University of Southern Queensland

School of Engineering

Mechanical Performance of Engineered Cementitious Composites (ECC) with Substitution of Fly Ash by Pond Ash

A dissertation submitted by

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Abstract

Pond ash is a residual waste material from coal combustion which poses significant environmental challenges when it comes to disposal, often leading in landfill. Previous literature demonstrates potential to adopt this waste material as a partial substitution for cement or fine aggregate in ordinary concrete. To contribute to the ongoing research in this area, effects on Engineered Cementitious Composites (ECC) were investigated to address the traditional weaknesses of conventional concrete.

ECC, also known as 'bendable concrete', is well known due to its crack width control, fatigue durability and flexural strength. This fibre reinforced mortar typically requires fine sand, fibres and an increased cement content as replacement for all coarse aggregate, generally increasing construction costs.

This study is the first to evaluate the performance of pond ash in ECC, more specifically as a partial substitution for fly ash. A typical control fly ash ECC batch was prepared to compare with the pond ash ECC samples, volumetrically replacing fly ash with 25%, 50% and 100% pond ash. A three-step mix process was adopted to optimise the fibre distribution and rheological properties to ultimately increase the performance of the samples.

Cube specimens were formed to assess the compressive strength of the specimens at both 7 and 28 days. Similarly, flexural beam test specimens were formed to evaluate the flexural strength and briquette specimens for the uniaxial tensile strength.

The results indicate that pond ash is a viable substitution for fly ash in ECC. Compressive strength results showed significant strength increase at 25% and 50%, with smaller increases reported for 100% pond ash replacement. Pond ash was not seen to provide any notable changes in strength for flexural strength and was generally consistent for all replacement levels. Similar to compressive strength, the uniaxial tensile strength increased at 25%, however demonstrated extremely poor strength at 100% replacement. Ultimately, 25% replacement reported the best overall mechanical performance, therefore warranting further research.

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Limitations of Use

CERTIFICATION OF DISSERTATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Nomenclature

ECC – Engineered Cementitious Composite

GGBS – Ground Granulated Blast-furnace Slag

HRWR – High Range Water Reducer

w/b – Water to Binder

CHAPTER 1

INTRODUCTION

1.1 Introduction

The construction industry plays a vital role in shaping the built environment and providing infrastructure that contributes to the modern world that we see today. However, mass production and use of traditional construction materials such as cement are significant contributors to environmental issues such as carbon emissions and the depletion of essential natural resources. While it is crucial that the modern world continues to develop, a balance between further developments and reducing the environmental impact of this infrastructure must be conserved.

Developed in 1824 by Joseph Aspdin and named after its resemblance with oolithic limestone on the Isle of Portland, Portland cement has been the cornerstone in creating concrete and is still widely used to this day (Gagg 2014). Typically, Portland cement acts as the matrix when combined with water and aggregates such as sand or gravel, with chemical additives available to alter and achieve the desired properties. Currently cement production alone contributes more than 7% of the worlds annual greenhouse gas emissions as a result of energy use and chemical reactions (Miller et al. 2021).

Driven by the goals of net zero emissions by 2050 and an attempt to reduce reliance of natural resources, the advancement of research surrounding sustainable construction materials has improved, particularly surrounding concrete and potential material substitutions. Waste materials such as fly ash, polyethylene terephthalate (PET) plastics, recycled aggregates and pond ash have surfaced as potential alternatives to reduce not only the cost, but the high greenhouse gas emissions associated with concrete production. This subsequently acts to reduce landfill area that is often required for unused waste.

More recently, pond ash has been investigated as a potential waste product that can be utilised in the production of concrete, either as a substitute for cement or fine aggregates. Pond ash has generally been overshadowed by fly ash which has been widely adopted due to its higher pozzolanic property and finer nature in comparison (Romeekadevi & Tamilmullai 2015).

Designed using micromechanics theory in 1990s by Li, engineered cementitious composites (ECC) have received attention worldwide due to its crack width control, fatigue durability and flexural strength and performance (Zhang et al. 2020; Kan et al. 2019). Unlike ordinary concrete, ECC can strain harden after the first crack, acting similarly to a ductile metal and increasing the strain capacity by 200-500 times (Kan et al. 2019). To achieve this, coarse aggregate must be removed leaving fine sand and typically 2% volume of fibres replacing all coarse aggregates which ultimately acts to increase the cement content and consequently greenhouse gas emissions (Zhang et al. 2020; Kan et al. 2019).

To cater to the higher demand for mega-structures and improve damage-tolerance, resilience and durability for infrastructure, ECC proves to be an ideal construction material (Zhang et al. 2020). However, there are still gaps in the existing body of research surrounding methods to develop greener versions of ECC while still maintaining its desirable characteristics. One of these gaps is the potential use of pond ash in ECC which this project endeavours to address.

1.2 The Problem

To aid in the war against climate change, the construction industry has the unique ability to use waste as key resources in construction materials such as concrete or ECC. Pond ash is an abundant waste material that currently resides in landfill, occupying precious land space and impacting the environment. However, research has recently shown potential for pond ash to be utilised in concrete as partial replacement of cement or fine aggregate.

No research has been undertaken with pond ash in ECC, therefore revealing a gap for another potential use for this waste material. This project will attempt to fill this gap in the existing literature by experimentally investigating the impact on mechanical properties of partial replacement of 25%, 50% and 100% pond ash with fly ash in ECC.

The results from this study should be used to verify if pond ash is a suitable sustainable replacement material. It will also contribute to the ever-growing knowledge of sustainable construction materials and potentially act as a foundation for future research on pond ash in ECC to continue.

1.3 Research Objectives

If the results on pond ash replacement in ECC are successful, it is expected to promote further research and eventually be adopted as a sustainable construction material for widespread use. This would help to limit this waste material from entering landfill and reduce the environmental impacts.

To achieve these goals, several objectives have been outlined below:

1. Produce pond ash ECC with fly ash replaced with pond ash by 25%, 50% and 100% volume.
2. Evaluate the use of pond ash in ECC.
3. Develop pond ash ECC knowledge and the effects on the mechanical performance of ECC.
4. Contribute to the existing knowledge base of alternative, sustainable ECC materials to assist further research in the field of green ECC.

1.4 Expected Outcomes

It is well known that in general, ECC is more expensive to produce than ordinary concrete while still putting strain on the environment and the Earth's natural resources. This project aims to expand the existing body of research surrounding potential sustainable alternatives to reduce the environmental footprint caused by the construction industry. To achieve this, thorough research and laboratory trials are required to understand the effect of these materials on the mechanical properties of ECC. Pond ash replacement has recently arisen as a potential alternative construction material and therefore, it is anticipated that this project will provide a foundation for future research surrounding pond ash in ECC.

The project will aspire to deliver the following outcomes:

1. Determine the effects of pond ash replacement on the mechanical properties of ECC.
2. Increase industry confidence in the viability of pond ash as a sustainable alternative in ECC.
3. Provide a knowledge base from which additional research can be conducted to further expand the understanding of pond ash ECC.

1.5 Thesis Outline

An outline of the dissertation chapters has been outlined below:

Chapter 1 Introduction to the project topic, problem, objectives and expected outcomes.

Chapter 2 Literature review containing an overview of previously published academic research related to the project. Past research, ideas and conclusions presented in this chapter can be utilised to identify a gap in existing research and formulate the methodology going forward.

Chapter 3 Methodology outlining the experimental mixture design, process and standards to which the experimental investigation with be undertaken.

Chapter 4 Experimental testing outlines the tasks completed for the experimental investigation. This includes sourcing the materials, an analysis of their properties, mixture design, testing and any challenges identified or mitigated throughout the process.

Chapter 5 Presentation of results, including an evaluation and discussion of the mechanical properties of pond ash ECC. This will consider the viability of pond ash ECC as a potential sustainable alternative in the construction industry.

Chapter 6 Concludes the project with a summary of key findings and recommendations for future research opportunities surrounding pond ash ECC.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

In recent history, rapid growth and heavy construction activity worldwide has resulted in an increasingly high raw material consumption, ultimately limiting supply of vital materials such as concrete (Yimam et al 2021).

In an attempt to simultaneously reduce potentially hazardous waste material from entering land fill and source sustainable raw material alternatives, possible uses for waste material are being explored. Coal combustion residue emitted from thermal power plants is just one waste material that has become a severe environmental problem due to common disposal methods resulting in land fill (Yimam et al 2021). In India alone it is estimated that approximately 200 million square metres of land area is used to store one million tons of pond ash (Harle 2019).

Industrial power plants are often coal based which requires enormous amounts of coal and produce an ash by-product that can be considered fly ash or bottom ash depending on particle size (Harle 2019).

Fly ash is more abundant and has already been adopted as an ideal component in concrete due to the ability for fine particles to bind together and solidify when mixed with water resulting in a safe and more effective product (Harle 2019). Furthermore, fly ash acts to increase durability and reduce permeability, W/C ratio, expansion due to alkali aggregate reaction and improve long term strength (Haldive & Kambekar 2013). Bottom ash is a much coarser by-product and makes up approximately 10% of the waste, however has very little use as it remains toxic when recycled (Harle 2019).

Pond ash is formed as a combination of fly ash and the much coarser bottom ash after being disposed of within an engineered ash impoundment in the form of a slurry, usually comprised of 1 part ash and 6 to 10 parts water (Harle 2019). After the slurry dries, slurry clinkers form that can be collected as pond ash which consists of a fused coarser and fine particle with a slightly pozzolanic nature (Yimam et al 2021, Harle 2019).

Concrete based construction is known to be able to utilise waste materials and by-products for industrial coal power plants with the use of fly ash as a common binder in concrete mix (Yuvaraj & Ramesh 2022). However, more recent research surrounding pond ash in concrete aims to utilise the waste material such that strength and quality of concrete are maintained while simultaneously reducing construction costs (Harle 2019)

Since the invention of Engineered Cementitious Composites (ECC) in the early 1990's, the material has made its way into construction sites, precast plants and repair projects as a class of ultra ductile reinforced cementitious composite. While the initial cost of raw materials required for ECC is higher than normal concrete, the potential strength is significantly greater with reports of tensile strain capacities up to 500 times that of normal concrete. When compared to normal concrete, the additional cost arises with the higher cement content and the addition of polymer fibres such as polyvinyl alcohol (PVA) (Li 2003)

To extend sustainable raw materials into the field of high strength, high ductility ECC, research is now being conducted with the hope to introduce eco-friendly waste materials such as pond ash or rice husk ash as substitutes to fly ash (Zhang et al. 2020).

2.2 ECC Using Alternative Materials

ECC have been developed using micromechanics-based design and can achieve strain capacity of over 3% while maintaining a crack width below 100µm when in tension which gives ECC excellent performance and high ductility (Lu et al. 2023). Within this micromechanics design, both the strength and energy criterion must be satisfied, where matrix toughness (J_{tip}) does not exceed the maximum complementary energy (J_b'). Simultaneously, the maximum fibre bridging strength (σ_c) must be larger than the strength criterion which determines additional cracking to occur after the first crack (σ_0) which has been illustrated in the figure below. In practice it is recommended that ECC be designed to suit $\sigma_0 / \sigma_c \geq 1.3$ and $J_b' / J_{tip} \geq 2.7$ (Lu et al. 2023).

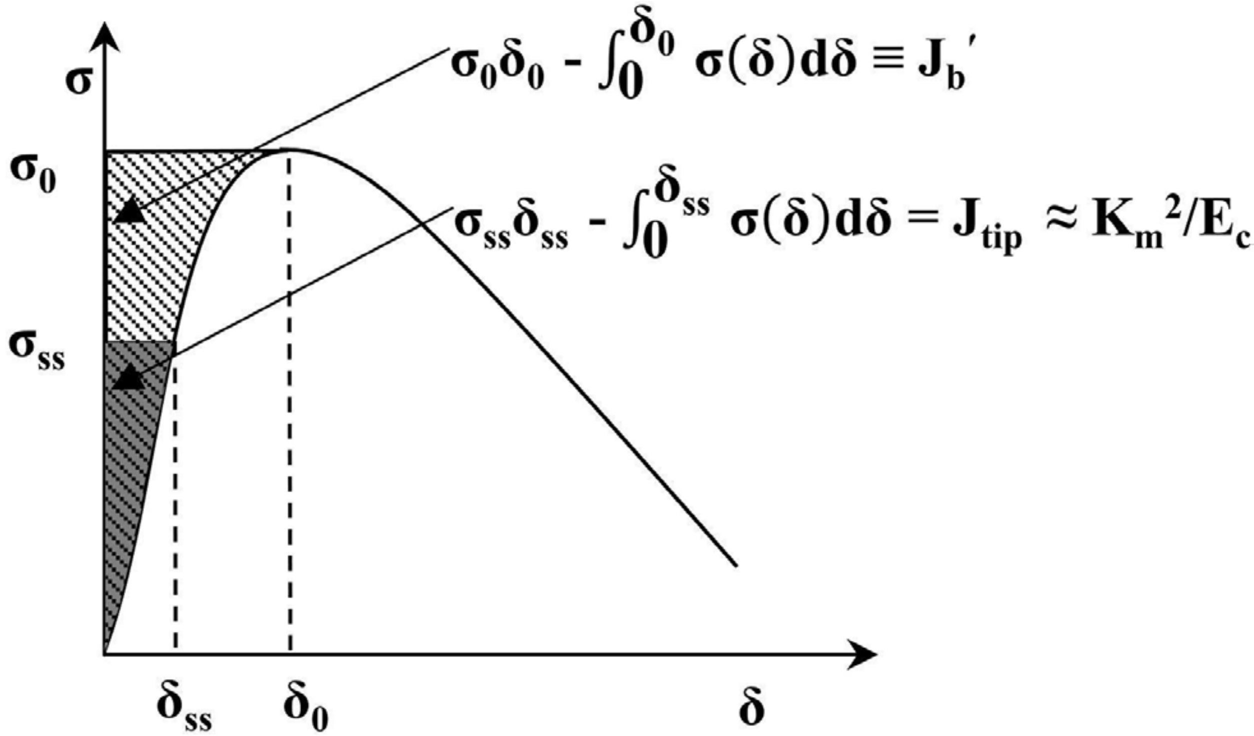

Figure 2-1 Typical curve for strain-hardening composites (Lu et al. 2023).

While this theory has proved effective in the development of high ductility and performance concrete, it generally limits ECC to include more expensive and less environmentally friendly materials. Although, research has been conducted in an attempt to find more cost effective, readily available and sustainable substitutes to continue the development of ECC moving forward.

Early research surrounding ECC sustainability noted that fly ash/cement ratio could be increased up to 5.6 which had a drastic effect on reducing the emissions by decreasing cement content from 838kg/m^3 to 190kg/m^3. In addition, high fly ash content was found to increase the properties and fibre dispersion within ECC, increasing the interfacial friction bonds leading to smaller cracks (Yang et al. 2007; Wang & Li 2007). Similar studies completed by Yu & Leung (2017) demonstrated 80% replacement of cement with fly ash and a water/binder ratio of 0.2 showed promising characteristic strength of 62.2 MPa and ductility of 3.7%. Zhang et al. (2014) concluded that self-healing behaviour of ECC was improved as fly ash content increased as the ductility increased, acting to reduce crack width. Ground Granulated Blast-furnace Slag (GGBS) with fly ash was also tested by Alyousif el al. (2015) as a possible alternative, although was found that the ductility was inferior when compared to the previously tested fly ash ECC. Overall, data collated by Mahmoudi et al. (2022) concluded that GGBS does produce positive results and demonstrating increases in tensile strain.

With past research suggesting that high quality fly ash increases the performance of concrete and ECC alike, demand has increased significantly, with Zhang et al. (2020) suggesting that it should no longer be considered a waste material as a result. Furthering the body of research around sustainable alternatives, slag and rice husk ash have been considered. A study by Zhu et al. (2012) found that slag as a partial replacement for fly ash demonstrated increased properties up to a 20% replacement while Zhang et al. (2020) concluded that rice husk ash as replacement of fly ash up to 50% improved the performance.

Literature has investigated a range of fibres for use in ECC such as polypropylene (PP), polyethylene (PE) and polyvinyl alcohol (PVA), however PVA fibres are over eight times cheaper than PE fibres and show higher tensile strength, generally making it the optimal fibre material for ECC research (Meng et al. 2017). While these alternative fibres have been researched and can provide promising results, they are not as well studied or used and will therefore not be considered in this project.

2.3 Pond Ash Concrete Performance

Research surrounding pond ash replacement has currently been condensed into two categories, either acting as a partial replacement for cement or fine aggregate. Mechanical properties for compressive, tensile and flexural strength of ordinary cement and mortars have been well documented to typically decreases in specimens supporting pond ash replacement greater than 20%, regardless of which material is being replaced (Yimam et al. 2021; Harle 2019; Lal et al. 2019; Kumar & Radhakrishna 2020; Yuvaraj & Ramesh 2021). However, the existing research on the effects of fine aggregate replacement of pond ash up to 20% greatly varies, which may be attributed to the different pond ash sources.

By directly comparing two different pond ash sources, Jung & Kwon (2013) concluded that the mechanical performance of pond ash replacement in concrete was greatly affected by the source of coal used to create the pond ash as it impacts the porosity, surface shape and roughness. These small details were also noted to affect the workability and absorption ratio of the mix with irregularly angulated surfaces demonstrating porous properties and requiring a greater w/c ratio due to the large surface area and interlocking effect (Jung & Kwon 2013). As a result, this research by Jung & Kwon (2013) noted that by increasing the w/c ratio for pond ash with these qualities, it allowed for a greater amount of cement binder to be sufficiently cured and therefore, presented higher characteristic mechanical properties.

Similarly, findings by Lal et al. (2019) suggested that fine aggregate replacement by pond ash exceeding 40% resulted in a reduction of compressive strength because of more porous particles in the mortar remaining less reactive with calcium hydroxide to form C-S-H gel, the paste responsible for concrete strength. Likewise at 20% pond ash replacement of sand the flexural strength reduced suggesting that the bond between pond ash particles and cement with sand show less pozzolanic reaction when exceeding 20% replacement (Lal et al. 2019). It should also be noted that the lower specific gravity and porous nature of pond ash leads to increased voids which may be resulting in the reduced strength performance compared to natural sand as a fine aggregate (Kumar & Radhakrishna 2020).

Research conducted by Kumar & Radhakrishna (2020) and Lal et al. (2019) established that compressive strength development of mortar with PA replacement of fine aggregate continued to increase past 28 days of curing. The addition of pond ash in the mix increases the requirement of water as outlined by Jung & Kwon (2013) which delays the hydration process and ultimately prolongs the curing time (Lal et al. 2019). This has been assumed to be a result of the pozzolanic action of pond ash and the release of absorbed water to continue the hydration process (Kumar & Radhakrishna 2020; Lal et al. 2019). This should be taken into consideration as the typical 28-day strength of pond ash concrete may decrease performance, but if given the opportunity for a longer curing duration then it may prove to outperform ordinary concrete.

