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Synthesis of Geopolymer Using Coal Fly Ash and Corn Stover

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SYNTHESIS OF GEOPOLYMER USING COAL FLY ASH AND CORN STOVER

by

Anu Paneru, Chemical Engineering

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ABSTRACT

The development of each nation is dependent on its infrastructure, and nations are competing with others in infrastructure, especially in the construction of roadways, since they play a vital role in the economic and social development of the nation. The conventional materials used for road construction are cement and asphalt, which pose significant environmental challenges. This thesis explores the potential of fly ash (FA) and corn stover (CS) in synthesizing geopolymer, as an alternative material for the construction of roads. The study examines the impact of FA and CS percentages and the particle sizes of CS on the compressive strength, porosity, and permeability of the geopolymer. The results indicate that incorporating CS in the FA may decrease the compressive strength of the geopolymer. Smaller CS particle sizes lead to lower compressive strength. However, porosity of the geopolymer increased with the incorporation of the CS. As with the compressive strength, an increase in particle size decreased porosity. Achieving the targeted permeability remains a challenge due to the particle size and the quality of the compactness of the materials used.

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DEDICATION

This thesis template is dedicated to everyone who has suffered the frustration of fighting with the “enhancements” of word processing software.

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CHAPTER 1

INTRODUCTION

1.1 Background

In the 21st century, the development of each nation is measured by its infrastructure advancement. For this reason, every nation is competing with others in infrastructure, especially in the construction of roadways. Roads make a crucial contribution to economic development and growth and bring important social benefits. They are of vital importance in making a nation grow and develop. Providing access to employment, social, health, and education services, an effective road network is crucial in fighting against poverty [1]. Roads open more areas and stimulate economic and social development. For those reasons, road infrastructure can be considered the most important of all public assets. Each year the United States invests about $435 billion in repairing roadways [2]. Asphalt and concrete are the only widely adopted materials trusted to deliver the requisite durability for roads and parking lots.

Major environmental concerns have been raised by the growing use of asphalt and concrete in the construction of pavement, adding to the problems related to motor vehicle emissions. Both asphalt and concrete are produced using unsustainable methods; asphalt depends on petroleum, while concrete needs to be made from mined rock, sand, and cement [3]. While efforts to reuse existing materials have emerged, the overall production still consumes substantial energy. Furthermore, the drainage systems designed to manage rainwater on these surfaces lead to water pollution, as runoff carries contaminants like surface debris and asphalt residues into municipal sewage networks or drains that eventually reach lakes, rivers, and streams [3].

Moreover, the application of asphalt and concrete contributes to harmful atmospheric emissions. The conversion of petroleum into asphalt releases significant quantities of volatile organic compounds (VOCs), adding pollutants to the air [4]. Similarly, the cement production process for concrete involves high temperatures and generates substantial VOC emissions [5] [6]. The environmental impact of building roads and parking lots is heightened by the application and curing of asphalt, which releases more toxic elements into the atmosphere, and using high-VOC paints for road markings [5]. To mitigate the negative impact on the environment, addressing these concerns demands an integrative strategy that considers sustainable construction processes and alternative materials.

1.2 Objective

The goal of this research is to study the impact of mixing corn stover (CS) and fly ash-based geopolymers to better understand their potential uses in the construction industry. The goal of the study is to examine how changes in the percentage of CS and the size of the particles affect the compressive strength, and porosity of the geopolymer. Furthermore, the study aims to pinpoint possible advantages (like enhanced workability and sustainability) as well as drawbacks (like biodegradability) related to CS in geopolymer road materials. The adjustments of the geopolymer formulation for appropriate qualities in road construction will be guided by this knowledge.

1.3 Thesis Organization

In addition to this introduction, the thesis is divided into four Chapters: Literature Review, Methods, Results and Discussion, and Conclusions and Future Work. These sections will make clear the findings of this study.

In CHAPTER 2, a review of the literature is provided regarding the potential for utilizing alternative materials to reduce the environmental impact of conventional road construction. It analyzes more sustainable materials like geopolymers and industrial waste. It explores the combination of fly ash (FA) with raw biomass, CS, acknowledging the challenges of uncertainty and biodegradability while highlighting the benefits like improved compactness and strength. Moreover, it discusses the roles of alkaline activators (NaOH and Na_2SiO_3) in the synthesis of geopolymer, highlighting the importance of its concentration and their addition sequence during the mixing process for controlling the reaction and its final properties.

CHAPTER 3 discusses the materials used in the synthesis of the geopolymer along with their properties. It also discusses the procedure followed for the synthesis of the geopolymer.

CHAPTER 4 covers the results from the compressive strength, porosity, and permeability tests performed on the samples. The figures allow for a visual representation of the data.

In CHAPTER 5, a conclusion is drawn from the research reported here. Suggestions for future enhancements and research applications and potential areas for future investigation are also discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 Alternative Materials for Concrete

The search continues with the objective of discovering alternative materials with less of an environmental impact due to the unsustainable nature of current materials used in road construction, such as concrete and asphalt [8]. Scholars are exploring a range of strategies to use the smallest quantity of natural resources while lowering carbon emissions and landfill waste.

Byproducts from the industry offer a useful resource. In road building, some of the traditional binders can be replaced with fly ash (FA), a leftover from coal combustion, and blast furnace slag, a byproduct of steelmaking [7]. These materials conserve natural resources while increasing strength and durability.

Utilizing recycled materials is an additional sustainable approach. Various road layers make use of recycled tire rubber, crushed concrete, and reclaimed asphalt pavement [8] [9]. By addressing waste management issues, these materials help to reduce the need for virgin aggregates.

As an alternative to conventional cement, geopolymers—inorganic polymers made by activating aluminosilicate minerals, which are typically waste byproducts—have gained attention [9] [12]. Comparable strength characteristics are provided by geopolymers; however, they have a significantly lower environmental impact.

