.8	3.8
SAM	0.07	0.32	N/A
Unit weight (lb./ft^3)	142.2	143.2	145.6
Plasticizer (lb./ft^3)	N/A	40	46
7 days	4192	5133	5603
28 days	5540	5825	**6418**
56 days	**5345**	6548	

The effects of nanoclay on CBA concrete are significant, as seen in Table 4.11; the compressive strength of 70% CBA nanoclay mixed concrete was 32.3% higher than the 70% CBA concrete without nanoclay after only 7 days of curing. Nanoclay enhances the strength of concrete at an early age due to its high specific surface area and fineness property that fills the cement matrix.

Table 4.11 The effect of nanoclay on compressive strength of concrete (psi)

	Compressive strength (psi)		
	70% CBA without Nanoclay	AI Control	70% CBA with 2.5 % Nanoclay
7 Days	3881	4192	5133
28 Days	4624	5540	5825
56 Days		5345	6548

Chapter 5 Conclusions, Recommendations, and Future Works

5.1 Conclusions

This project's objective was to determine if using new sustainable materials, such as CBA, to concrete will reduce natural raw material usage, energy consumption, and greenhouse gas emissions while maintaining or improving concrete performance compared to the control. Using coal bottom ash in the construction industry will reduce the technical and economic problems associated with power plants by reducing solid waste. Therefore, to consider CBA as a fine aggregate replacement, this project work has established the following promising results:

- ❖ The finding for both BS and CBA confirmed that both materials could replace a minimum of 50% fine aggregate in a concrete mix, which is the optimum content after 56 days of curing for both BS and CBA.
- ❖ 60% CBA was the optimum content for both AI and Kost projects at 90 days of curing.
- ❖ The compressive strength of CBA concrete increases over time due to the pozzolanic reaction of CBA.
- ❖ The durability test showed higher performance than the controls for all projects in the thesis.
- ❖ CBA concrete compressive strength, tensile strength, and MOE were higher than the control after 56 days of curing for both CBA and BS.
- ❖ The key issue with replacing fine aggregate with CBA is workability; an increased CBA leads to a significate decrease in workability. This was resolved using a high-range water reducer or superplasticizer to obtain desirable workability.
- ❖ The optimum content CBA concrete had a unit weight similar to the controls. However, BS optimum content had a slightly higher unit weight than the controls, which might be the lower absorption capacity of BS and higher specific gravity. CBA's unit weight

decreases with an increase in CBA replacement, possibly due to CBA's higher water demand, which leads to pore formation and larger pore sizes

- Nanoclay has increased the optimum content to 80% CBA after 28 days of curing.

5.2 Recommendations

A superplasticizer rather than a water reducer is recommended to obtain high-performing concrete and desirable workability.

5.3 Future Works

- Determine the durability of concrete under freeze-thaw.
- Finalize the testing process up to 90 days of curing to see if there was any change over time.
- Air void content of hardened concrete and compared to SAM number

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