No published research has investigated the effect of pond ash in ECC, therefore there is a research gap in the performance of pond ash and its effect in ECC.

2.4 Pond Ash Concrete Properties

2.4.1 Workability

The existing literature on the effects on workability of pond ash replacement in ordinary cement and mortar presents varied results with decreases in workability more heavily reported. These differences may result from the different tests, either using cement or mortar, and pond ash replacement of either fine aggregate or cement. It should also be noted that pond ash can vary depending on the power plant which may impact the results (Harle 2019; Lal et al. 2019; Yuvaraj & Ramesh 2021).

The effect of pond ash replacement of fine aggregate in concrete has been reported by Yimam et al. (2021) to have a direct correlation to the workability in concrete mix, with pond ash content exceeding 10% replacement of fine aggregate resulting in low workability. Similar findings by Harle (2019) found reduced workability and suggested the use of a plasticiser. Dynamon SR 500R was found to not only increase the workability but also the compressive strength of the concrete at 20% pond ash replacement of fine aggregate (Harle 2019).

Kumar and Radhakrishna (2020) reported that the water/cement ratio in ordinary concrete was required to increase proportionally with pond ash replacement of fine aggregate to achieve the desired workability. Using a Scanning Electron Microscope (SEM) image of pond ash, it shows a higher presence of porous particles than fine aggregate, which acts in conjunction with increased surface area and water absorption property to justify the reason for higher water demand (Kumar & Radhakrishna 2020).

Sofi and Phanikumar (2015) noted contradicting results, with the addition of pond ash increasing the overall workability, while adding grooved steel fibres acted to reduce the workability of the mix. However, the mix design in these tests incorporated the use of pond ash through replacement of cement in concrete rather than fine aggregate which may explain the differences in results.

No published research has been found on the effect on workability of pond ash substitution in ECC and is therefore a knowledge gap to be explored.

2.4.2 Compressive Strength

The characteristic strength of concrete is typically associated with its compressive strength in mega pascals (MPa) after curing for 28 days. Major factors can impact the compressive strength of ordinary concrete including the w/c ratio, extent and progress of hydration, age and curing conditions (Gagg 2014).

Figure 2.2 shown below outlines the typical compressive strength range that is expected at a particular w/c ratio, indicating a prominent relationship between compressive strength and the w/c ratio used. A strong correlation is demonstrated that as the w/c ratio increases there is a corresponding decrease in compressive strength.

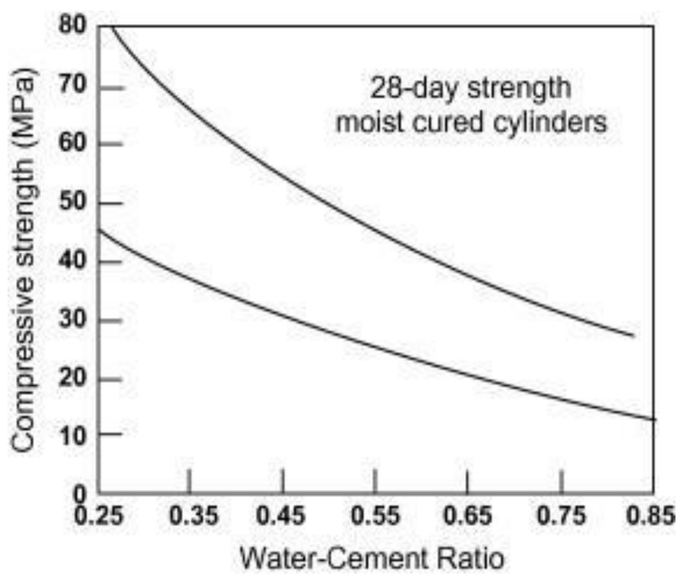

Figure 2-2 Typical range of strength to w/c ratio relationships of portland cement concrete (Gagg 2014).

It has been well documented that the compressive strength of ordinary concrete or mortar reduces as pond ash replacement of fine aggregate increases beyond 20% replacement (Yimam et al. 2021; Harle 2019; Lal et al. 2019; Kumar & Radhakrishna 2020; Jung & Kwon 2013 and Haldive &

Kambekar 2013). However, there are generally discrepancies in the results between 5% to 20% replacement with results by Haldive & Kambekar (2013), Harle (2019) and Lat et al. (2019) suggesting that 20% PA replacement is the most optimal regarding compressive strength. Yimam et al (2021) noted small increases in compressive strength up to 10% replacement with decreasing strength proportional to percentage replacement when exceeding 10%. Others such as Kumar & Radhakrishna (2020) considered PA replacement from 20% up to 100% and found a strong trend demonstrating reduced performance. No two studies tested PA from the same location or to the same standard.

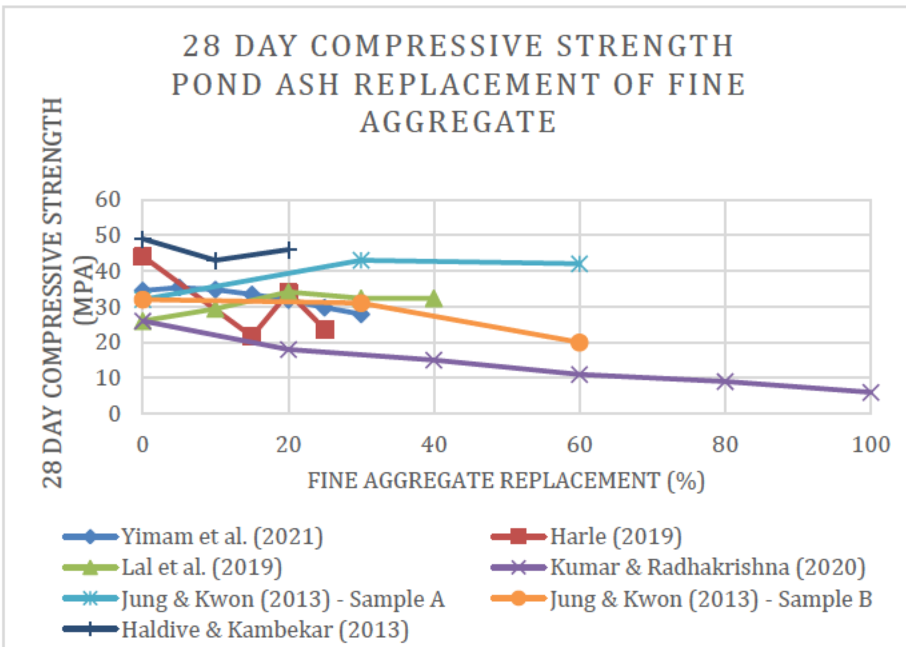

Figure 2-3 Pond ash replacement of fine aggregate concrete compressive strength variation at 28 days

While Jung & Kwon (2013) sample B pond ash provided results generally consistent with research conducted by others, the research conducted using pond ash from an alternative source demonstrated abnormal results increasing the characteristic strength significantly up to 30% replacement and maintaining it until 60%. This research was conducted with the same method as sample B and outlines the significance of the source of pond ash on the performance of pond ash concrete as suggested by Harle (2019), Lal et al. (2019) and Yuvaraj & Ramesh (2021). This inconsistency may also be explained by the variation in chemical properties present within pond ash, especially silica values (Harle 2019). All research utilised pond ash replacement by percentage weight in contrast to percentage volume.

Thorough research has been conducted by Haldive & Kambekar (2013) with testing on pond ash replacement of fine aggregate in addition to testing a combination of pond ash replacement of fine aggregate simultaneously with fly ash replacement of cement. Pond ash replacement was seen to outperform the control mix up to 20% replacement, however this was only achieved after curing for 90 days. Haldive & Kambekar (2013) states that pond ash initially acts as a pore filler and only after 10-12 days the fine particles of pond ash react with calcium hydroxide in cement to form cementitious material.

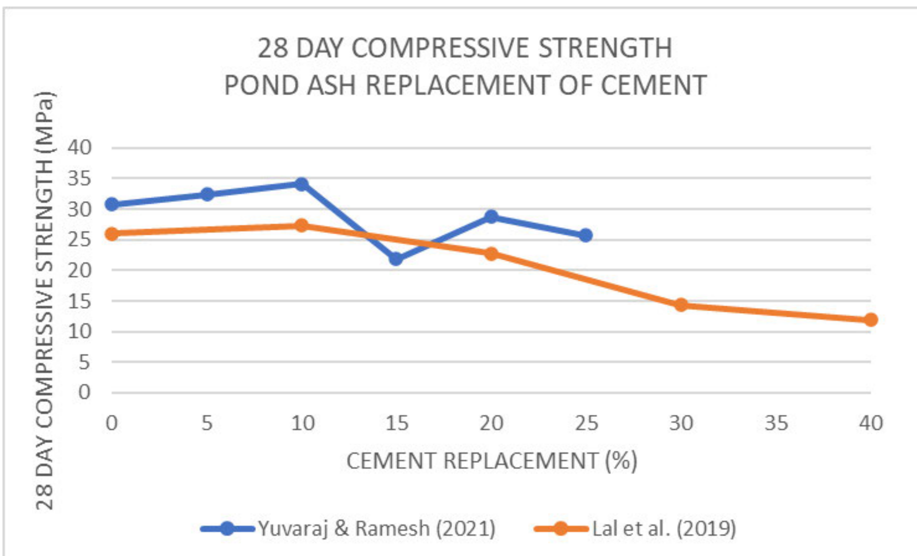

Figure 2-4 Pond ash replacement of cement concrete compressive strength variation at 28 days

Combining pond ash and fly ash replacement of fine aggregate reported a decrease in compressive strength at 28 days for all percentage replacements (Haldive & Kambekar 2013). However, Romeekadevi & Tamilmullai (2015) noted that during similar testing, the desired characteristic strength of 60MPa high strength concrete was achieved with cement replacement up to 10% fly ash, 5% pond ash and 5% lime which is consistent with the cement replacement findings by Yuvaraj & Ramesh (2021) and Lal et al. (2019).

2.4.3 Tensile Strength

The tensile strength in concrete is a vital mechanical property of concrete, although is generally estimated to only support 7% to 15% of its corresponding compressive strength (Liao et al. 2020). Therefore, this relationship provides a link for not only compressive strength in concrete to be heavily dependent on w/c ratio, extent and progress of hydration, age and curing conditions but subsequently also the tensile strength (Gagg 2014).

While there is very limited research on the tensile strength in pond ash replaced concrete, similar relationships can be seen between the general estimate for splitting tensile strength by Liao et al. (2020) and research conducted by Romeekadevi & Tamilmullai (2015). Cement replacement with a combination of fly ash, pond ash and lime were reported to produce splitting tensile strengths of approximately 12% - 14% of the mix's respective compressive strength, supporting the estimate by Liao et al. (2020).

The results from research conducted by Romeekadevi & Tamilmullai (2015) has been collated and displayed in Figure 2.5 below. The splitting tensile strength is seen to reduce as pond ash replacement of cement increases, which is consistent with the results from the characteristic compressive strength testing.

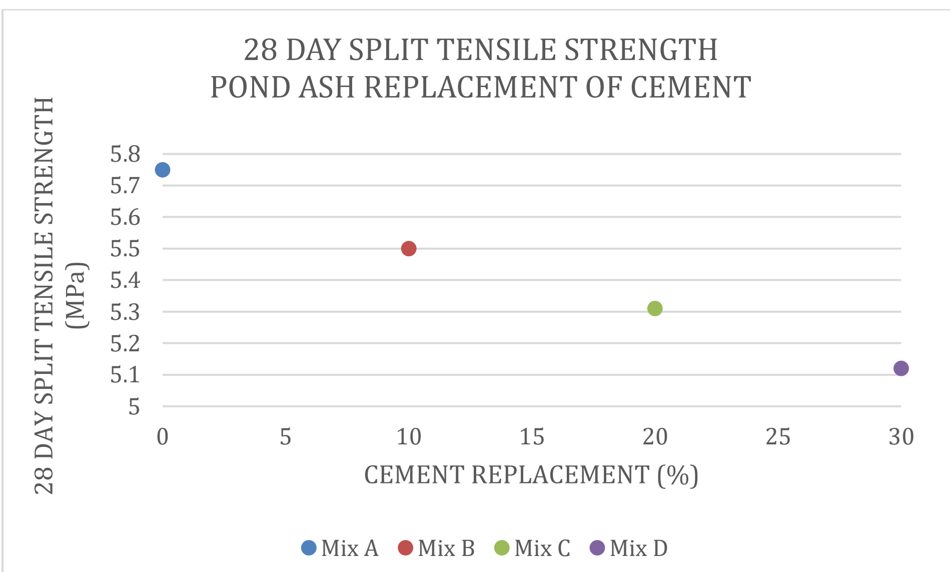

Figure 2-5 Pond ash replacement of cement concrete split tensile strength variation at 28 days

Table 2-1 Pond ash replacement of cement concrete split tensile strength mix proportions

Mix Proportion	Fly Ash (%)	Pond Ash (%)	Lime (%)
Mix A (0% Cement Replacement)	0	0	0
Mix B (10% Cement Replacement)	5	2.5	2.5
Mix C (20% Cement Replacement)	10	5	5
Mix D (30% Cement Replacement)	15	7.5	7.5

No further research has been conducted surrounding tensile strength testing in pond ash replaced concrete. However, with the limited research available the conclusion can be drawn that it will remain consistent with the estimated relationship with compressive strength as outlined by Liao et al. (2020).

2.4.4 Flexural Strength

A number of variations of pond ash replacement in concrete have been explored with the flexural strength observed and recorded, including pond ash replacement of sand or cement and a combination of pond ash, fly ash and lime replacement of cement.

Due to bonding between pond ash particles and cement with sand, pond ash replacement of sand was observed to increase or maintain flexural strength up to 30% replacement when compared to the control mix at 28 days. It was noted that beyond these limits of replacement the pond ash and cement showed less pozzolanic reaction which limited its ability to form harder mass (Lal et al. 2019).

Pond ash replacement of cement generally indicated a decrease in mortar strength with the exception of the increase in flexural strength at 20% replacement, however this appears to be an outlier and there is no explanation as to why this increase occurred (Lal et al. 2019). It should also be noted that while flexural strength saw small decreases up to 40% cement replacement, all samples exceeding 40% demonstrated significantly less flexural strength (Lal et al. 2019).

Sofi & Phanikumar (2015) conducted research on the flexural behaviour of concrete with pond ash replacement of cement, observing the addition of grooved type steel fibres. The addition of steel fibres ultimately delayed the initiation of flexural cracks and crack width, increasing the failure load of concrete beams under three-point bending. After comparing results with cement replacement testing completed by Lal et al. (2019), the flexural strengths recorded are mostly consistent with increases up to 20% pond ash replacement and subsequent decreases from any further replacement. This suggests that the outlier in the study by Lal et al. (2019) was in fact occurring at 10% replacement instead of 20%, ultimately concluding an increase in flexural strength up to 20% pond ash replacement of cement, with decreases in strength when exceeded.

Flexural strength of high strength cement replacement with fly ash, pond ash and lime were concluded to decrease at all cement replacement mix percentages, indicating a reduction in flexural strength that coincides with decreasing cement content (Romeekadevi & Tamilmullai 2015).

2.5 Improving the properties of Pond Ash ECC

Structural performance of ECC can be determined based on correlations between rheological properties, fibre dispersion and composite tensile properties (Li & Li 2012). To simplify the methods used to characterise rheological properties the marsh cone test and mini-slump flow test have been deemed as effective and practical methods by Li & Li (2012) and Yang et al. (2009).

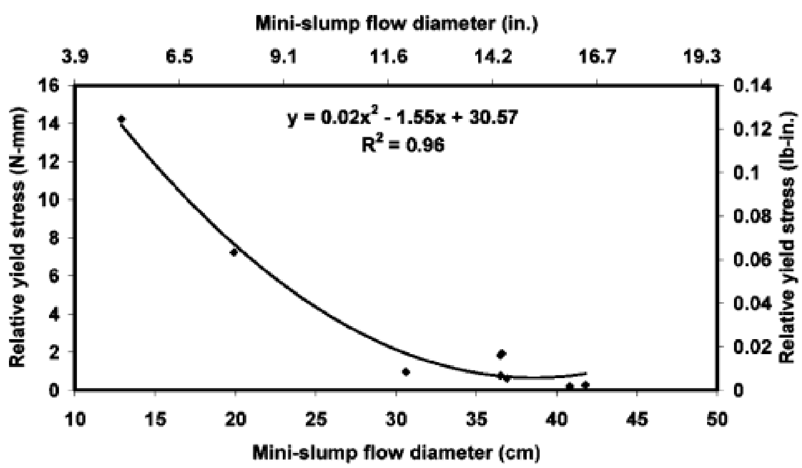

Figure 2-6 Relative yield stress versus mini-slump flow (Yang et al. 2009)

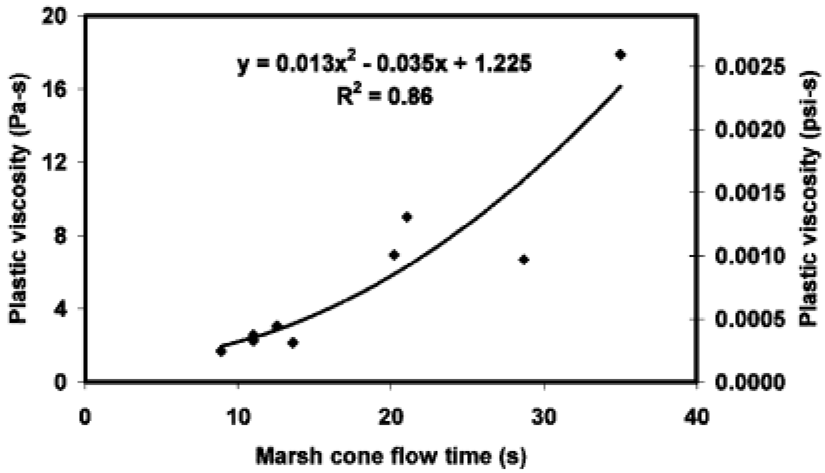

Figure 2-7 Plastic viscosity versus marsh cone flow time (Yang et al. 2009)

As illustrated Figure 2.6, the slump flow of ECC mortar is seen to increase as the relative yield stress decreases. In a mini-slump flow test, the flow occurs when the stress due to weight of the mortar in the cone is higher than the yield stress. The marsh cone flow test is generally related to the viscosity of the mix and will begin to flow when the yield stress is exceeded as recorded in Figure 2.7 (Yang et al. 2009).