Despite the benefits, these alternatives face challenges. Concerns exist over long-term durability, potential leaching issues, and occasionally increased costs [10] [11]. Ongoing research and extensive field trials are essential to address these concerns and promote widespread adoption of these sustainable materials.

2.2 Biomass in Road Construction

Compared to biochar, the direct incorporation of raw biomass and coal FA in road construction is a less researched area. Understanding the possible advantages and limitations of this method is becoming increasingly popular, though.

According to studies, FA mixes' compactness can be increased by adding raw biomass, especially fibrous materials like wood residues and agricultural byproducts [12]. The enhanced interaction within the FA mixture is a result of the biomass fibers working as reinforcement.

In the long run, raw biomass might also increase the efficacy of FA mixtures. Cementitious products can be formed when FA's calcium hydroxide reacts with silica and alumina components found in biomass [13]. These can improve the road material's long-term strength and resilience.

The breakdown of unprocessed biomass in FA mixtures may produce internal spaces that increase porosity. This property affects the longevity of freeze-thaw materials because it might provide room for expansion, which would lessen the chance of cracking from water freezing and expanding [12].

However, there are issues with using unprocessed biomass. The workability and consistency of biomass can be greatly impacted by changes in its interaction with FA, which can be caused by variations in biomass type, particle size, and pretreatment

[14]. Furthermore, if a breakdown happens unevenly within the road structure, the raw biomass's biodegradability could compromise long-term performance.

2.3 Use of Corn in Construction Sector

Road building could benefit from the use of corn stover (CS), an abundant agricultural waste left over after corn is harvested. CS can be used to improve subgrade performance since, as a soil stabilizer, research indicates that it increases soil strength and compactness [15] [16]. Because of its low weight, it can be used as a fill material to lessen the strain on the underlying soil layers while building roads and foundations [17]. Furthermore, CS fibers have the potential to improve durability and crack resistance in cement composites by acting as a bio-based reinforcement [18]. The strength benefits of CS stem from its cellulose content, which provides structural integrity. However, to comprehend CS's long-term performance and achieve its full potential in these applications, more research is necessary.

2.4 Use of 12 M NaOH

Sodium hydroxide (NaOH) content is a key variable in the polymerization process. By dissolving silica and alumina from the precursor materials—typically FA or other aluminosilicate sources—it acts as the alkaline activator and promotes the development of geopolymer gels, which hold the system together [18].

According to research, 12 M NaOH is a frequently utilized concentration for several reasons. First, higher NaOH molarity usually causes more reactive species to dissolve from the source material, which accelerates reaction kinetics and increases the formation of geopolymer strength [19]. Nonetheless, there is a range in which the concentration of NaOH is ideal. When compared to traditional Ordinary Portland Cement mortar, geopolymers having a NaOH concentration below 12 M showed reduced strength [20]. The compressive strength of concentrations over 12 M was lower than that of geopolymer with a 12 M molarity, defying the common assumption that a larger molarity of NaOH equates to greater strength [21].

Research has shown that when geopolymers are synthesized using 12 M NaOH, reactivity, workability, and strength development are frequently balanced favorably [22]. Additionally, compared to greater concentrations that may be more dangerous to handle, the usage of 12 M NaOH offers an adequate level of practicality even though it does require safety precautions.

2.5 NaOH followed by Na_2SiO_3 on Preparation of Geopolymer Mix

When synthesizing a geopolymer with coal FA, NaOH is added first, and then sodium silicate. This is often done in two steps. The different functions that these alkaline activators play in the reaction pathway are the reason for this sequential strategy. Reactive silica and alumina species are released into the solution by NaOH, which mainly acts as a dissolving agent by targeting the aluminosilicate structures in FA [19]. Initiating the dissolution process is essential for the creation of geopolymer gels.

Although NaOH and sodium silicate can be added simultaneously, sequential addition frequently provides greater control over the reaction process, allowing modification of characteristics like workability, strength development, and setting time [23].

CHAPTER 3

METHODS

3.1 Materials Used

3.1.1 Class F Fly Ash – FA

The FA used in this experiment was donated by ECO Materials Technology, South Jordan, Utah, USA. FA is generated from combustion coal in a high temperature furnace. It consists of calcium oxide (CaO), iron oxide (Fe_2O_3), silicon dioxide (SiO_2), and aluminum oxide (Al_2O_3). It is rich in silicon dioxide and used extensively in construction, notably in concrete, for its strengthening properties. It may reduce the impact on the environment by partly substituting for cement in concrete compositions.

Figure 3-1: Class F FA.

Table 3-1: Chemical composition of FA used [24].

Chemical Analysis	***Results %***	***ASTM Limit Class F/C***	***AASHTO Limit Class F/C***
Silicon Dioxide	51.30	-	-
Aluminum Oxide	27.18	-	-
Iron Oxide	12.21	-	-
Sum of Primary Oxides	90.69	70.0/50.0 min	70.0/50.0 min
Sulfur Trioxide	0.89	5.0 max	5.0 max
Calcium Oxide	2.72	-	-
Magnesium Oxide	0.83	-	-
Sodium Oxide	0.23	-	-
Potassium Oxide	2.41	-	-
Sodium Oxide Equivalent	1.82	-	-
Moisture	0.73	3.0 max	3.0 max
Loss on Ignition	3.22	6.0 max	5.0 max
Carbon	2.10	-	-
Available Alkalis	0.59	Not required	1.5 max*

3.1.2 Corn Stover – CS

The CS used in this experiment was donated from Idaho National Lab, Idaho Falls, Idaho, USA. To produce geopolymers, CS can be added along with FA because it is rich in cellulose and lignin. Its organic composition strengthens the geopolymer matrix, which could improve its lifespan and mechanical strength. Combining these two resources could result in sustainable building materials in addition to making use of agricultural waste.

Figure 3-2: CS of particle size 180 μm (LEFT) and particle size 710 μm (RIGHT).

Table 3-2: Chemical composition of CS used [25].

Element Corn Stover	***%composition***
Structural Ash	3.46
Extractable Inorganics	2.23
Structural Protein	1.58
Extractable Protein	0.96
Water extracted Glucain	0.53
Water extracted Xylan	0.26
Water extractives Others	2.36
EtOH Extractives	2.62
Lignin	16.52
Glucan	37.52
Xylan	21.77
Galactan	1.66
Arabinan	3.37
Acetate	2.45
Total	97.28

3.1.3 Sodium Hydroxide – NaOH

When NaOH is mixed with aluminosilicate materials like FA, it starts a chemical reaction, which leads to the creation of geopolymers. Because of its high alkalinity, which causes silicates and aluminates to dissolve, a robust and environmentally friendly binding material that is very versatile and employed in construction can be created. The NaOH solution was 12 M and was purchased from Fisher Scientific, Hampton, New Hampshire, USA. The product specifications shown in **Table 3-3** are available on the website.

Table 3-3: Specification of Sodium Hydroxide (12 N) used [26].

Specifications	***Value***
Color	Colorless
CAS Max%	65.16, 34.84
Linear Formula	NaOH
Concentration	12.0N ± 0.5N (12M)
UN Number	UN1824
Density	1.38 g/mL
Solubility Information	Soluble in water
Quantity	4 L
Formula Weight	40
Grade	Certified
Identification	Passes Test
Packaging	Poly Bottle
Specific Gravity	1.38 g/mL
Traceability to NIST	Traceable to NIST
Physical Form	Liquid
Chemical Name or Material	Sodium Hydroxide

3.1.4 Sodium Silicate – Na_2SiO_3

Sodium silicate acts like a silica source and binder. When sodium silicate is mixed with an alkaline activator like NaOH, it acts like a binder, forming a robust geopolymer.

The sodium silicate solution we used was purchased from Sigma-Aldrich, St. Louis, Missouri, USA. The properties shown in **Table 3-4** are available on the website.

Table 3-4: Specification of Sodium Silicate used [27].

Test	***Specification***
Appearance (Color)	Colorless
Appearance (Form)	Liquid
Titration by HCl	13.4 – 14.4 %
% NaOH	-
Gravimetric Analysis	12.0 – 13.0 %
% Si	-
Specification: PRD.0.ZQ5.10000018173	-

3.2 Experimental Setup

The mold used in the experiment is from American Cube Mold, made of polyethylene (HDPE). It contains 5.08 cm (2 in) 3-gang mold and comes with a curing cover and a tamper.

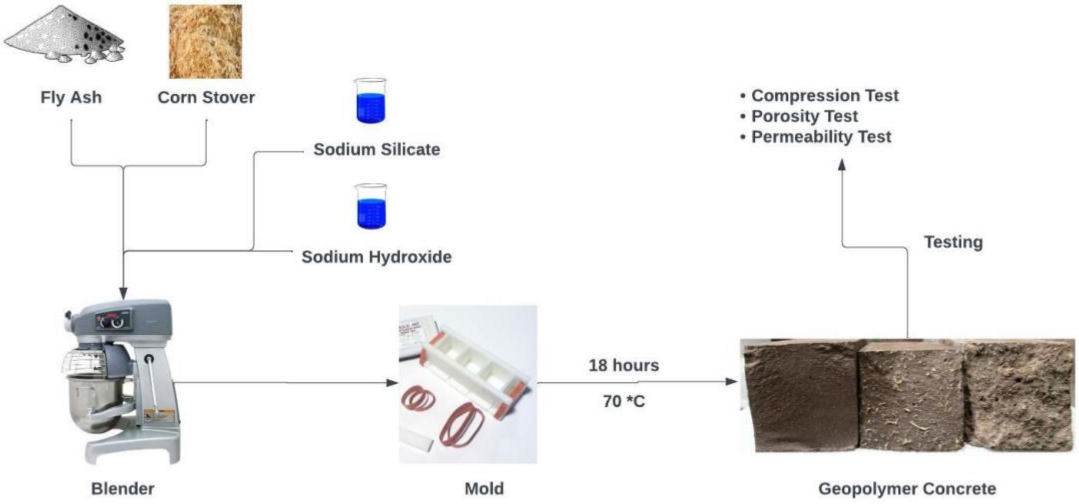

Figure 3-3: Experimental setup of synthesis of geopolymer using FA and CS.

3.3 Sample Preparation

3.3.1 Compositions

The ratios of the FA and CS compositions that we have chosen to prepare our samples is displayed in **Table 3-5**. The ratios greater than the specified ratios had far lower strength and were hence excluded from the report.

Table 3-5: The experimental conditions for creating geopolymers from CS and FA are shown in the following table. Each experimental condition was tested in triplicate, and the ratios and particle sizes of the FA and CS are listed.

Experimental Condition	***Mass Ratio of FA to CS***	***Particle size of CS (μm)***
1	100:0	-
2	95:5	180
3	90:10	180
4	95:5	710
5	90:10	710

3.3.2 Mix Process and Sample Matrix

Compared to standard geopolymer formulation, the primary changes made during the making of geopolymer were the addition of CS, the size of the CS used, and the ratio of FA to CS. A total of forty-five samples were made, three of each composition and three batches of each.

By combining FA, CS, NaOH, and Na_2SiO_3 in a certain ratio, geopolymer, a substance used in construction, can be created. The mass ratio of FA and CS to alkaline activators is 1.86, while the mass ratio of Na_2SiO_3 to NaOH is 0.33. At the same curing temperature, every sample was created using the very same method. In separate beakers, the alkaline activators and the masses of FA and CS were measured. After pouring the weighed samples of CS and FA, one at a time, into the mixing bowl, the mixer was set to stir. Three minutes later, the weighed NaOH samples were added gradually and mixed for the next three minutes. After that, the mixer was switched off, and samples that had adhered to the mixing bowl's side were physically scraped using a silicon spatula. After one minute, the mixer was started, and three more minutes of mixing were performed, with the weighed Na_2SiO_3 added gradually. The samples that were stuck to the sidewalls were then scraped again after the mixer was switched off, and once more after three minutes. After one minute, the mixer was left it running constantly for the following four minutes. The mixing process took about fifteen minutes in total.