While there are many factors that impact the plastic viscosity and relative yield stress of an ECC mix, water/binder (w/b) ratio and high range water reducer/binder ratio are recorded to have the largest impacts respectively (Yang et al. 2009). Therefore, Yang et al. (2009) recommend that the w/b ratio stay in the range of 0.25 ± 0.05 with any further adjustments be made through the use of high range water reducer. It should be noted that while viscosity modifying admixtures generally improve fresh properties of ECC, the high cost limits the practical use and likelihood of being adopted in construction applications.

No research has been conducted surrounding rheological control of pond ash ECC, therefore optimising the relative yield stress, plastic viscosity and admixtures has not been investigated.

2.5.1 Mix Design

Typically, existing research surrounding pond ash replacement in ordinary concrete has been undertaken by either replacing cement or fine aggregate which may be similar in ECC. While pond ash has not yet been researched in conjunction with ECC, the existing research on sustainable materials in ECC generally adopt a water/binder ratio of approximately 0.2-0.25 and silica sand/binder ratio of 0.3-0.35, which is consistent throughout the literature with other alterations such as replacement materials and additives considered on a case-by-case basis (Zhu et al. 2012; Zhang et al. 2020; Zhang et al. 2021). This is also consistent with water/binder ratio recommendations made by Yang et al. (2009) in his research surrounding the rheology of ECC.

While fine aggregate replacement of pond ash has been investigated in ordinary concrete, research conducted on sustainable materials in ECC have not altered the sand, water, or fibre quantities within the ECC mix, opting for cement or fly ash replacement as the most suitable replacement materials.

2.5.2 Mixing Methods

No mixing methods using Australian Standards have been reported within the existing literature surrounding pond ash replacement in ordinary concrete. Compared to ordinary concrete, ECC requires the addition of PVA fibres which has not been outlined in AS 1012.2 (Australian Standard – Methods of testing concrete) and therefore additional care must be taken with knowledge drawn from literature.

Generally, the ECC mixing method follow a standard three step procedure as outlined below with high shear mixers usually required to uniformly distribute the contents (Zhu et al. 2012; Zhang et al. 2020; Zhang et al. 2021). It should also be noted that the mixing time for the liquid materials varies from 2-10 minutes.

1. Combine and mix all dry materials for 2 minutes.
2. Add and mix liquid materials.
3. Add and mix fibres for 5 minutes or until evenly distributed.

Building on the research completed by Yang et al. (2009), additional research was completed by Zhou et al. (2012) in an attempt to optimise the mix design of ECC by creating a more uniform fibre distribution and therefore increased hardened properties. To achieve this, the optimal proportions outlined by Yang et al. (2009) are combined initially to suit the optimal rheological properties, where the additional materials can be later added with minimal effect to the optimised fibre distribution.

The outlined mix method by Zhou et al. (2012) are as follows:

1. Mix optimal amount of liquid, solid materials with superplasticiser at for 1 minute at low speed and 2 minutes at high speed.
2. Add and mix fibres at high speed for 2 minutes.
3. Add and mix the remaining water for 2 minutes at high speed.

There has been no published literature on pond ash replacement in ECC and therefore no evidence to suggest any adjustments be made to the mixing techniques outlined in the existing research on ECC.

2.6 Curing of Pond Ash Concrete

Curing conditions of pond ash replacement in ordinary concrete have not been investigated or discussed within the existing literature, suggesting that standard concrete curing conditions have been adopted and that no additional techniques or considerations were required.

Research conducted by Kumar & Radhakrishna (2020) highlighted that pond ash replacement of river sand greater than 60% impacted both the initial and final setting time, resulting in a need for 48-hour initial curing times. It was concluded that due to the high porosity of pond ash that the water absorbed was released into the concrete at a slower rate.

While testing by Sofi & Phanikumar (2015) did not exceed 28 days curing time, similar suggestions were made in their research after noting that the pozzolanic reaction proceeds slower in pond ash modified concrete which reduces initial strength compared to ordinary concrete. As a result, it was proposed that if longer curing times were adopted it may exceed the strength of normal concrete (Sofi & Phanikumar 2015).

Compressive strength testing of pond ash replaced concrete exceeding the typical 28 day curing time was conducted by Lal et al. (2019) and Yuvaraj & Ramesh (2021) where both studies determined that the suggestions made by Kumar & Radhakrishna (2020) and Sofi & Phanikumar (2015) where correct up to certain replacement levels. This research suggests that the strength of pond ash replacement in ordinary concrete is higher than the control mix up to 25% replacement of concrete and 30% replacement of fine aggregate after 28 days (Kumar & Radhakrishna 2020; Sofi & Phanikumar 2015).

Existing literature on sustainable alternatives in ECC typically use similar curing conditions, utilising a standard curing room at a temperature of approximately 18 – 28°C after demoulding with a relative humidity of approximately 50% or 95% until the desired age for testing was reached (Zhu et al. 2012; Zhang et al. 2021; Yang et al. 2007; Lu et al. 2023).

Research by Xu et al. (2021) reported on the impacts of relative humidity during curing on the first cracking strength, ultimate tensile strength and tensile strain capacity. Results suggest that relative humidity has a small benefit to first cracking strength and ultimate tensile strength as the relative humidity increases from 25% to 95%. However, tensile strain capacity was seen to reduce as a result. This literature suggests that generally curing environments with higher relative humidity is beneficial regardless of the fly ash to cement ratio.

There is no indication that pond ash replacement in ECC would require curing methods that differ to the typical curing techniques utilised in the existing literature on sustainable alternatives in ECC. However, it should be noted that the literature supports pond ash replaced concrete being most effective at longer curing times.

2.7 Summary

Generally, recycling pond ash as a replacement for cement or fine aggregate in ordinary concrete has varied results with potential increases in respective mechanical performance reported up 60% and 10% replacement respectively by weight. However, no research has been performed to evaluate pond ash use as a replacement of fly ash in ordinary concrete or ECC.

Research highlights the cause of discrepancies within results across literature may have occurred due to different w/b ratios, mixing methods or source of pond ash and ultimately the effect this has on its chemical composition. While the outcome varies, typically results are satisfactory until high levels of replacement with pond ash replacement of 20% fine aggregate and 10% cement by weight generally displaying favourable results.

As pond ash possesses high porosity it should be noted that the absorbed water is released back into the concrete at a slower rate, ultimately increasing the curing times and strength development. Consequently, this allows pond ash concrete to exceed the strength of normal concrete when cured for longer periods and may provide an explanation to the possible reduction in characteristic strength compared to ordinary concrete at 28 days.

The additions of fibres in the matrix for ECC provides additional aspects to consider, ensuring workability and strength via uniform fibre distribution. To achieve workability the literature review highlights key mix design recommendations of w/b ratio and silica sand to binder ratios of 0.2-0.25 and 0.3-0.35 respectively. An adjusted four step mixing method is recommended where these mix design parameters can’t be met to ensure suitable workability. The mixing of ECC should be done with a high shear mixer to achieve uniform fibre distribution and curing should follow standard techniques.

2.7.1 Knowledge Gaps

Pond ash replacement has not previously been studied in ECC, however has the capabilities to reduce the high demand on high quality fly ash in the construction industry within ECC, a durable and ductile cementitious material. As the effects of pond ash on the mechanical properties of ECC are currently unknown, this project will assist in bridging the knowledge gap by substituting pond ash with fly ash at 25%, 50% and 100% replacement, by volume.

CHAPTER 3

METHODOLOGY

3.1 Outline

In an attempt to bridge the knowledge gap in determining the mechanical properties and performance of pond ash ECC, experimental testing and an analysis will be undertaken. To achieve this, fly ash will be substituted by volume with fly ash in the ECC mix by various percentages up to 100% replacement. Mechanical property results will then be determined to consider the overall performance of pond ash replacement in ECC to determine the effectiveness and provide a basis for further studies to expand the growing knowledge base on pond ash ECC.

The following methodology will be adopted for this project:

1. Source all materials and equipment required to carry out the casting and testing of samples.

2. Finalise the pond ash ECC mix design.

3. Prepare one control batch of ECC and three batches of pond ash ECC by substituting fly ash with 25%, 50% and 100% pond ash by volume.

4. Assess the rheological matrix properties and workability of the batches are acceptable using a mini-slump cone and marsh cone test.

5. Prepare a series of cube, dogbone and beam test specimens for each batch of ECC to test the compressive, uniaxial tensile strength and flexural strength.

6. Conduct destructive laboratory testing to determine the mechanical properties of the control ECC mix and pond ash ECC.

7. Analyse and discuss the experimental results from testing.

8. Determine the mechanical viability of pond ash in ECC.

3.2 Assumptions

For the purpose of this project, the following assumptions have been made:

1. The pond ash used for the project is representative of the pond ash expected to be obtained for general use.

2. The pond ash contains similar material properties as those reported in previous literature.

3. The characteristics of the remaining materials are generally similar to those reported in previous literature in regard to mixture design, methods and rheological control.

3.3 ECC Mix Design

A variety of ECC mixes were identified throughout existing literature on sustainable replacement of ECC materials. High fly ash ECC has been heavily researched with work by Yang et al. (2007) and Wang et al. (2007) being the most notable, demonstrating the effectiveness of high fly ash substitution in ECC. Zhang et al. (2020) highlighted the growing supply shortage of high-quality fly ash in the construction market and proposed an alternative solution with rice husk ash substitution of high fly ash ECC. Utilising the past work of Zhang et al. (2020), a similar approach will be adopted for this project with controlled replacement of fly ash with pond ash. This approach utilises a water to binder ratio of 0.2 and silica sand to binder ratio of 0.3 which is consistent with water and binder ratio recommendations made by Yang et al. (2009) in his research surrounding the rheology of ECC. It should also be noted that Zhang et al. (2020) found that more superplasticiser was required for higher fly ash replacement levels to maintain the desired workability.

While a range of fibre types have been identified through the existing research such as the PE fibres used in research conducted by Zhang et al. (2020), Meng et al. (2017) outlined that PVA fibres are the most optimal fibre due to their higher tensile strength and lower cost. As a result, this project will adopt the commonly available, high performance RECS15 PVA reinforcement fibres.

In addition to the alterations to the fibre type, the mix design approach by Zhang et al. (2020) will be further altered to exclude silica fume from the binder materials. Ultimately this material isn't commonly included as part of existing literature and has been excluded to stay within project budget and more accurately assess the impact of pond ash replacement.

3.4 Producing Laboratory Specimens

3.4.1 ECC Mixing

As no mixing methods are outlined for ECC in the Australian Standards, an appropriate mixing method approach will be developed using methods in existing literature. Typically, ECC mix methods utilise a standard three step procedure where dry materials are combined and mixed, followed by liquids and finally the fibres until evenly distributed (Zhu et al. 2012; Zhang et al. 2020; Zhang et al. 2021). Recommendations by Yang et al. (2009) suggested that optimal water to binder proportion of 0.25 ± 0.05 should be utilised with the addition of HRWR (High Range Water Reducer) to create a high plastic viscosity and low yield stress. While the three-step process has proven successful throughout literature (Yang et al. 2009; Wang and Li 2007; Zhang et al. 2020), Zhou et al. (2012) optimised this mix method to suit the optimal rheological properties and optimise fibre distribution. However, the water to binder proportion recommendations by Yang et al. (2009) will be satisfied in this mix design and therefore both the mix design and method will be adopted as per the literature by Zhang et al. (2020) as this most closely resembles the experimental testing for this project and aligns with recommendations made by Yang et al. (2009). The proposed mix proportions by volume have been outlined below in table 3.1.

Table 3-1 Mix proportions by volume

MIX DESIGN	**Control**	**25%**	**50%**	**100%**
PVA Fibres	2% Vol	2% Vol	2% Vol	2% Vol
Cement	1.00	1.00	1.00	1.00
Water	0.36	0.36	0.36	0.36
Silica Sand	0.54	0.54	0.54	0.54
Fly Ash	0.80	0.60	0.40	0.00
Pond Ash	0.00	0.20	0.40	0.80

It is recommended throughout literature that a high shear mixer be used to ensure a uniform distribution of fibres. It should also be noted that as per AS 1012.2:2014, the minimum batch size shall exceed 10% of the volume required for testing purposes and that all variations to the standard procedures be recorded (Standards Australia, 2014a).

Mixing Sequence:

1. Load mixer with all dry solid ingredients and mix for 2 minutes.

2. Add water and super plasticiser as per manufacturers specifications to the mixer and mix for 10 minutes.

3. Perform mini-slump cone test and marsh cone test on ECC matrix as per AS 1012.3.5:2015.

4. Slowly add PVA fibres into the fresh mortar and mix for 5 minutes until fibres are uniformly mixed.

Concrete mixing was undertaken at the University of Southern Queensland Toowoomba labs on 31st July and completed on 3rd August 2023. As shown in Figure 3.1, a Hobart Planetary Mixer was used to achieve higher shear mixing action to distribute the PVA fibres more uniformly as recommended within literature. To comply with time limits set by ASTM C109/C109M, moulding of specimens was started within 2 minutes and 30 seconds after mixing the mortar batch.

Figure 3-1 Hobart Planetary Mixer

3.4.2 Specimen Details

In general, 3 specimens were cast for each test to ensure reliable results could be obtained. Compression specimens were the exception, where 6 specimens were cast for each test to allow for testing at both 7- and 28-day testing age to record the characteristic strength change over time.

Compression specimens were cast in cubes with a specimen mould size of 50mm (Height) x 50mm (Width) x 50mm (Depth) as specified by ASTM C109/C109M and detailed in past literature (The American Society for Testing and Materials 2021; Zhang et al. 2020). These standard moulds were available for use at the University of Southern Queensland.

Due to limitations at the University of Southern Queensland, uniaxial tensile testing could not be completed to Australian Standards. Alternatively, the uniaxial tensile test was prepared to be completed as per recommendations by Yokota et al. (2008) as seen in Figure 3.2 and later utilised by Zhang et al. (2020) in similar ECC testing. The dogbone shaped specimen size have been outlined as 330mm (Height) x 60mm (Width) x 13mm (Depth) as shown in the Figure 3.2 below.

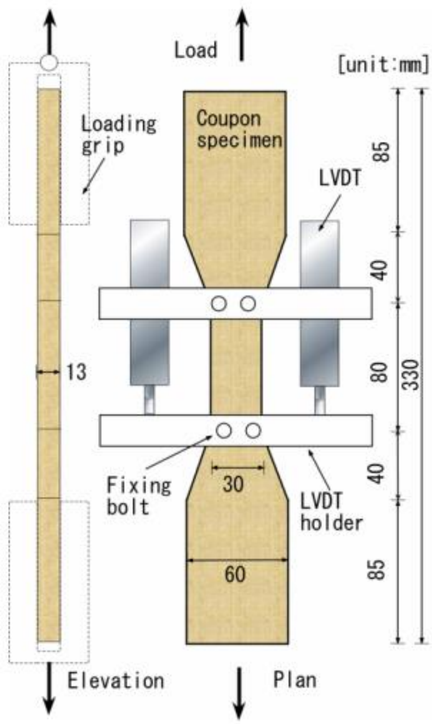

Figure 3-2 Tensile test specimen specification (Yokota et al. 2008)

However, the University of Southern Queensland staff had previously noted specimens failing prematurely as a result of the clamping force required during testing. As per staff recommendations tensile casting was completed as per ASTM C307-23 with briquet moulds seen in Figure 3.3, readily available at the University of Southern Queensland for casting. It should be noted that ASTM C307-23 does not recommend this specimen for mortars, grouts or monolithic surfacing containing aggregate greater than 6.25 millimetres, however the PVA fibres sourced for this project are 12 millimetres in lengths (The American Society for Testing Materials 2023d). While this is outside the recommended scope for the standard and will require future testing beyond the scope of this project, it is expected that this specimen will offer an indication of pond ash ECC tensile strength.

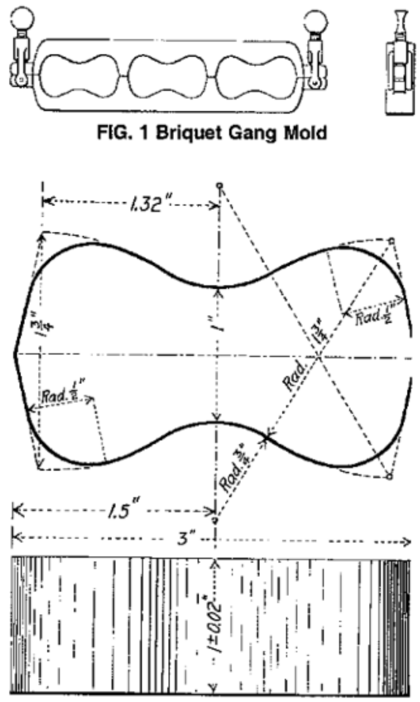

Figure 3-3 Briquet specimen for tensile testing (The American Society for Testing Materials, 2023d)

Flexural beams specimens were used as per ASTM E399 with specimen specifications to match previous testing by Zhang et al. (2020) (The American Society for Testing and Materials 2023a). The dimensions were 305mm (Height) x 76mm (Width) x 38mm (Depth). Moulds this size where not readily available at the University of Southern Queensland so several moulds were constructed to suit using available form ply.

3.4.3 Specimen Casting

The moulding procedure for the compression, flexural and tensile test specimens were completed as per AS 1012.8.3:2015. Casting was commenced without delay to prevent segregation of the mortar. The entire surface of the mould was rodded at both the first and second layer to force out air bubbles within the mortar. The number of strokes varied until full compaction appeared to be reached. Finally, the tops of the specimens were struck off and the surface was smoothed, avoiding a mirror finish (Standards Australia, 2015).

All specimen mixing, rheological testing was completed with the assistance of University of Southern Queensland lab technical staff in Toowoomba.

3.4.4 Specimen Curing Conditions

Specimen curing was completed in the laboratory as per AS 1012.8.3:2015, ensuring all samples were covered and then stored undisturbed on a rigid horizontal surface for no less than 18 hours and no more than 36 hours. Specimens were then demoulded and promptly returned to standard curing conditions. To comply with Australian standards, the specimens were cured at 27 degrees Celsius in the fog room at the University of Southern Queensland Toowoomba lab until testing. The curing environment was set to a relative humidity of 86% with research conducted by Xu et al. (2021) demonstrating benefits to tensile strength performance at higher relative humidities.

3.5 Experimental Testing

3.5.1 Rheological Properties

The Rheological properties of the mortar was tested prior to the completion of ECC mixing. Following the research completed by Yang et al. (2009), a mini-slump flow and marsh cone time test were confirmed as viable methods and were therefore used to determine the yield stress and plastic viscosity of the ECC mix respectively.

As illustrated in Figure 3.4, the mini-slump flow test was completed as per ASTM C230/C230M specifications. Ultimately this test has been previously used throughout literature to determine the yield stress of cementitious mortars and can therefore be utilised to assess the effects of pond ash content in ECC on yield stress (Ferraris 1999; Yang et al. 2009).

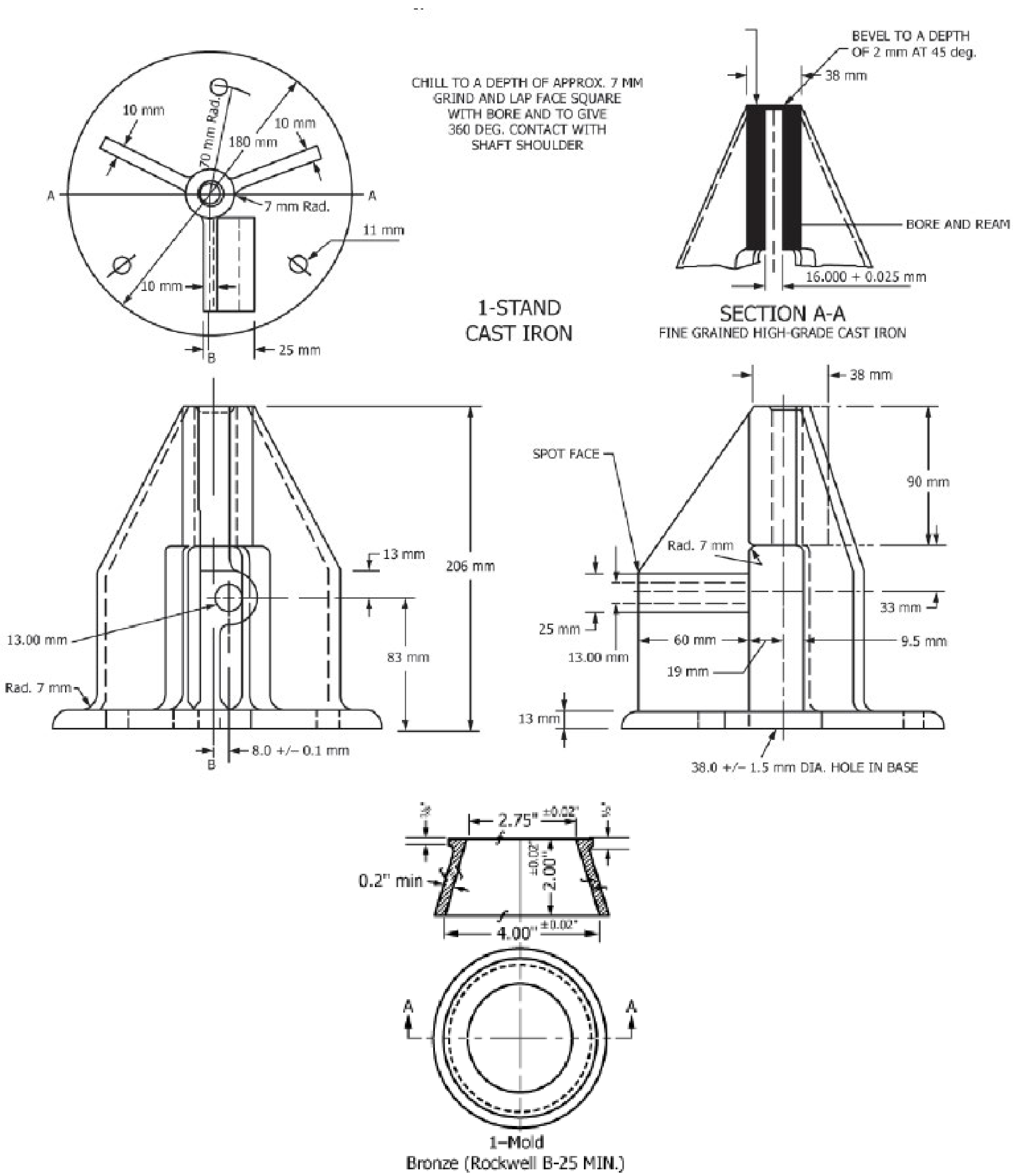

Figure 3-4 Flow table and test mould (The American Society for Testing and Materials, 2023c)

The mini-slump test as specified by Yang et al. (2009) was completed using a truncated cone with a bottom diameter of 100mm, top diameter of 70mm and 60mm high. Following the procedure outlined in C1437-20, the equipment was cleaned and dried before placing the flow mould in the centre of the plate. The mini slump cone was filled in layers of 25mm in thickness and tamped 20 times with a tamper to ensure uniform distribution of the mortar. The mortar was cut off at the top of the cone to create a level surface flush with the top of the mould and excess mortar wiped clean. The table was dropped 25 times within 15 seconds and completing the test by lifting the mould away from the mortar. Once the mortar had stopped flowing, the mortar’s diameter was measured at the locations scribed on the table top to the nearest millimetre with the flow being the average base diameter.

The modified marsh cone depicted in Figure 3.5 was partially filled with 850 mL of mortar with the orifice at the bottom closed. The internal orifice diameter was measured at 20 mm as specified by Yang et al. 2009. The flow time was then recorded from when the orifice was opened until all the ECC mortar had flowed out or when the flow had completely stopped.

Figure 3-5 Modified marsh cone test funnel

3.5.2 Compression Testing

Compression testing was undertaken with three specimens from each batch at both 7 days and 28 days of curing time. Testing was completed as per AS 1012.9:2014 using a 100 kN, 810 Material Test System with the results from the three specimens averaged. Figure 3.6 illustrates the compression testing setup with the 50mm x 50mm x 50mm cube specimen loaded ready for testing.

After being removed from the curing environment, the specimen measurements were recorded while simultaneously inspected for defects. Similarly, the compression testing machine was inspected and cleaned before loading the specimens as depicted in Figure 3.6. The specimen was centrally placed in the machine and upper platen was brought into contact with the specimen before testing commenced. A force without shock was applied at a continuous rate of 20 $\pm$ 2 MPa per minute until failure with results recorded as per AS 1012.9:2014 (Standards Australia, 2014b).

Figure 3-6 Compression testing apparatus

The compressive strength of each specimen was calculated by dividing the maximum force recorded by the cross-section area of the specimen (Standards Australia 2014b).

$$\boldsymbol{C = \frac{P}{wd}} \qquad \textbf{(4.1)}$$

Where:

C = compressive Strength (MPa)

P = maximum force applied to the specimen (kN)

w = width of the specimen (mm)

d = depth of the specimen (mm)

3.5.3 Tensile Testing

As uniaxial tension testing at the University of Southern Queensland was not possible to Australian Standards, experienced lab technicians proposed the use of briquet specimens for testing as a substitution. Briquet moulds previously created via 3D printing were available for casting allowing uniaxial testing to be completed using a 2500 N Hounsfield H1KS testing machine with reference to ASTM C307-23.

After being removed from the curing environment, the specimen measurements were recorded while simultaneously inspected for defects. Similarly, the uniaxial testing machine was inspected and cleaned before loading the specimens as depicted in Figure 3.7. The specimen was centrally placed and secured in the machine grips before testing commenced. A displacement was applied to the specimen at a continues rate of 1 mm per minute until failure, with strength results and failure patterns recorded.

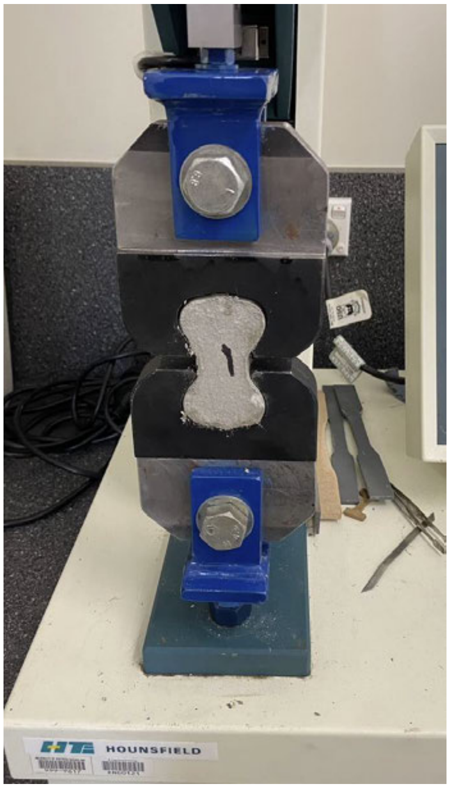

Figure 3-7 Uniaxial testing apparatus

The direct tensile strength was calculated at maximum load using Equation 4.2:

$$\boldsymbol{S = \frac{P}{bd}} \qquad \textbf{(4.2)}$$

Where:

S = the stress applied to the specimen (MPa)

P = the load at the moment of crack or break (N)

b = width at the waist of the briquet specimen (mm)

d = depth of the briquet specimen (mm) (The American Society for Testing and Materials 2023d)

3.5.4 Flexural Testing

Flexural testing was undertaken with three specimens from each batch. Testing was completed as per AS 1012.11:2000 using an 11 kN LoadTrac ll testing apparatus with the results from the three specimens averaged. Figure 3.8 illustrates the flexural testing setup as per clause 5 of AS 1012.11:2000.

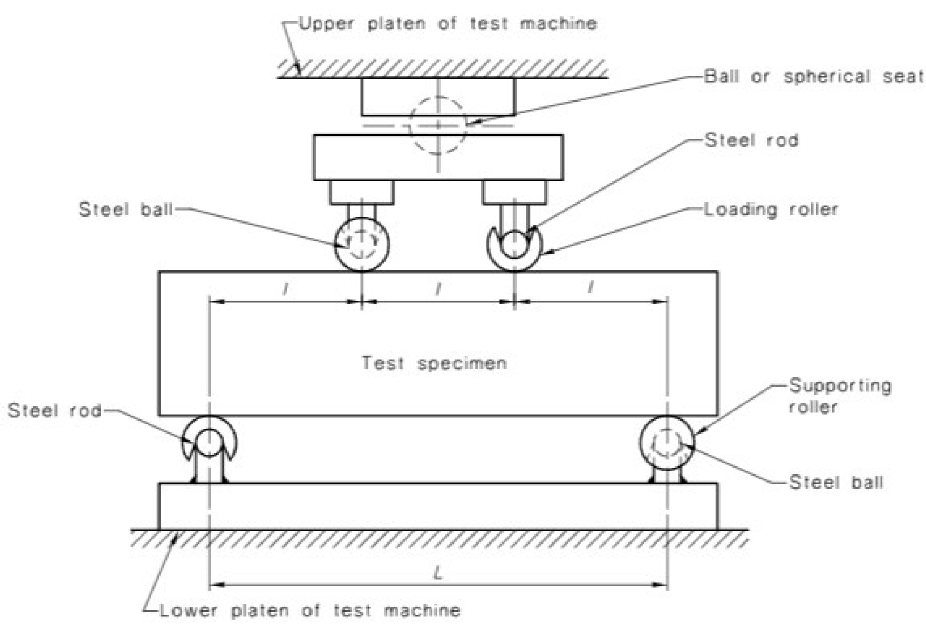

Figure 3-8 Suitable flexure testing apparatus (Standards Australia, 2000b)

After being removed from the curing environment, the specimen measurements were recorded while simultaneously inspected for defects. Similarly, the flexural testing machine was inspected and cleaned before loading the specimens as depicted in Figure 3.9. The specimen was centrally placed on the machines supporting rollers. The loading roller was then brought into contact with the specimen to prepare for loading. A force without shock was applied at a continuous rate of 1

± 0.1 MPa per minute until failure with results and type of failure recorded as per clause 6 of AS 1012.11:2000.

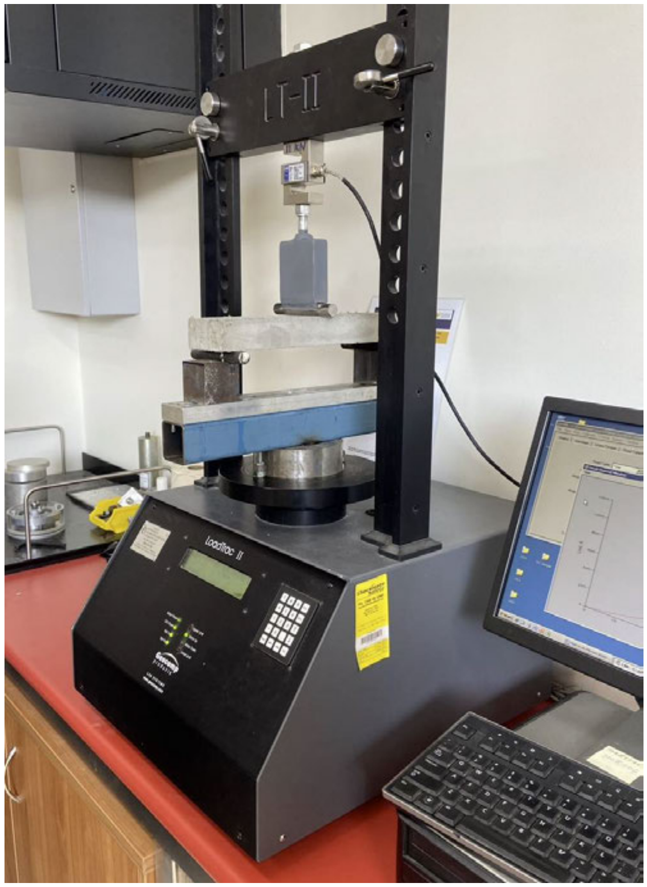

Figure 3-9 Flexural testing apparatus

Where fracture occurs in the middle third of the beam, the modulus of rapture was calculated using Equation 4.3.

$$\boldsymbol{f_{cf} = \frac{3PL(1000)}{2BD^2}} \qquad \textbf{(4.3)}$$

Where:

F_{cf} = modulus of rupture (MPa)

P = maximum force applied to the specimen (N)

L = the length between supports (mm)

B = the average width of the specimen (mm)

D = the average depth of the specimen (mm) (Standards Australia 2000b)

CHAPTER 4

EXPERIMENTAL INVESTIGATION

4.1 Materials

Pond ash was sourced from Millmerran Fly Ash in Grays Gate with black coal sourced exclusively from the nearby Commmodore open cut coal mine and processed using recycled waste water and air cooled condensers to reduce water consumption by up to 90% of traditional power stations. When compared to the fly ash sourced for this project, the pond ash appears to be more clumped, although still a fine powder as seen in Figure 4.1 below.

Figure 4-1 Pond ash

RECS 15 PVA fibres as illustrated in Figure 4.2 was sourced from Domcrete, a local supplier in New South Wales. RECS 15 is the surface treatment used to aid in dispersion and increase strain hardening within the matrix. Properties for RECS 15 PVA fibres have been provided in Table 4.1 which are similar to PVA fibre properties utilised in literature (Li et al. 2002).

Table 4-1 Typical RECS15 PVA fibre properties

Fiber Length	8 Millimetres
Filament Diameter	38 Microns
Tensile Strength	1600 Megapascals
Flexural Strength	40 Gigapascals

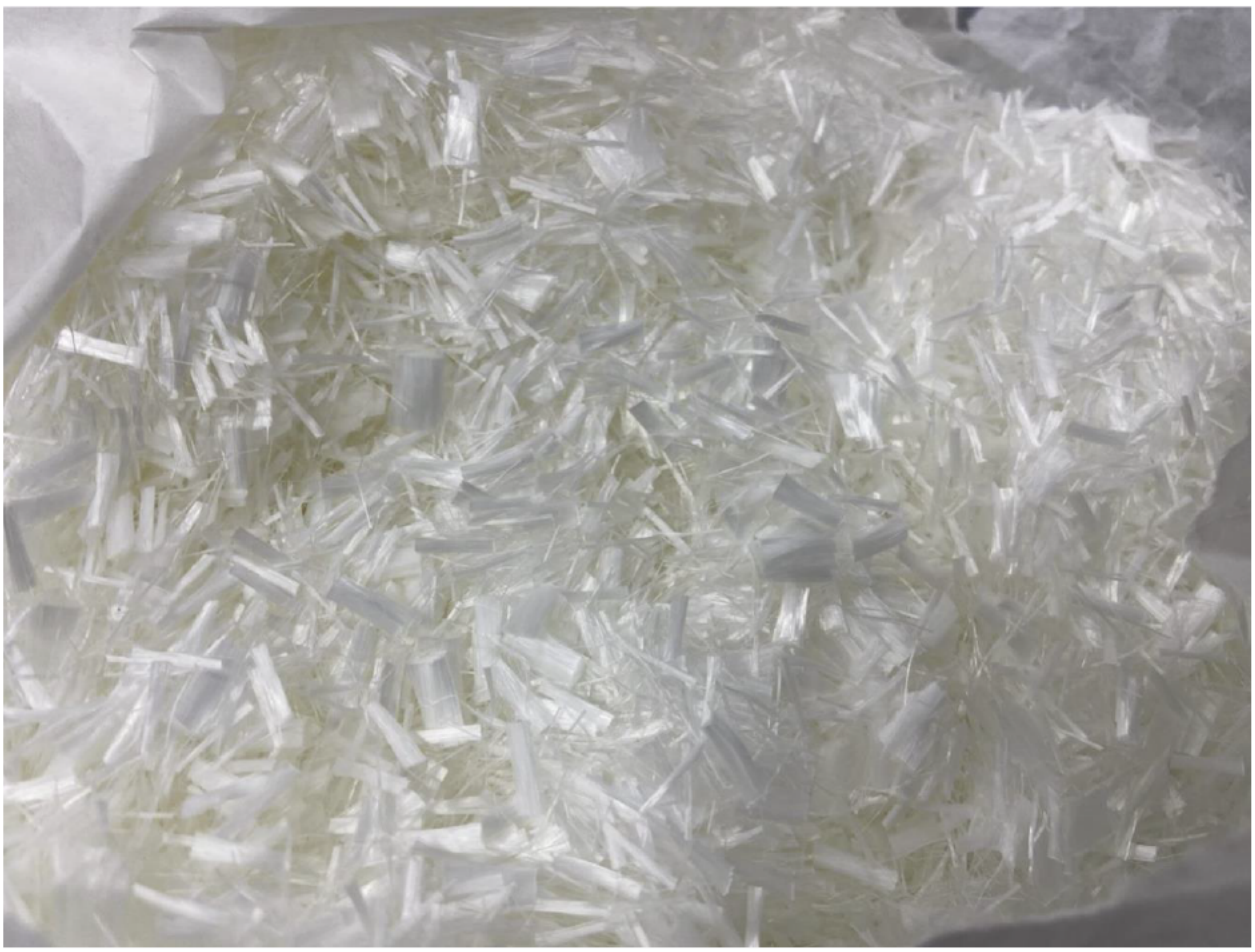

Figure 4-2 RECS15 PVA fibers

Graded silica white sand was sourced from Domcrete in 20kg bags as seen in Figure 4.3. Unfortunately, the technical data was not able to be sourced from the supplier.

Figure 4-3 Silica sand

Cement Australia grade 1 fly ash (Figure 4.3) was sourced from individual 20kg bags from Darling Downs Brick Sales, Toowoomba and satisfying the specific requirements of AS 3582.1. Typical values achieved from Gladstone fly ash has been outlined in Table 4.2.