Figure 3-4: Mixing of FA, CS and chemicals.

Molds were prepared and thoroughly oil lubricated. Using the tamper that came with the mold, each portion of the mold was filled with the mixture and tamped in accordance with the instructions given in the guidebook. The lids were placed over the upper part of the mold and secured with stiff rubber.

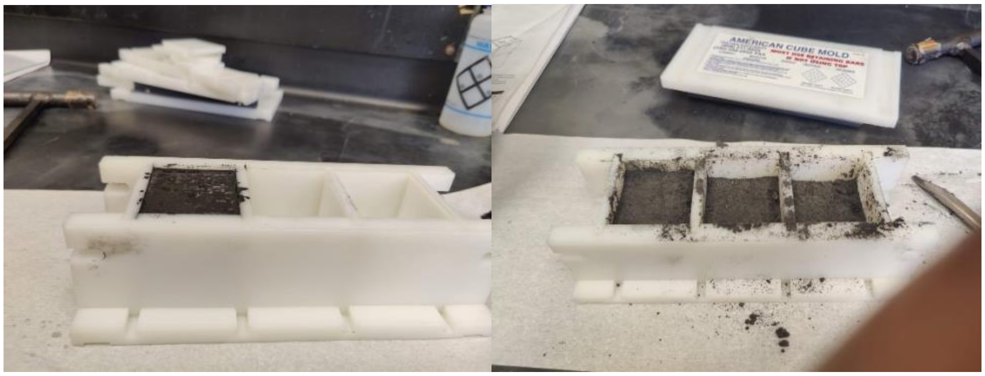

Figure 3-5: Mixture poured in a square mold.

After that, the molds were put inside the oven, which had been preheated to 70 ℃. After the samples had been cured for eighteen hours in the oven, the oven was shut off and the molds allowed to stay inside it for a minimum of twenty-four hours.

Figure 3-6: Mold placed inside the oven for curing.

The samples were taken out of the molds after a day and kept inside zip-lock bags for the following five days. The compression tests were carried out on the seventh day following the samples' preparation.

Figure 3-7: Samples after being demolded.

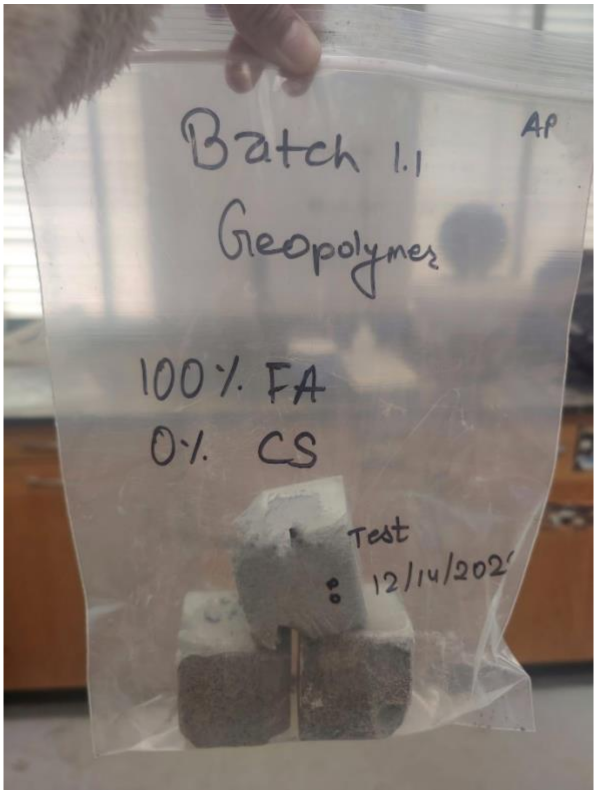

Figure 3-8: Samples placed for curing.

3.4 Testing of Samples

3.4.1 Compression Test

According to the global method of testing, the standardized method for testing the compressive strength of the material is by crushing. It is an important characteristic of construction materials because it shows the maximum load that the material will endure before collapsing. Higher compressive strengths allow a material to endure greater forces before breaking, making them more appropriate for load-bearing structures like foundations and columns. The samples prepared with different material ratios and particle sizes were placed between plates of the compression testing machine, and load was applied until the samples were crushed. The data for load and peak stress were recorded for individual specimens. The data are tabulated below with the histogram of individual sample type.

The samples were tested in accordance with ASTM C109. Each of the 45 samples had a varied FA and CS ratio in addition to a different CS size. They were kept apart at room temperature and cured in separate batches for a total of seven days. A hydraulic compression test machine (Test Mark Industries, East Palestine, Ohio, USA) was used to perform the compression test (**Figure 3-9**). The loading channel applied was 658.4 kPa/sec (300 lbs/sec). If a crack or fracture in the sample caused the stress on the cylinder to fall below 85% of the load, this loading was considered to have crushed the sample.

Figure 3-9: Hydraulic compression test machine used for testing compressive strength.

Figure 3-10: Samples after compression test.

3.4.2 Porosity Test

The porosity of a material is crucial because it directly affects water permeability, freeze-thaw resistance, and structural strength. When engineers understand porosity, they can choose materials that best balance durability, water drainage, and load-bearing ability. This information is essential for the construction of sturdy and secure roadways.

Figure 3-11: Porosity test setup.

In order to perform the porosity test, 5–10 g of samples were immersed in DI water (**Figure 3-11**) for 24 hours, after which they are removed and vacuum filtered (**Figure 3-12**).