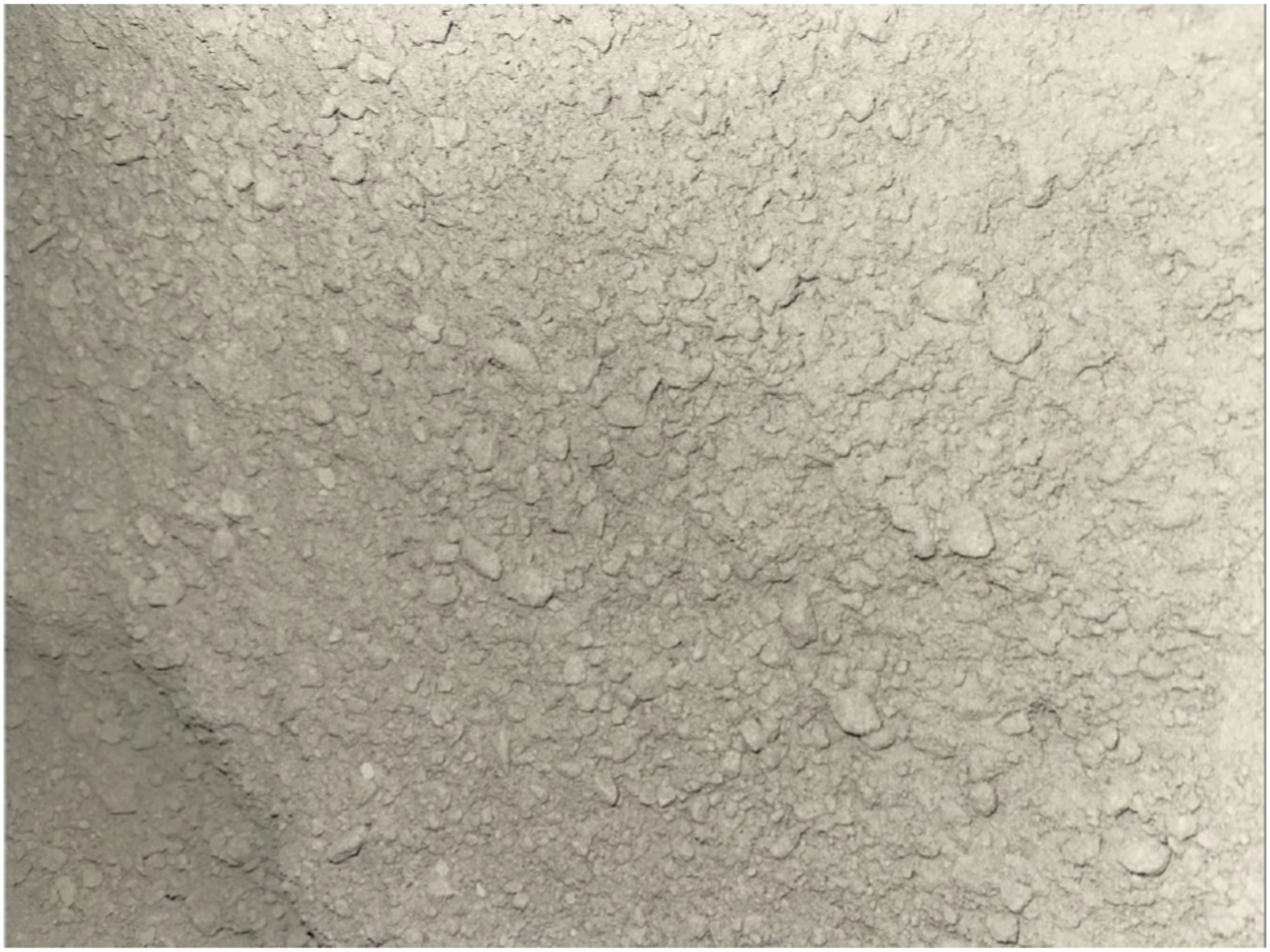

Figure 4-4 Fly ash

Table 4-2 Typical fly ash properties

Property	Typical Fly Ash (Gladstone)	AS 3582.1
Fineness passing through 45um sieve	88%	Minimum 75%
Loss on ignition	1%	Maximum 4%
Moisture content	0.1%	Maximum 4%
SO_3 Content	0.2%	Maximum 3%

Similarly, Cement Australia general purpose cement (Figure 4.5) was also sourced from individual bags from Darling Downs Brick Sales, Toowoomba. This mix complies with general purpose cement mixes as per AS 3972 and is suitable for a wide range of applications. Cement Australia mortar plasticiser was also sourced from Darling Downs Brick Sales, conforming with AS 1478 and combined with potable water from the laboratory.

Figure 4-5 Cement

4.2 Material Quantities

The required volume of ECC was calculated with a 20% allowance made for wastage as outlined in Table 4.3.

Table 4-3 ECC volume calculations

Quantity	**Shape**	**Specimen Size (mm)**			**Volume of each sample (m^3)**	**Total volume (m^3)**
28	Cube	50	50	50	0.0001	0.0035
12	Beam	305	76	38	0.0009	0.0106
12	Dogbone	75	25	40	0.0001	0.0009
					Total fresh volume (m3)	**0.015**
					Total including wastage (m3)	**0.019**
					Total per batch (m3)	**0.005**

Table 4.4 outlines the mix proportions adopted during casting. Initially it was planned to use 140kg/m^3 of water, however this didn't appear to be enough to create a workable mortar. After discussing with University of Southern Queensland laboratory staff it was decided to increase the water dosage to 280kg/m^3 which was then kept consistent for the remainder of the batches. Ideally trialling proportions would have allowed for a more optimal mix design, especially surrounding water content in particular, however time and material limitations prevented this from occurring.

Table 4-4 Fly ash ECC mixture proportions

	Weight per unit volume (kg/m3)
PVA Fibers	4
Cement	416
Water	280
Silica Sand	364
Fly Ash	292

Pond ash replacement of fly ash quantities within the ECC batches has been tabulated in Table 4.5 below. The volumetric replacement was conducted based on the apparent particle density of both pond ash and fly ash. All other ECC mixture proportions remained consistent throughout all batches.

Table 4-5 Pond ash ECC mixture proportions

Constituent	**Batch**			
	Control	**25%**	**50%**	**100%**
Fly Ash (kg/m³)	292	219	146	0
Pond Ash (kg/m³)	0	46	91	182

The total volume of materials required to cast the desired specimens have been calculated based on the mix proportions outlined in Table 4.6.

Table 4-6 ECC material quantities

Constituent	**Weight (kg)**
PVA Fibres	0.2
Cement	16.6
Water	9.7
Silica Sand	14.6
Fly Ash	6.6
Pond Ash	3.2

4.3 Sample Preparation

Production of ECC samples was completed throughout the week from 31st July to 4th August 2023 at the University of Southern Queensland Z1 laboratory, Toowoomba. Due to the limited number of moulds a single batch was prepared each day using a Hobart Planetary Mixer as shown in Section 3.4.1. The mixing procedure followed the mixing proposal outlined in Section 3.4.1 using the revised mix proportions previously illustrated in Table 4.4. During the mixing process for the control batch it was determined via visual inspection that 10 minutes of mixing for the liquids was not necessary and was reduced to 8 minutes. Similarly, it was determined that mixing the fibres should be increased to 8 minutes to ensure more uniform distribution of the fibres. This was monitored for the remaining batches and determined to be a sufficient mixing duration to ensure uniform distribution within the mix.

An evaluation of the mortar matrix rheology was completed for each batch of ECC using the mini slump tests and marsh cone as recommended by Yang et. al. (2009) and outlined in Section 3.7. The results for these tests vary significantly as pond ash replacement of fly ash increases and is discussed in more depth in Section 5.2. Figure 4.6 and 4.7 illustrates the obvious difference from the control batch mini slump test compared to the 100% pond ash replacement batch after testing. This translated to the pond ash mix being significantly easier to work with but provided little stability. The increase in workability could indicate that a reduction in water content may be beneficial for the high pond ash specimens.

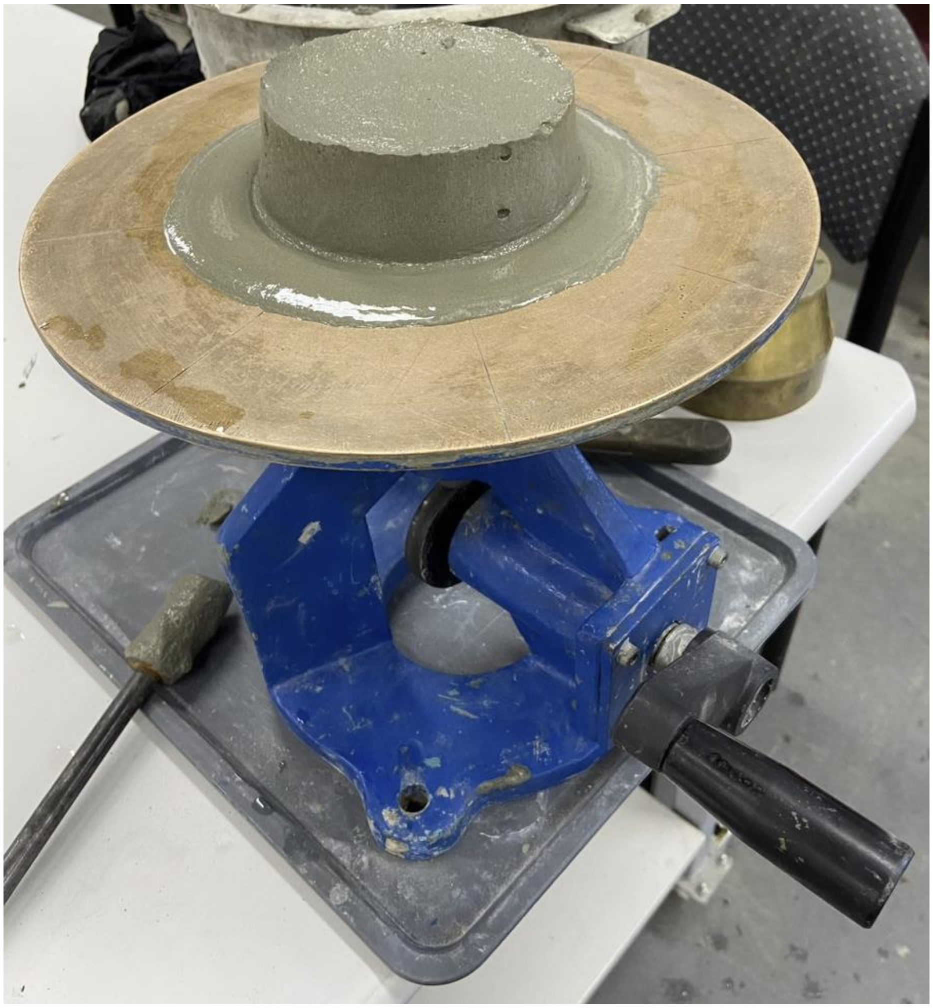

Figure 4-6 Mortar mini slump flow test: Control

Figure 4-7 Mortar mini slump flow test: 100% Pond ash replacement

Following the completion of fresh testing, the PVA fibres were added and mixed for 8 minutes until uniformly distributed and then cast as per the procedure outlined in Section 3.6.3.

Steel moulds were used to cast the 50mm x 50mm x 50mm cubes for compressive testing as shown in Figure 4.8.

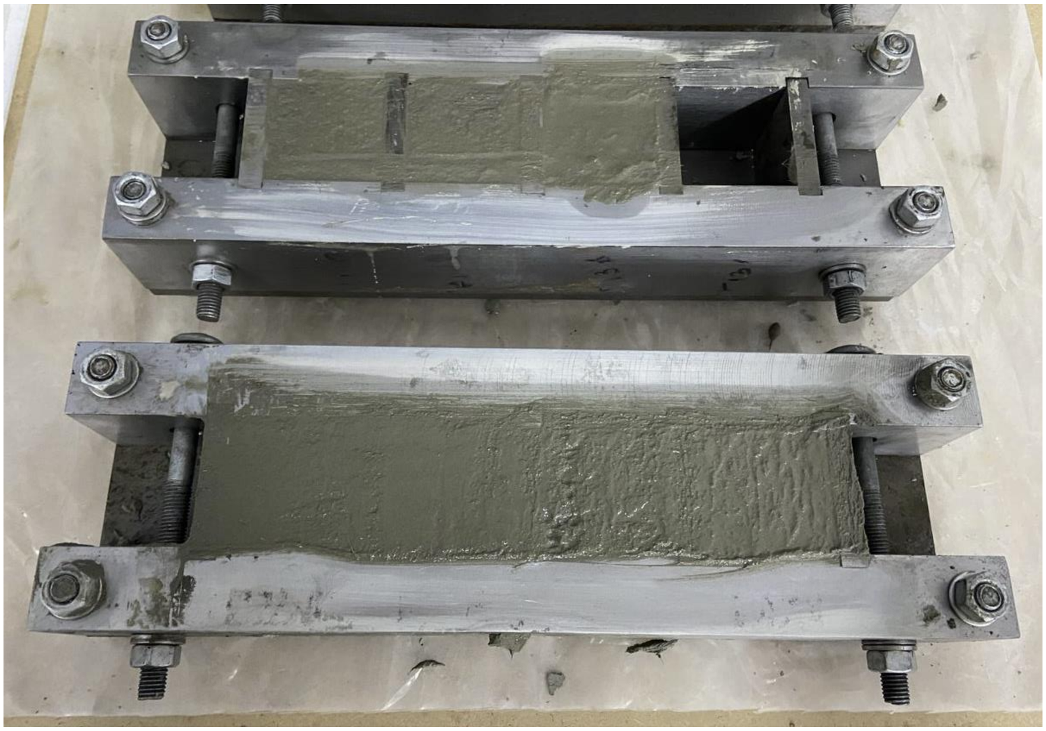

Figure 4-8 Compressive specimens cast in steel moulds

3D printed gang moulds were used to cast the briquettes for tensile testing illustrated in Figure 4.9.

Figure 4-9 Tensile specimens cast in 3D printed gang mould

Custom made ply moulds were used to cast the 305mm x 76mm x 38mm beams for flexural testing as shown in Figure 4.10.

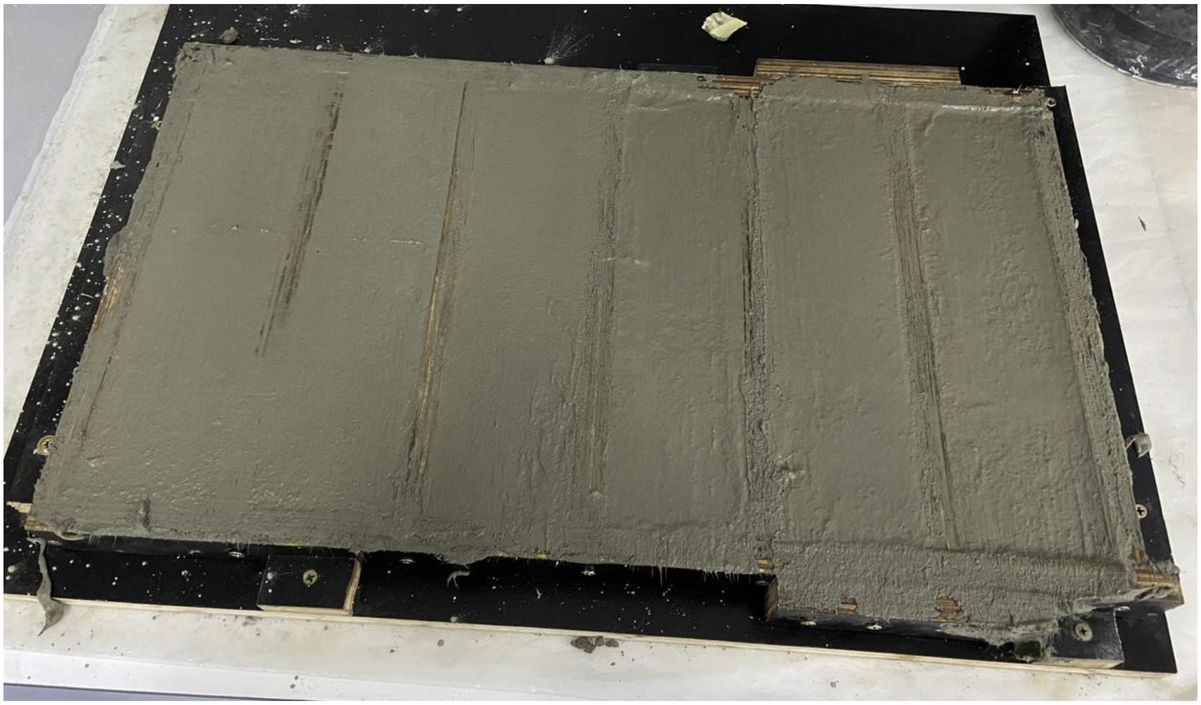

Figure 4-10 Flexural specimens cast in ply moulds

The specimens were then left undisturbed in the lab for 24 hours before being placed in the University of Southern Queensland fog room as illustrated in Figure 4.11 and detailed in Section 3.6.4. While the control batch, 25% and 50% pond ash replacement batches showed no signs of bleeding, the 100% pond ash replacement batch suffered significant paste loss across all specimen types. Demoulding of all specimens was completed after 24 hours with the exception of the 100% pond ash replacement batch. As pond ash replacement increased, it was evident that longer curing times were required, with Sofi & Phanikumar (2015) validating curing times from 24 to 48 hours before demoulding. Based on this information and visual inspection, the 100% pond ash replacement batch was left to cure for 32 hours which appeared to be suitable during the demoulding process.

Figure 4-11 University of Southern Queensland fog room – Z1 Lab

4.4 Experimental Testing

Experimental testing of specimens was conducted over a period of 4 days for both 7 day compressive testing and 28 day compressive, tensile and flexural testing. This was completed over 4 days to achieve the standard testing times as casting was completed over 4 days, with one batch cast per day.

Z1 laboratory technicians at the University of Southern Queensland assisted in all experimental testing to ensure accurate results. The dimensions, weight and any defects were recorded at 28 days for all specimens prior to testing to help analyse the test results.

4.4.1 Compression Testing

Compression testing was performed using a 100 kN capacity 810 Material Test System where possible as it utilised a finer load cell for more accurate data. A 2 channel automatic cube and cylinder compression machine CT340-CT440 with a 2000 kN capacity was utlised for 25% pond ash replacement specimens as their compressive strength exceeded the capacity of the 810 Material Test System. Using a windows computer connected to the testing system, results were recorded in MTS Test Suite and exported into a text file for further analysis. The specimens were weighed, measured and inspected for defects before testing commenced.

The specimen type and dimensions were input into the machine prior to testing with loading automatically set to 0.9 kN/s. Compressive strength results from the machine were both manually recorded and directly exported in excel format for further analysis.