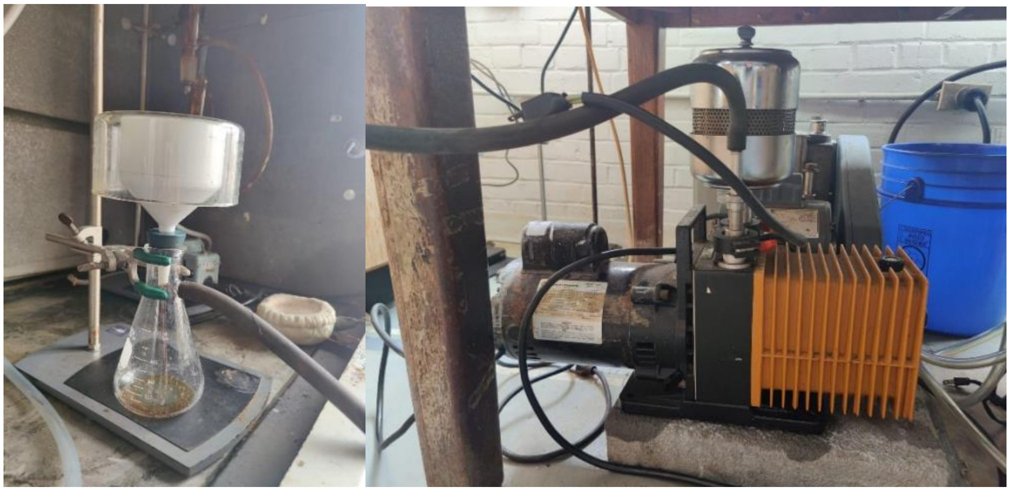

Figure 3-12: Collecting small geopolymer particles and separating by water vacuum filtration.

Afterwards, the samples' wet weights were carefully measured and noted. The samples were then put in the oven (**Figure 3-13**) for 72 hours at 105 ℃, and every 24 hours, the dry weight of the samples were carefully noted.

Figure 3-13: Placing samples in the oven.

The porosity was calculated using the following formula:

$$Porosity\,\% = \frac{Wet\ weight - Dry\ weight}{Dry\ weight} * 100 \qquad \textbf{Eq. 3-1}$$

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Compressive Strength

4.1.1 Compression test of synthesized geopolymer CS (710 μm particles) at 0%, 5%, and 10%

The compressive strength data for the samples is tabulated in **Table A-6**. The average strength for 100% FA was 9510.6 kPa (1379.4 psi). When the CS particle size was 710 μm, the average strengths of 95% FA with 5% CS and 90% FA with 10% CS ratio were 7940 kPa (1151.6 psi) and 5642 kPa (818.3 psi), respectively. The graph of the compressive strength for the individual sample is presented below for a specific FA to CS ratio, (**Figure 4-1**).

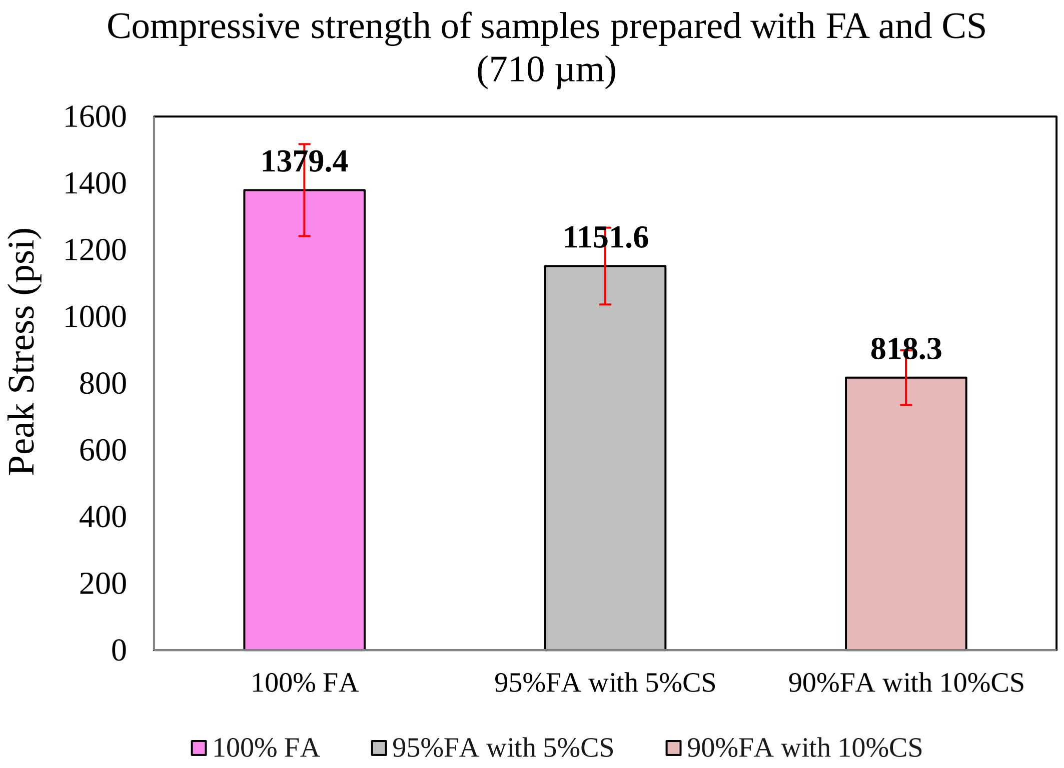

Figure 4-1: Compressive strength of synthesized geopolymer with CS (710 µm particles) at 0%, 5%, and 10%, with standard error bars.

4.1.2 Compression test of synthesized geopolymer with CS (180 µm particles) at 0%, 5%, and 10%

Nine samples total—three sets of three samples each—were prepared for each mixture. The CS-containing average strengths were 4702.9 kPa (682.1 psi) for 90% FA with 10% ratio and 4496.8 kPa (652.2 psi) for 95% FA with 5% CS, with a particle size of 180 µm. The compressive strength of the lower percentage composition of CS was found to be the highest, as shown in **Figure 4-2**. However, experimental variability means that no significant difference in compression strength can be found between the 5% and 10% CS samples.

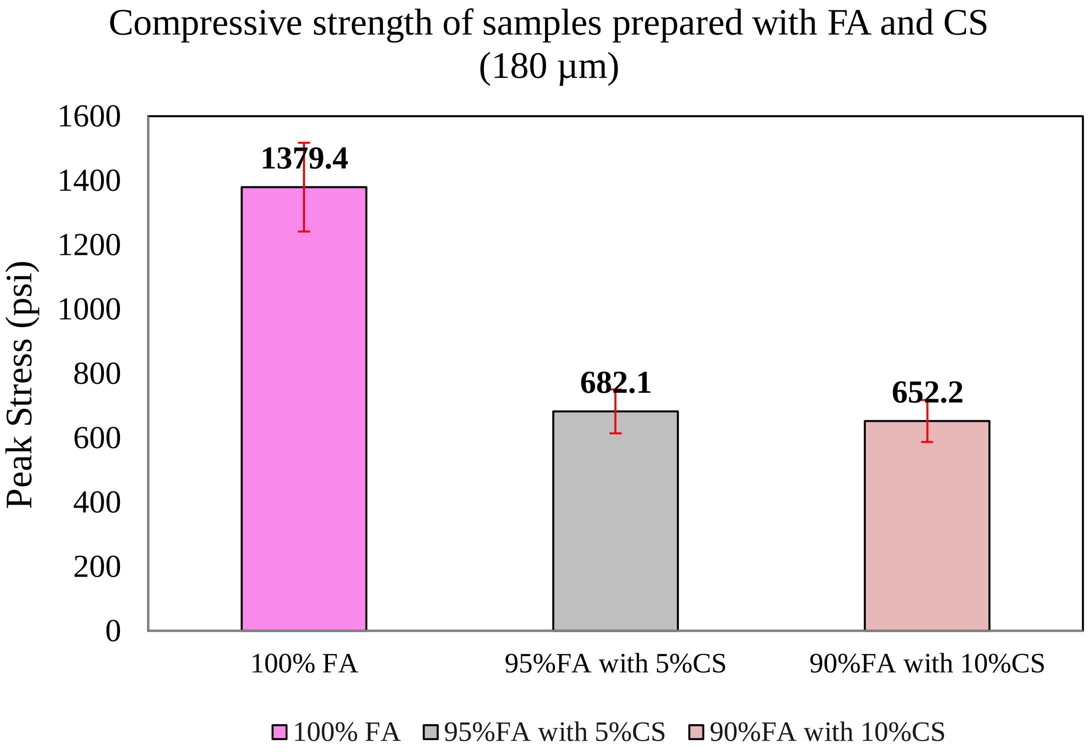

Figure 4-2: Compressive strength of synthesized geopolymer with CS (180 µm particles) at 0%, 5%, and 10%, with standard error bars.

In a standard matrix scenario, coarse and fine aggregates are mixed with cement for creating concrete that interlocks between its individual components to increase strength. On the other hand, aggregates are not present in our case. It is therefore possible that the matrix's interlocking is not fully developed, resulting in a failure to attain the desired level of strength. Additionally, since the mix designs do not contain the coarse aggregates, and rely heavily on fine graded fly ash, this mix has relatively high packing density owing to micro/nano particles and requires a considerable increase in mixing energy and the use of specialized mixing equipment.

4.2 Porosity Test

The porosity % data for the samples is tabulated in **Table A-12**. The porosity test was conducted after the compression test was completed. The test was conducted using sample pieces that weighed between 5 and 10 grams. The porosity of the samples was measured at 24, 48, and 72 hours.

4.2.1 Porosity Test of Synthesized Geopolymer with CS (710 µm particles) at 0%, 5%, and 10%

1) In 100% FA samples, porosity tests showed readings of 39.26% (24 hours), 40.78% (48 hours), and 40.98% (72 hours).
2) Comparable results were obtained from porosity tests on 5% CS and 95% FA, which were 45.65% (24 hours), 45.93% (48 hours), and 45.97% (72 hours).
3) The results of porosity testing on 10% CS and 90% FA were 45.92%, 46.28%, and 46.35% after 24, 48, and 72 hours, respectively.

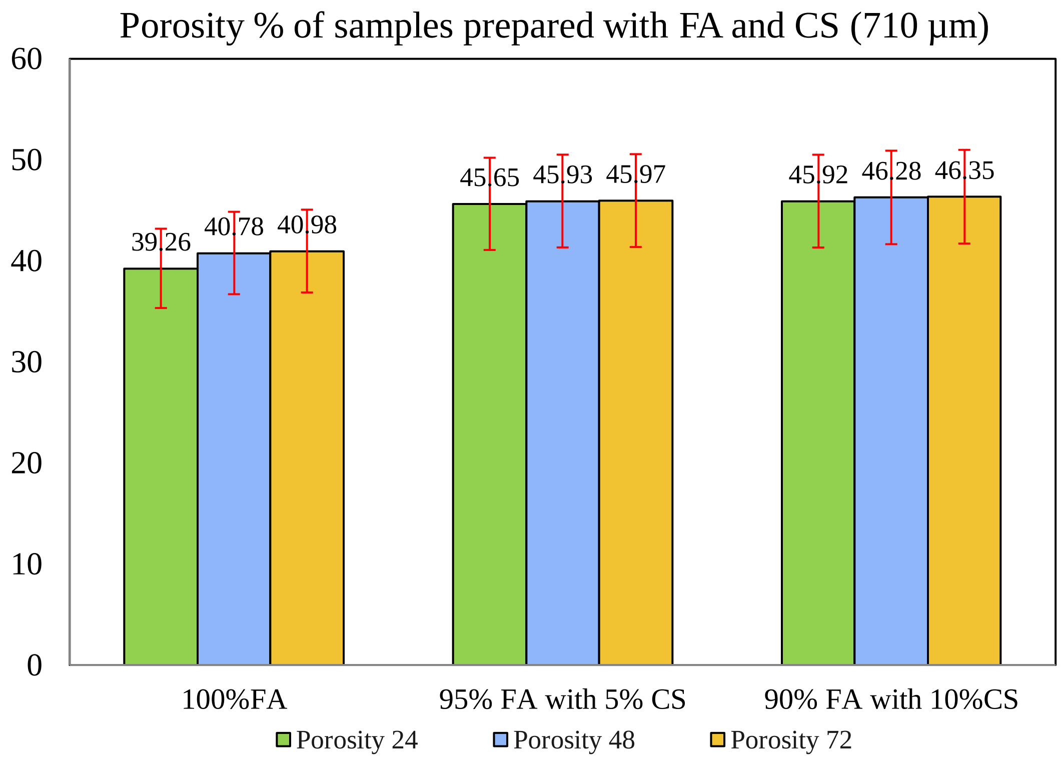

Figure 4-3: Porosity of synthesized geopolymer with CS (710 µm particles) at 0%, 5%, and 10%.