Figure 4-12 810 Material Test System testing setup

4.4.2 Tensile Testing

Uniaxial tensile testing was performed using a Hounsfield H5KS testing machine with 2.5 kN capacity, as per ASTM C307-23. Using a windows computer, the results for force and elongation were compiled in an excel sheet using QMat software for further analysis. The specimens were weighed, measured and inspected for defects before testing commenced. Loading was completed at a rate of 0.5 mm/min with the total load and elongation until failure recorded and exported in excel.

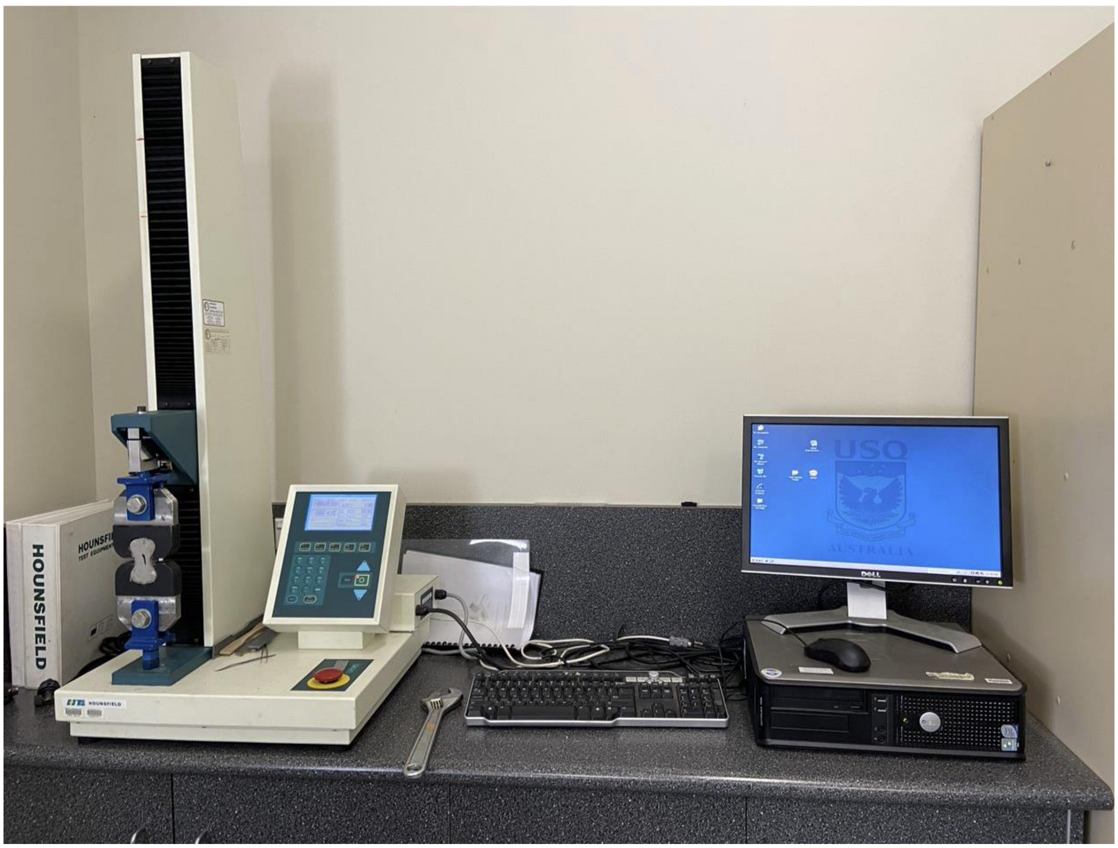

Figure 4-13 Hounsfield H5KS testing setup

4.4.3 Flexure Testing

Flexural testing was conducted using a Load Trac ll machine with an 11 kN capacity. Beam specimens were weighed, measured and inspected for defects with the loading points on specimen confirmed before testing commenced.

With the assistance of laboratory staff, the specimen was loaded evenly into the flexural testing machine before loading was applied at a rate of 1.0 MPa per minute. A CBR data logger connected to a windows computer was utilised to record the loading and displacement of the specimen during testing. Results were manually recorded and directly exported in excel format for analysis.

Figure 4-14 Load Trac ll testing setup

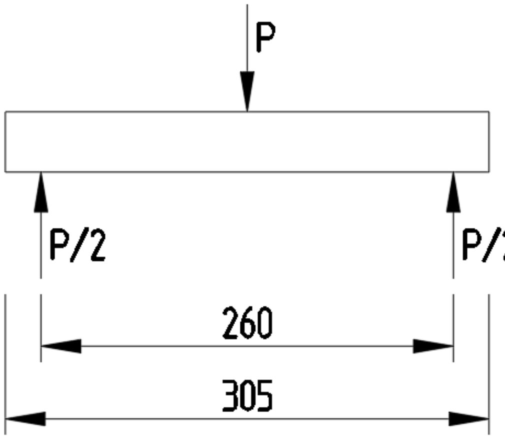

Figure 4-15 Equilibrium forces acting on beam specimen

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Introduction

The production of ECC in this project was produced with more water than initially planned which was required to create a workable mortar. While this water content was suitable for the initial batch it was kept consistent for the remaining batches. Ideally with time and resources permitting, the water content could be tailored to each mix design to obtain the desired workability and determine the characteristic strength. Visual inspection demonstrated that the mixer had sufficient mixing energy for uniform distribution of the fibres and testing was able to be completed on the desired 7- and 28-day mortar age. While the results are encouraging, they can likely be refined further to determine the true potential of pond ash in ECC.

5.2 Fresh ECC Testing

The fresh rheological properties of the mortar were completed as per Sections 3.5.1 and 4.3. The experimental data has been outlined in Appendix D, Table D-1.

Following Sections 3.5.1 and 4.3, the mortar rheology was determined. Research by Yang et al. (2009) outlines promising results in ECC demonstrating high plastic viscosity and low yield stress. High slump flow is indicative of low yield stress while longer marsh funnel flow time indicates high plastic viscosity. As graphed in Figure 5.1, the lowest relative yield stress and highest relative plastic viscosity was achieved with the control sample.

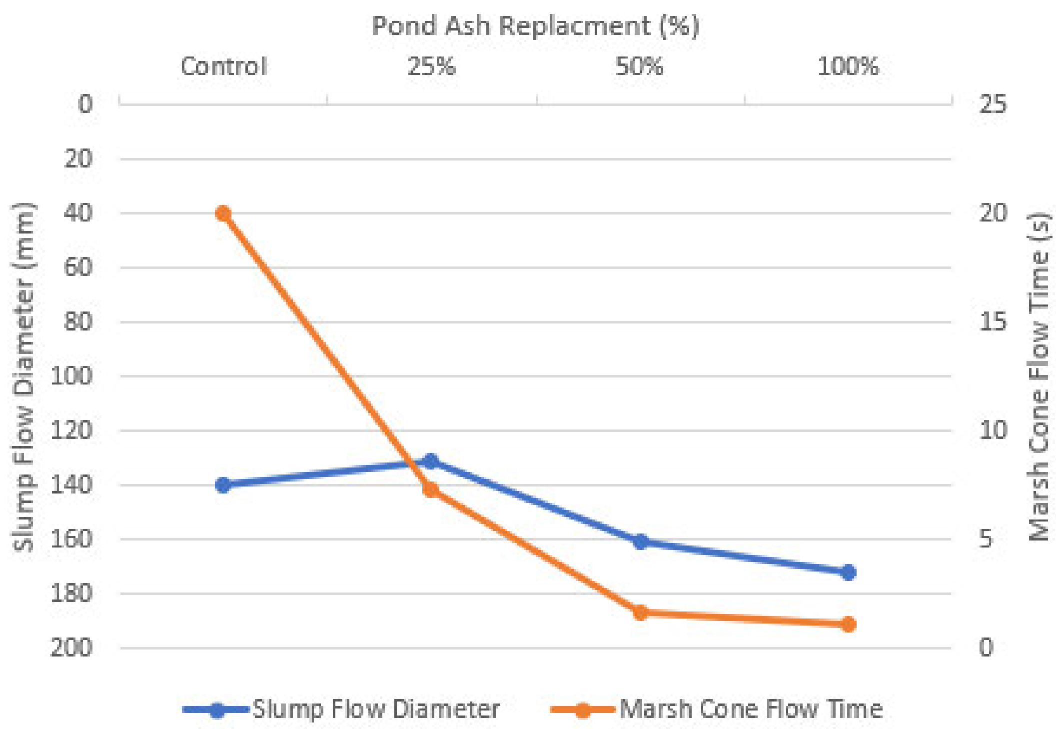

Figure 5-1 Fresh mortar rheological properties

The mini slump flow test indicated that as pond ash replacement of fly ash increases, the mortar yield stress generally decreases with the exception of 25% showing a slight increase. Furthermore, the marsh funnel flow cone demonstrates a similar trend with decreasing plastic viscosity as pond ash content increases. It should be noted that while the control sample demonstrates the highest marsh cone flow time, this is due to the mortar no longer flowing through the twenty millimetre cone orifice as shown below in Figure 5.2. Clearly plastic viscosity this high should be avoided due to the lack of workability.

Figure 5-2 Control ECC mortar stuck in flow cone

No previous research has been conducted on pond ash replacement of fly ash in ordinary concrete and therefore no comparisons can be drawn. Existing literature does generally indicate a decrease in workability when replacing fine aggregate with pond ash (Yimam et al 2021; Harle 2019; Kumar and Radhakrishna 2020). However, replacement of cement by pond ash did show increases in workability similar to experimental results gathered from fresh mortar testing (Sofi and Phanikumar 2015). As previously discussed, water content appeared higher than necessary for pond ash samples which also may explain the higher workability compared to the control batch. Previous literature has put a large emphasis on the source of pond ash ultimately acting as a large determining factor for workability and strength. Pond ash sourced from Southeast Queensland may be a contributing factor to the to higher workability experienced.

Regarding the mini slump flow test as seen in Figure 4.6 and 4.7, no other visible changes occurred in consistency or colour that is of note between the control sample and 100% pond ash replacement sample.

No testing was completed to consider the ECC matrix rheology due to time constraints. It should be noted that the addition of PVA fibres to the mortar did not appear to negatively affect the workability of the ECC. This is likely attributed to the Hobart planetary mixer used and its ability to adequately distribute the fibres through the mix to prevent clumping and overall reduced workability (Zhu et al. 2012; Zhang et al. 2020; Zhang et al. 2021).

5.3 Density

The density test results for the 28 day beam specimens have been illustrated in Figure 5.3. The specimens were dry with dimensions and weight recorded prior to commencing testing. As pond ash replacement of fly ash increases it was generally seen that density increased with the exception of 100% replacement. The average density of the control sample was recorded as 1707 kg/m^3, however, as represented by the error lines, include an outlier with one specimen presenting a noticeably lower density. While this was noted, the existing trend remains even when excluding that sample. Pond ash replacement levels of 25% and 50% steadily increase in density by approximately 4.7-4.8% while the 100% replacement samples show a small decrease of 3.3%. This may be attributed to the high levels of bleeding that occurred while curing the 100% pond ash samples, ultimately reducing the density of the samples. The density for all specimens fall into the typical ECC density range of 950 kg/m^3 to 2300 kg/m^3 (Nawy 2008). No comparisons can be made to existing literature as pond ash replacement of fly ash in both ordinary concrete and ECC have not previously been investigated.

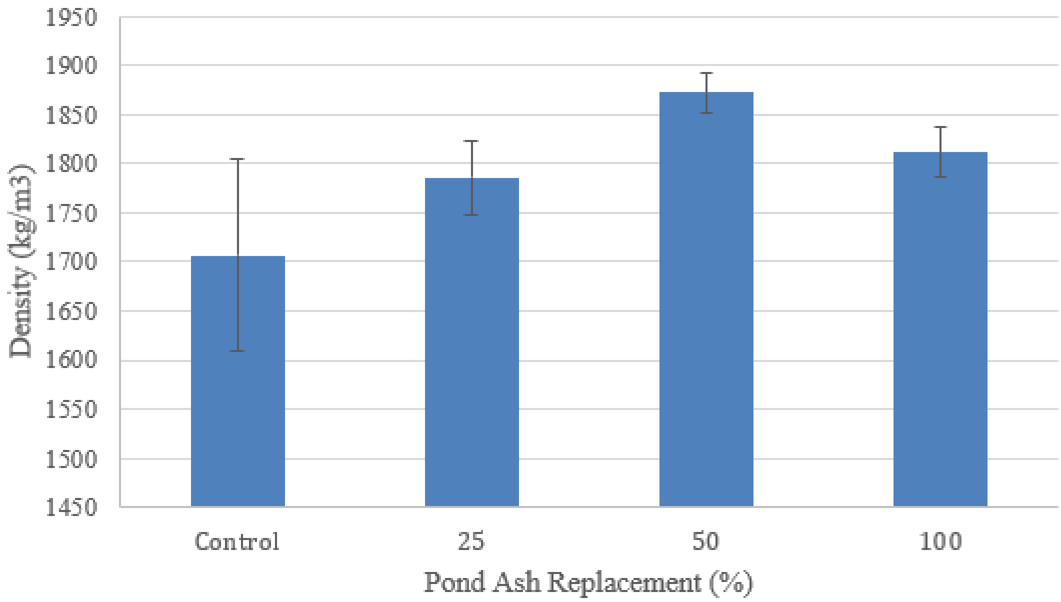

Figure 5-3 Average density results

5.4 Compression Testing

Compressive testing was conducted as discussed in Sections 3.5.2 and 4.4.1 with a tabulation of the results and details outlined in Appendix D, Table D-2 and D-3. The average 7 day and 28 day compressive strength of the control and pond ash replaced ECC samples have been illustrated in Figure 5.4 and 5.5 below.

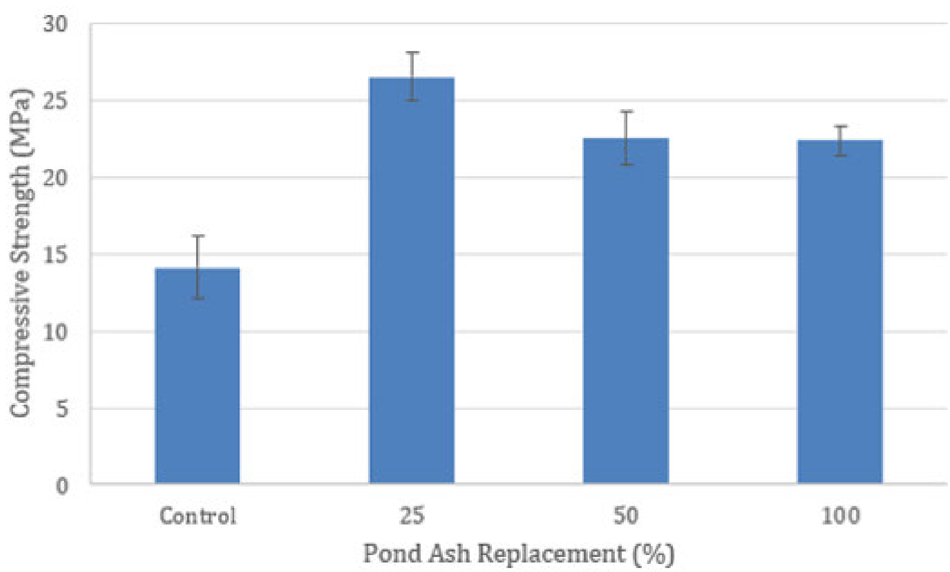

Figure 5-4 7-Day compressive strength for ECC cube specimens

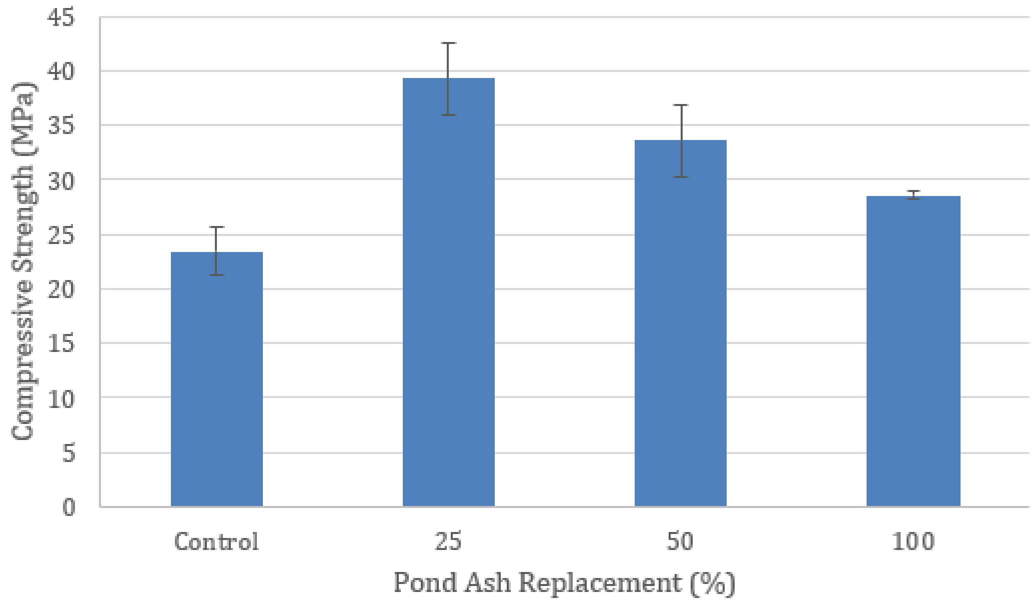

Figure 5-5 28-Day compressive strength for ECC cube specimens

Past literature on pond ash replacement of fine aggregate or cement present large variations in results. The compressive strength trend of pond ash replacement of fly ash more closely resembles the replacement of fine aggregate in ordinary concrete. Past literature of cement replacement by Lal et al. (2019) and Yuvaraj & Ramesh (2021) indicate strength gains at or below 10% replacement, however, unlike the results gathered from pond ash in ECC, start to see decreases by the 25% replacement mark. Compressive strength results for pond ash ECC best match the past research on fine aggregate replacement presented by Lal et al. (2019) and sample A from Jung & Kwon (2013) with notable increases in strength reported compared to the control samples. While results don't align with other literature on fine aggregate replacement, namely Yimam et al. (2021), Haldive & Kambekar (2013), Harle (2019), Kumar & Radhakrishna (2020) or Jung & Kwon (2013) sample B, it does highlight the variations present when working with pond ash of different sources. As outlined by Jung & Kwon (2013), Harle (2019), Lal et al. (2019) and Yuvaraj & Ramesh (2021) pond ash source has a significant role in determining the overall strength of the sample. Despite this, direct comparisons are hard to quantify when pond ash replacement is occurring with a different material.