4.2.2 Porosity Test of Synthesized Geopolymer with CS (180 µm particles) at 5%, and 10%

1) Porosity tests on 95% FA and 5% CS showed values of 47.28% (24 hours), 47.58% (48 hours), and 47.71% (72 hours).
2) Similarly, porosity tests on 90% FA and 10% CS showed values of 50.22% (24 hours), 50.52% (48 hours), and 50.80% (72 hours).

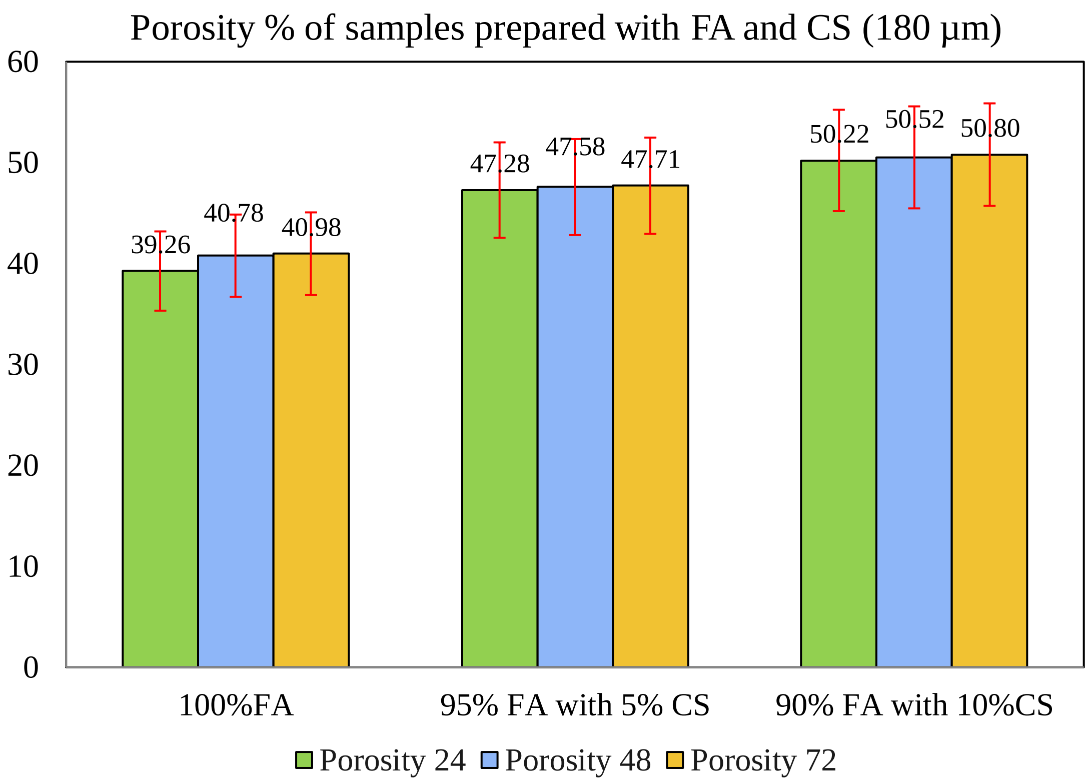

Figure 4-4: Porosity of synthesized geopolymer with CS (180 μm particles) at 5%, and 10%.

CS addition appears to increase geopolymer porosity. This increase is more pronounced with higher CS percentages and smaller CS particle sizes. However, the variability in the data means that no definite conclusions can be drawn.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

Previous studies indicate that adding corn stover (CS) to geopolymers for pavements could have advantages. With its silica and alumina content, CS—especially if used raw—may contribute to the process of synthesizing of geopolymer. Furthermore, the fibers in CS may improve the workability of the different mixes or even increase the hardened geopolymer's resistance to cracks. The organic components in CS might create pores, influencing the material's porosity and thermal insulation characteristics. Based on findings from the various experiments conducted, the following conclusions were drawn:

1) Compressive strength usually decreases as the proportion of CS in the geopolymer increases. This implies that, to preserve load-bearing capacity, there may be a limit to the percentage of CS incorporation.
2) At the same CS proportion levels, bigger CS particles (710 μm) seem to contribute to higher compressive strengths than smaller particles (180 μm).
3) The porosity of the geopolymer may increase with the addition of CS. Greater porosity may be the result of smaller particle sizes and higher CS content.

5.2 Future Work and Implementation

Sustainability in building materials is becoming more and more important as environmental concerns and the depletion of natural resources increase. Geopolymer is made from industrial wastes like FA. Agricultural wastes from food production are renewable. These unavoidable wastes may offer viable solutions for sustainable building materials because they use fewer mined resources. However, there are technological gaps that must be addressed to synthesize geopolymers from these types of wastes, such as CS and FA. Future research should explore the best way to balance the performance of the geopolymer with the content of CS.

First, to improve the strength of the geopolymer with CS in it, partial replacement of the binding materials like cement may be beneficial. Also, the addition of traditional aggregates like sand and gravel will enhance the strength of the geopolymer. The properties of the geopolymer can also be impacted by improper curing conditions, such as temperature, relative humidity, and setting time. Curing conditions can be optimized by ensuring the proper hydration and synthesis of geopolymer, which are critical to achieving maximum strength.