It should be noted that 0% to 20% generally considered to be the optimal pond ash replacement range for past research. While a more generalised approach was considered for this project, it highlights the potential for further research to be undertaken more specifically within the range of 0% to 20% replacement which may highlight more promising results than intervals of 25% replacement tested in this project.

Comparing the compressive strength of specimens from 7 to 28 days it is seen that the strength development speed increases as pond ash replacement increases. 7 day strength was noted as 60%, 67%, 67% and 78% of the 28 day compressive strength for the control, 25% 50% and 100% replacement samples respectively. Previous literature suggests that pond ash samples demonstrated a slower pozzolanic reaction leading to reduced initial strength compared to ordinary concrete, however this isn't obvious based on results gathered. While this doesn't contradict these findings by Sofi & Phanikumar (2015), Lal et al. (2019) and Yuvaraj & Ramesh (2021) it does suggest that if time permitted that additional tests would be beneficial to determine if notable strength gains would continue in pond ash samples if curing time was increased past 28 days. It should be considered that the 100% pond ash replacement sample demonstrated notably lower strength gain from 7 to 28 day compressive testing which may be attributed to the significant bleeding that occurred during the initial curing period, ultimately reducing moisture content for the pozzolanic reaction to occur.

While it is unknown why the control mix was significantly weaker than the pond ash replacement samples for compressive strength, it can be concluded that the results are still a good representation of the design mix and the effects of pond ash replacement. This is because the tensile and flexural tests presented more comparable results, therefore indicating the mix was suitable. This will be discussed further in Section 5.5 and 5.6 respectively. The 25% pond ash replacement sample demonstrated the most positive results with compressive strength increasing by 168% from the control sample. This is close to the optimal range outlined in past literature for fine aggregate replacement and may suggest that an intermediate replacement value than those tested may have yielded results even more promising. The 50% and 100% replacement levels showed consecutive decreases in compressive strength of 85%.

The visual failure patterns for the compressive strength cubes displayed similar results across all samples, this pattern has been illustrated in Figures 5.6 to 5.13 below. Upon closer inspection of the loading graph shown in Figure 5.14 it is evident that the 25% samples were loaded at a faster rate due to the alternative testing machine used as explained in Section 4.4.1. This was required as the 100 kN machine did not have enough capacity to cause the first 25% sample to fail. Upon retesting this sample in the 2000kN compressive machine, it failed prematurely at 86 kN indicating that it had previously been weakened from prior testing. Despite this the 25% samples still demonstrated a significant increase in strength in comparison. This graph also illustrates a reasonable level of residual strength maintained by the specimens after failure with the 25% specimens showing the most significant decrease in strength.

Figure 5-6 7-day compressive specimen failure patterns (Control)

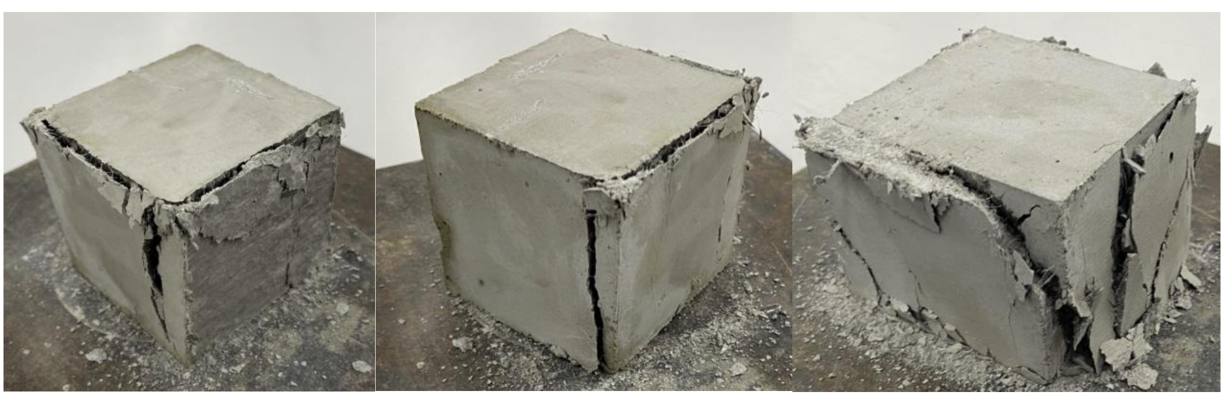

Figure 5-7 7-day compressive specimen failure patterns (25% replacement)

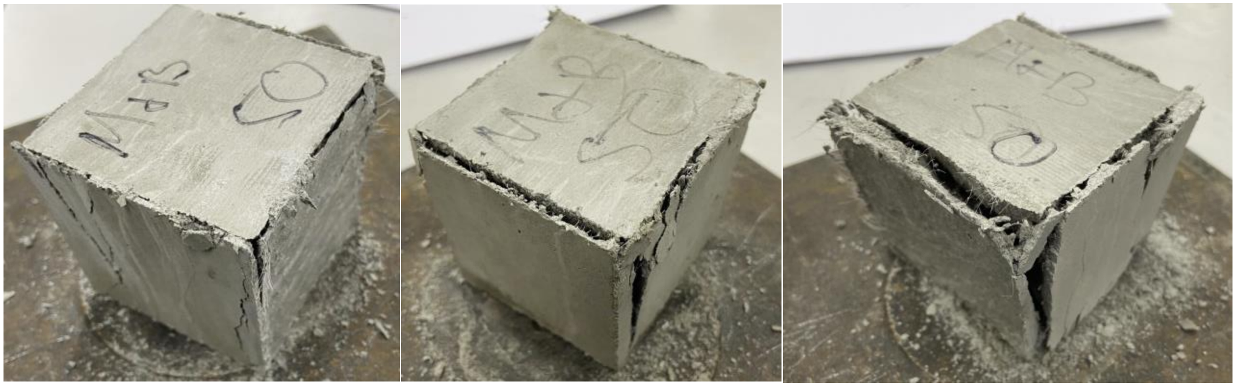

Figure 5-8 7-day compressive specimen failure patterns (50% replacement)

Figure 5-9 7-day compressive specimen failure patterns (100% replacement)

Figure 5-10 28-day compressive specimen failure patterns (Control)

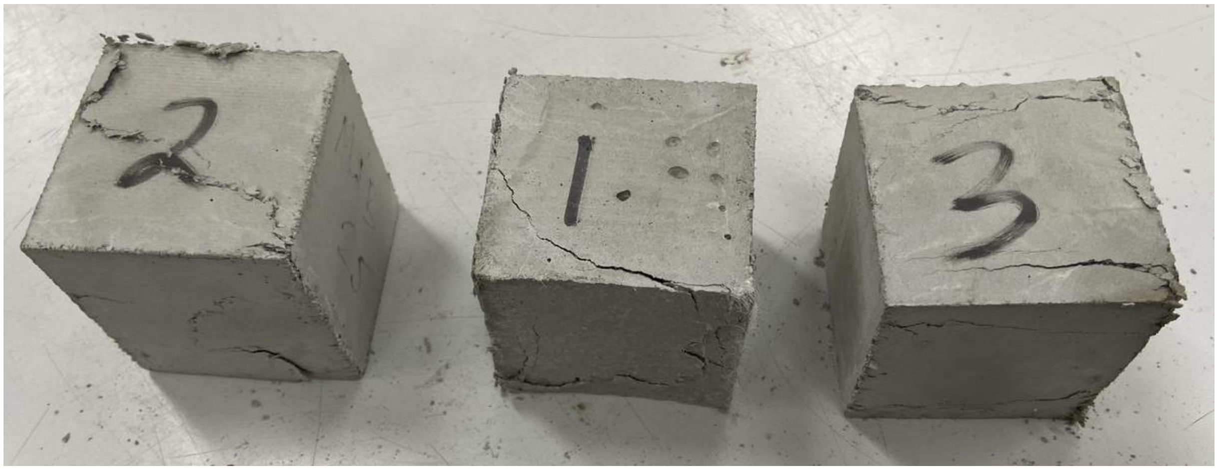

Figure 5-11 28-day compressive specimen failure patterns (25% replacement)

Figure 5-12 28-day compressive specimen failure patterns (50% replacement)

Figure 5-13 28-day compressive specimen failure patterns (100% replacement)

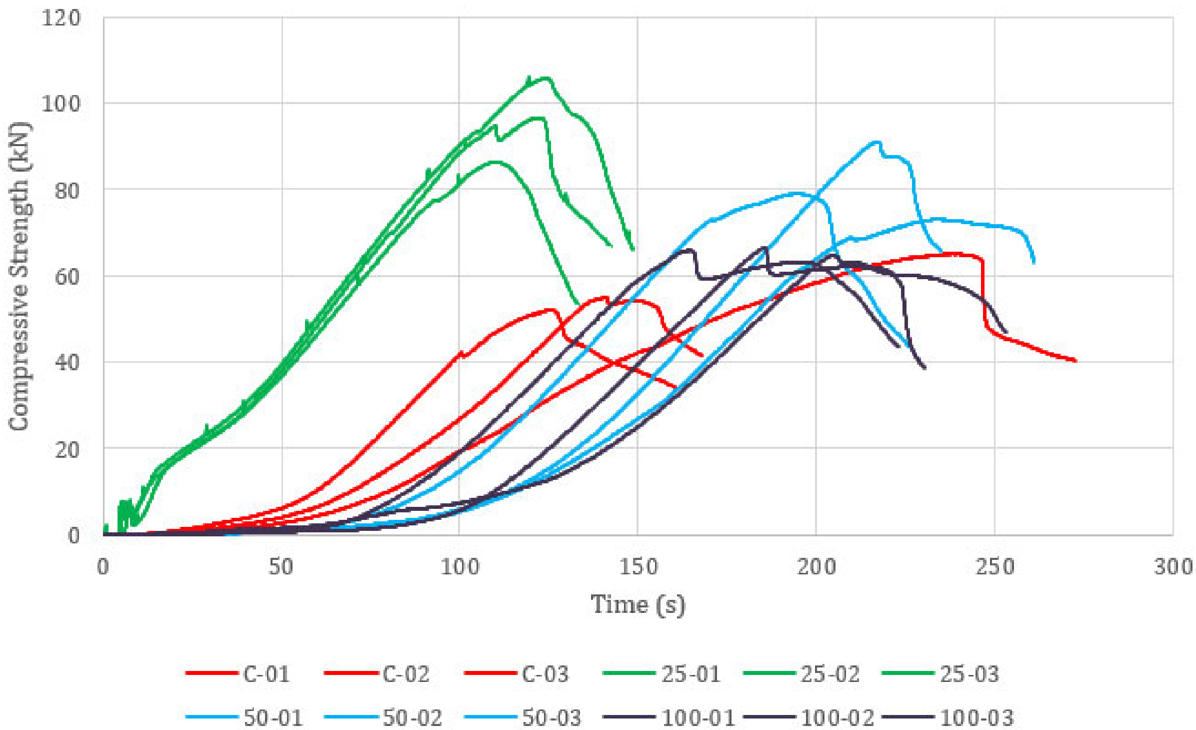

Figure 5-14 Comparison of all ECC compressive cube specimens

Overall pond ash replacement of fly ash in ECC demonstrated promising results with increases at all replacement levels, this may be attributed to the properties of pond ash sourced from the Commmodore open cut coal mine. Similar results were recorded with sample A pond ash by Jung and Kwon (2013) with pond ash replacement of fine aggregate.

5.5 Tensile Testing

Uniaxial testing was conducted as discussed in Sections 3.5.3 and 4.4.2 with a tabulation of the results and details outlined in Appendix D, Table D-4 and D-5. The average 28 day uniaxial strength of the control and pond ash replaced ECC samples have been illustrated in Figure 5.15 below.

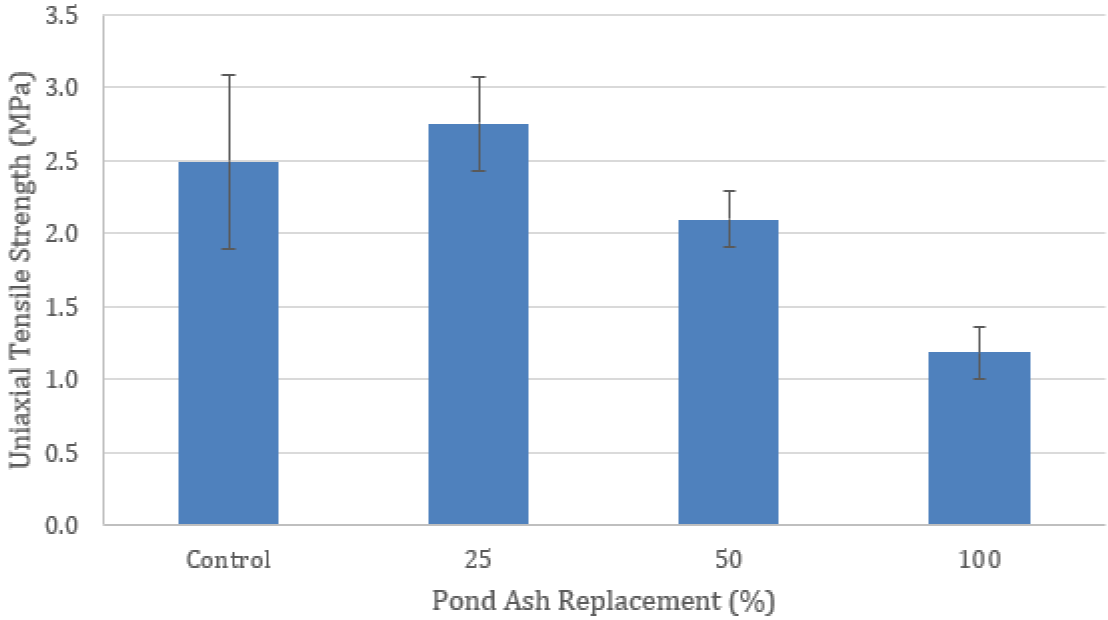

Figure 5-15 28-Day uniaxial tensile strength for ECC dogbone specimens

Past literature has minimal input concerning the tensile strength of pond ash replaced specimens. Research by Romeekadevi & Tamilmullai (2015) note splitting tensile strengths of approximately 12% to 14% of the respective compressive strength which supports the estimation of 7% to 15% made by Liao et al. (2020). However, that concludes all past research currently available with no research that has previously been conducted on uniaxial tensile testing of pond ash replacement in ordinary concrete or ECC.

Similar conclusions to research completed by Romeekadevi & Tamilmullai (2015) can be drawn from the results gathered surrounding pond ash replacement of fly ash in ECC demonstrating a trend of decreased tensile strength as pond ash replacement increases, with the exception of the 25% batch. However, when considering the tensile strength relative to the compressive strength it’s seen that the decreasing trend is true for all pond ash batches. Results demonstrate a relative tensile strength of 11%, 7%, 6% and 4% outlining the below expected performance of the 50% and 100% replacement samples. Given that tensile strength is generally relative to the characteristic strength of concrete, these results are unexpected. An outline of typical ECC properties by Nawy (2008) further support this, suggesting an ultimate tensile strength ranging from 4-12 MPa.

A likely cause of the reduced tensile strength as pond ash increases is the occurrence for more voids with Kumar & Radhakrishna (2020) noting that the porous nature of pond ash leads to increases in the number of voids which may impact mechanical performance. This will be discussed further in Section 5.7.

Despite the differences within results, the visual failure patterns for the tensile strength dogbones displayed similar results across all samples, this pattern has been illustrated in Figures 5.16 to 5.19 below. Upon closer inspection of the loading graph shown in Figure 5.20, it is hard to quantify any differences in residual strength upon failure as the recording software appears to cutoff upon failure for a number of specimens. From the limited data present, it appears that the specimens could typically withstand 35% of the ultimate load after failure. It should also be noted that one of the 100% pond ash replacement samples failure while loading the machine and was therefore excluded from the results.

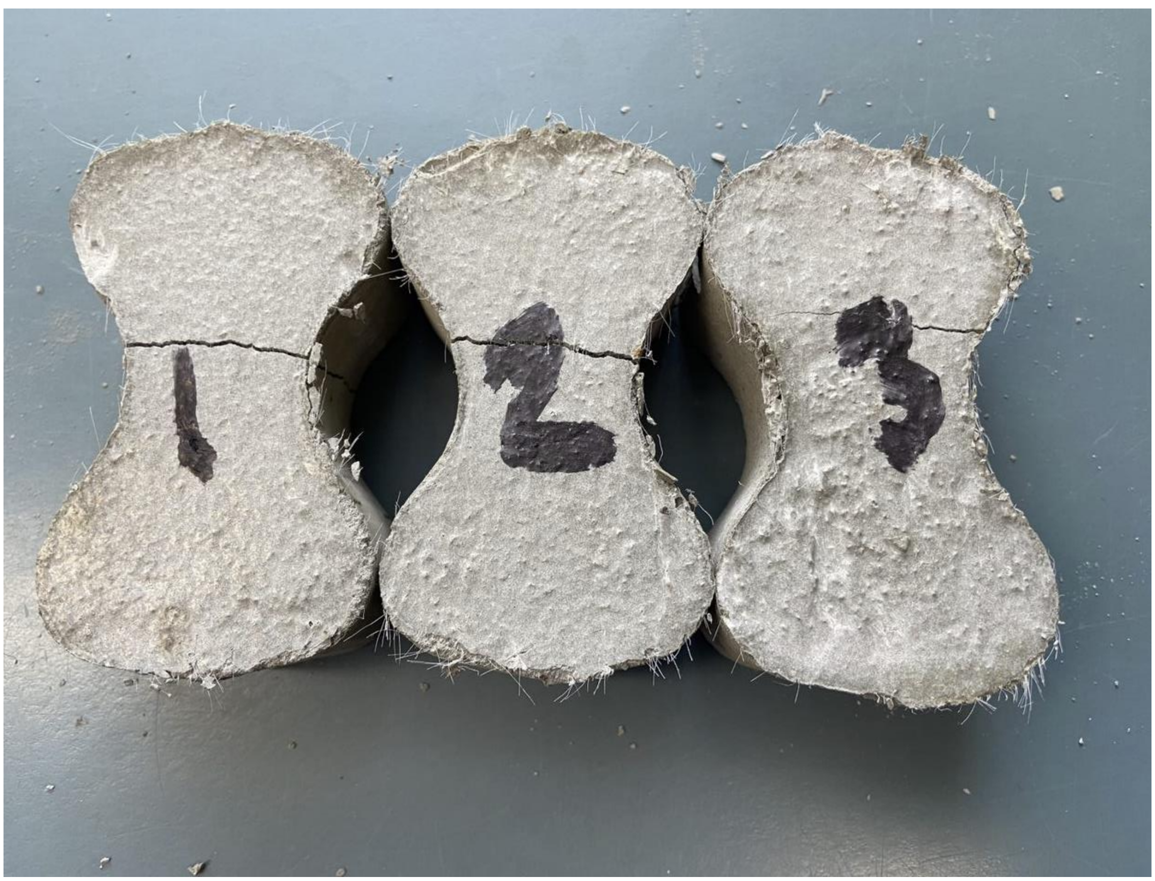

Figure 5-16 Tensile specimen failure patterns (Control)