Second, adding CS whose size is comparable to coarse aggregates can be explored as a means of achieving permeability in a geopolymer. However, evaluation is needed to ensure the long-term stability and strength of such geopolymers under challenging environmental circumstances. In addition, pre-treating the CS may reduce its biodegradability.

Lastly, to evaluate the effectiveness of the geopolymer synthesized using CS and FA, other tests should be conducted. These tests include the slump test to assess the workability of the geopolymer mixes, the split tensile test to determine tensile strength, the fineness test to measure CS particle size distribution for optimized performance and the shrinkage test to evaluated dimensional stability which is crucial for preventing cracking in pavements.

APPENDIX A

DETAILED DATA OF EACH COMPOSITION

This appendix contains the specific data generated by the study.

A.1 Detailed Data of Compressive strength

Table A-1: 100% FA, 0% CS.

Samples	*Max Load (lbs.)*	*Max Stress (psi)*
1	4280	1070.6
2	5670	1417.9
3	5230	1307.3
4	6540	1635.6
5	4530	1132.5
6	5910	1478.1
7	4960	1239.7
8	6710	1677.7
9	5820	1455.0
Avg.	5517	1379.4

Table A-2: 95% FA, 5% CS (710 µm).

Samples	*Max Load (lbs.)*	*Max Stress (psi)*
1	4130	1032.7
2	4200	1049.2
3	4280	1070.6
4	4430	1108.6
5	4330	1082.2
6	4610	1153.1
7	4780	1196.0
8	5370	1342.0
9	5320	1329.6
Avg.	4606	1151.6

Table A-3: 90% FA, 10% CS (710 μm).

Samples	***Max Load (lbs.)***	***Max Stress (psi)***
1	3790	947.7
2	3460	865.6
3	3310	827.5
4	2830	707.2
5	2830	708.1
6	3080	770.6
7	4000	998.9
8	4370	1092.9
9	1790	446.6
Avg.	3273	818.3

Table A-4: 95% FA, 5% CS (180 µm).

Samples	***Max Load (lbs.)***	***Max Stress (psi)***
1	2860	715.4
2	2850	712.9
3	3430	857.5
4	2460	614.7
5	2000	501.0
6	1720	431.2
7	2130	532.7
8	4210	1053.3
9	2880	720.2
Avg.	2727	682.1

Table A-5: 90% FA, 10% CS (180 µm).

Samples	***Max Load (lbs.)***	***Max Stress (psi)***
1	2740	685.3
2	2910	728.4
3	3240	810.4
4	1930	481.5
5	1610	402.7
6	1920	480.7
7	2930	733.2
8	3170	793.3
9	3020	754.3
Avg.	2608	652.2

Table A-6: Average stress data of each composition of FA and CS with 710/180 μm particles.

Composition	*Max Loads (lbs.)*
100% FA	1379.4
95% FA, 5% CS (710 μm)	1151.6
90% FA, 10% CS (710 μm)	818.3
95% FA, 5% CS (180 μm)	682.1
90% FA, 10% CS (180 μm)	652.2

A.2 Detailed Data of Porosity %

Table A-7: 100% FA, 0% CS.

Samples	Porosity 24	*Porosity 48*	*Porosity 72*
1	44.30	44.67	44.81
2	42.35	42.64	43.00
3	35.73	36.09	36.21
4	39.08	39.20	39.39
5	40.38	40.77	41.23
6	37.87	38.13	38.36
7	40.98	41.29	41.34
8	44.57	44.89	44.92
9	28.11	39.37	39.51
Avg.	39.26	40.78	40.98

Table A-8: 95% FA, 5% CS (710 µm).

Samples	**Porosity 24**	***Porosity 48***	***Porosity 72***
1	43.58	43.77	43.89
2	44.71	44.79	44.98
3	49.14	49.27	48.83
4	46.50	46.83	46.85
5	50.46	50.62	50.71
6	44.91	45.04	45.08
7	45.63	46.23	46.36
8	43.02	43.60	43.79
9	42.88	43.19	43.22
Avg.	45.65	45.93	45.97

Table A-9: 90% FA, 10% CS (710 µm).

Samples	**Porosity 24**	***Porosity 48***	***Porosity 72***
1	47.53	48.04	48.11
2	46.97	47.43	47.53
3	44.37	44.73	44.80
4	44.38	44.56	44.62
5	47.76	47.94	48.07
6	47.60	47.83	47.85
7	44.89	45.36	45.37
8	46.60	47.11	47.24
9	43.17	43.56	43.59
Avg.	45.92	46.28	46.35

Table A-10: 95% FA, 5% CS (180 μm).

Samples	**Porosity 24**	***Porosity 48***	***Porosity 72***
1	48.18	48.45	48.59
2	47.02	47.13	47.20
3	49.84	50.50	50.68
4	46.86	47.42	47.48
5	46.52	47.21	47.15
6	45.85	45.94	46.14
7	48.17	48.25	48.40
8	46.20	46.30	46.57
9	46.92	47.04	47.22
Avg.	47.28	47.58	47.71

Table A-11: 90% FA, 10% CS (180 μm).

Samples	**Porosity 24**	***Porosity 48***	***Porosity 72***
1	49.60	49.92	50.30
2	46.62	46.73	47.15
3	44.91	45.27	45.70
4	49.61	49.80	49.95
5	50.80	51.07	51.23
6	47.88	48.06	48.32
7	47.49	47.90	47.98
8	62.81	63.37	63.64
9	52.27	52.61	52.89
Avg.	50.22	50.52	50.80

Table A-12: Average porosity % of each composition of FA and CS with 710/180 μm particles.

Samples	**Porosity 24**	***Porosity 48***	***Porosity 72***
100% FA	39.26	40.78	40.98
95% FA, 5% CS (710 μm)	45.65	45.93	45.97
90% FA, 10% CS (710 μm)	45.92	46.28	46.35
95% FA, 5% CS (180 μm)	47.28	47.58	47.71
90% FA, 10% CS (180 μm)	50.22	50.52	50.80

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