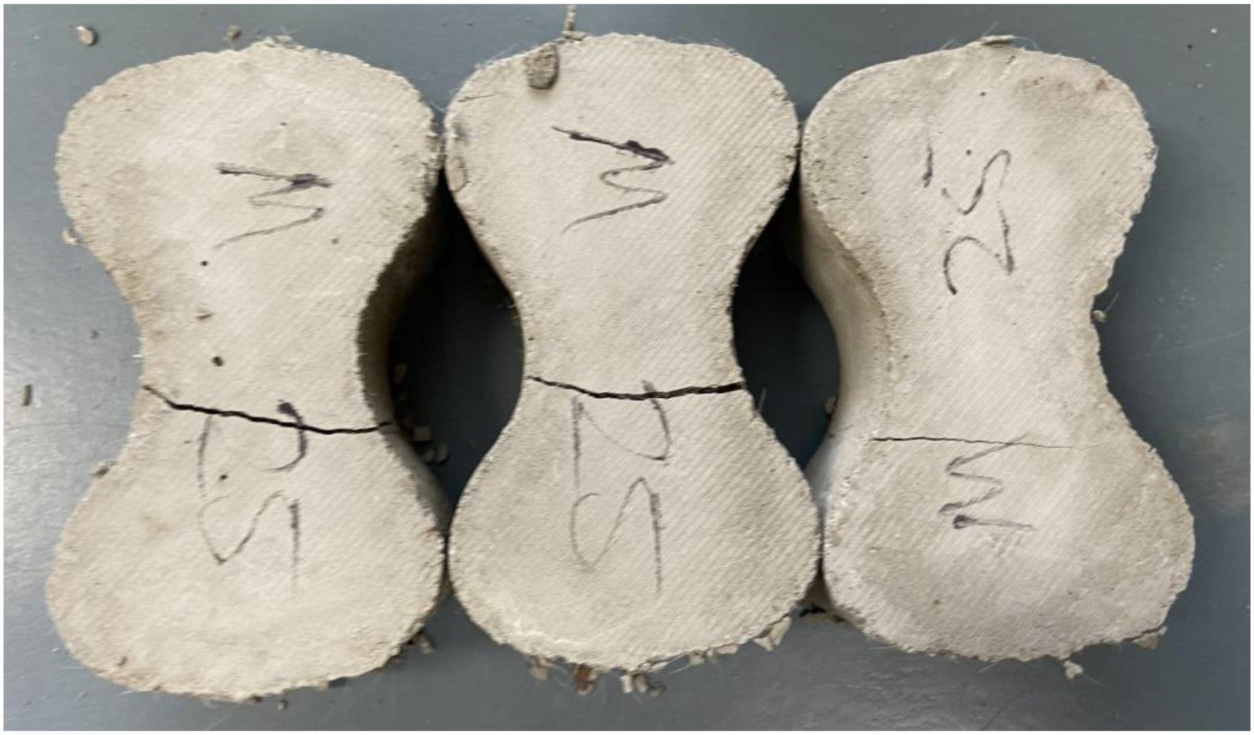

Figure 5-17 Tensile specimen failure patterns (25% Replacement)

Figure 5-18 Tensile specimen failure patterns (25% Replacement)

Figure 5-19 Tensile specimen failure patterns (100% Replacement)

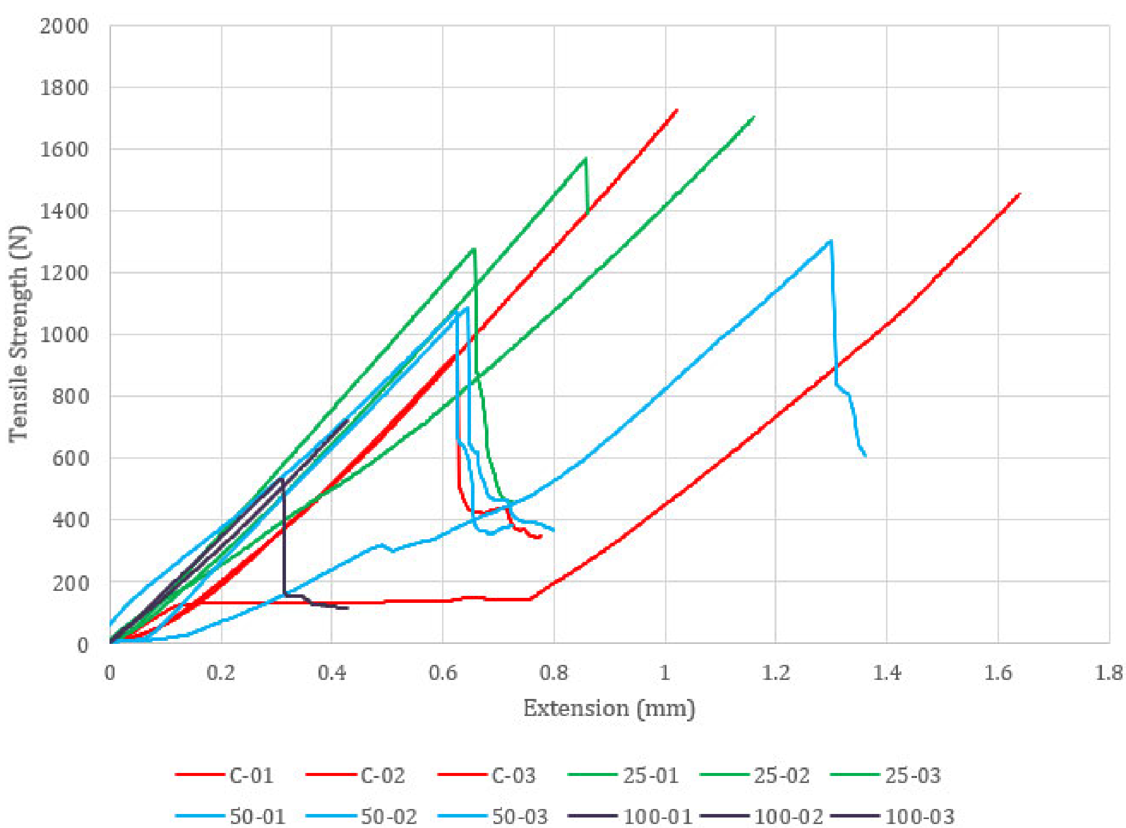

Figure 5-20 Comparison of all ECC tensile dogbone specimens

5.6 Flexural Testing

Flexural testing was conducted as discussed in Sections 3.5.4 and 4.4.3 with a tabulation of the results and details outlined in Appendix D, Table D-6 and D-7. The average 28 day flexural strength of the control and pond ash replaced ECC samples have been illustrated in Figure 5.21 Below.

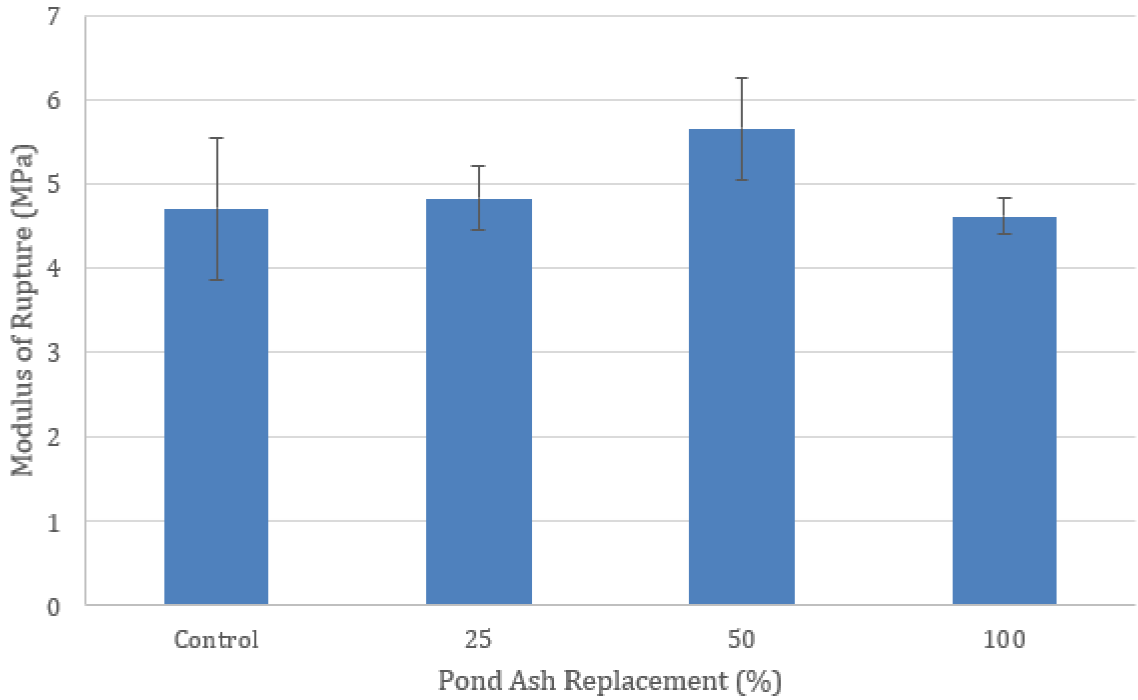

Figure 5-21 28-Day Flexural strength for ECC beam specimens

Existing research surrounding the flexural strength of pond ash in ordinary concrete generally demonstrates an increase in strength when replacing up to 30% fine aggregate and decrease in strength with all replacement levels of cement (Lal et al. 2019; Sofi & Phanikumar 2015 and Romeekadevi & Tamilmullai 2015). Once again, no previous literature has previously investigated replacement of fly ash making direct comparisons difficult.

Unlike compressive and uniaxial tensile testing, results gathered from flexural testing showed consistent results. A small increase in strength of 3% was observed with 25% pond ash replacement followed by a 17% increase from 25% to 50% replacement. 100% pond ash replacement indicated a decrease of 19% with a similar strength to the control batch. Two obvious outliers are indicated by the larger error lines shown in Figure 5.21. While these have been included to demonstrate the true average, it should be noted that without the inclusion of these two tests, one from both the control and 50% replacement batches, the results from control to 100% replacement would be very similar ranging from 5.27 MPa to 4.62 MPa respectively. With this consideration in mind, no trend has been observed within the flexural tests, ultimately showing minimal effects on flexural strength due to pond ash replacement of fly ash. Despite the promising results showing no decrease in flexural strength, the modulus of rupture for these specimens fall short of the typical range of 10 MPa to 30 MPa for ECC outlined by Nawy (2008).

As expected from the results, the visual failure patterns for the flexural strength beams displayed similar results across all samples with a single crack evident on each beam as illustrated in Figures 5.22 to 5.25 below. The loading graph shown in Figure 5.26 highlights the consistency of all specimens with an outlier present in the control and 50% replacement sample as previously discussed. Interestingly, the 100% samples show a significantly reduced residual strength compared to the other batches and may be associated with the poor tensile strength observed within the tensile testing.

Figure 5-22 Flexural specimen failure patterns (Control)


Figure 5-23 Flexural specimen failure patterns (25% Replacement)


Figure 5-24 Flexural specimen failure patterns (50% Replacement)

Figure 5-25 Flexural specimen failure patterns (100% Replacement)

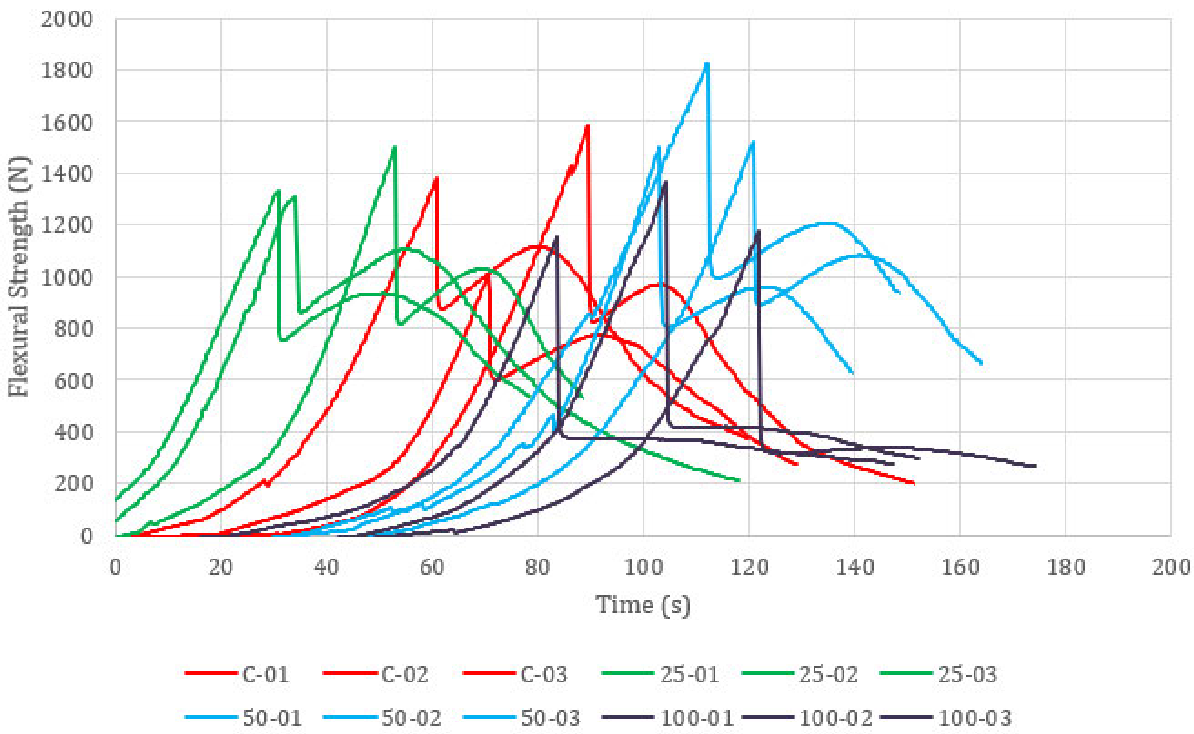

Figure 5-26 Comparison of all ECC flexural beam specimens

5.7 Scanning Electron Microscopy (SEM) Investigation

Samples from the 100% pond ash were taken from the internal matrix of the uniaxial tensile specimens for a Scanning Electron Microscopy (SEM) investigation. This investigation highlighted that the 100% pond ash replacement samples have a high presence of voids as illustrated in Figure 5.27 and 5.28. The size of voids recorded ranged from 30 to 550 micrometres and are generally shown as darker cater areas attached Figures. While time constraints prevented a full investigation of the control, 25% and 50% replacement samples, the reduction in tensile strength of 100% pond ash may be attributed to the higher void ratio. This is reinforced with research by Kumar & Radhakrishna (2020) noting that the porous nature of pond ash may lead to an increase in voids. Therefore, it would be expected that the 100% pond ash samples to be most affected. It is recommended that future research continue to assess the effects of pond ash replacement on internal matrix at various replacement percentages.

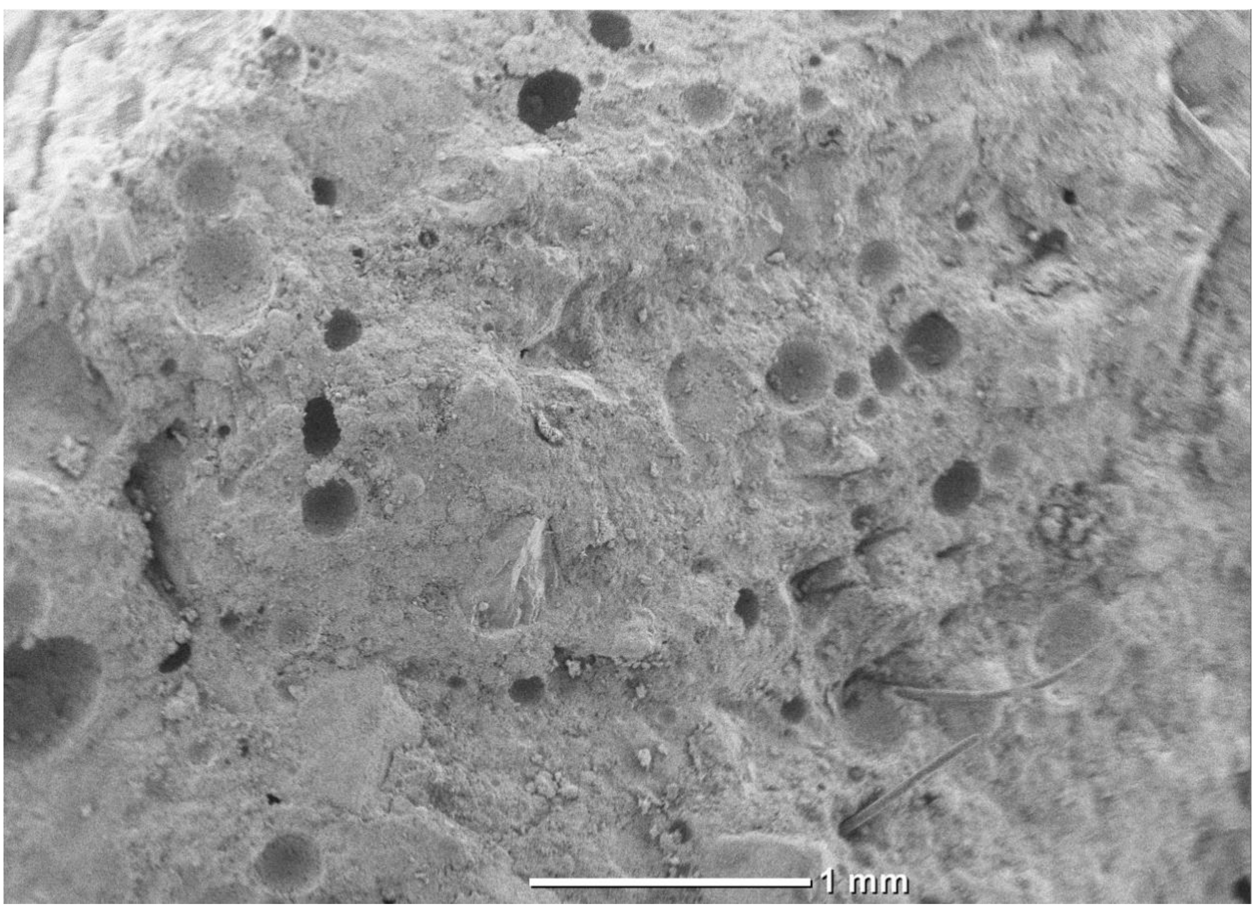

Figure 5-27 Voids present at 28 days (100% Replacement)

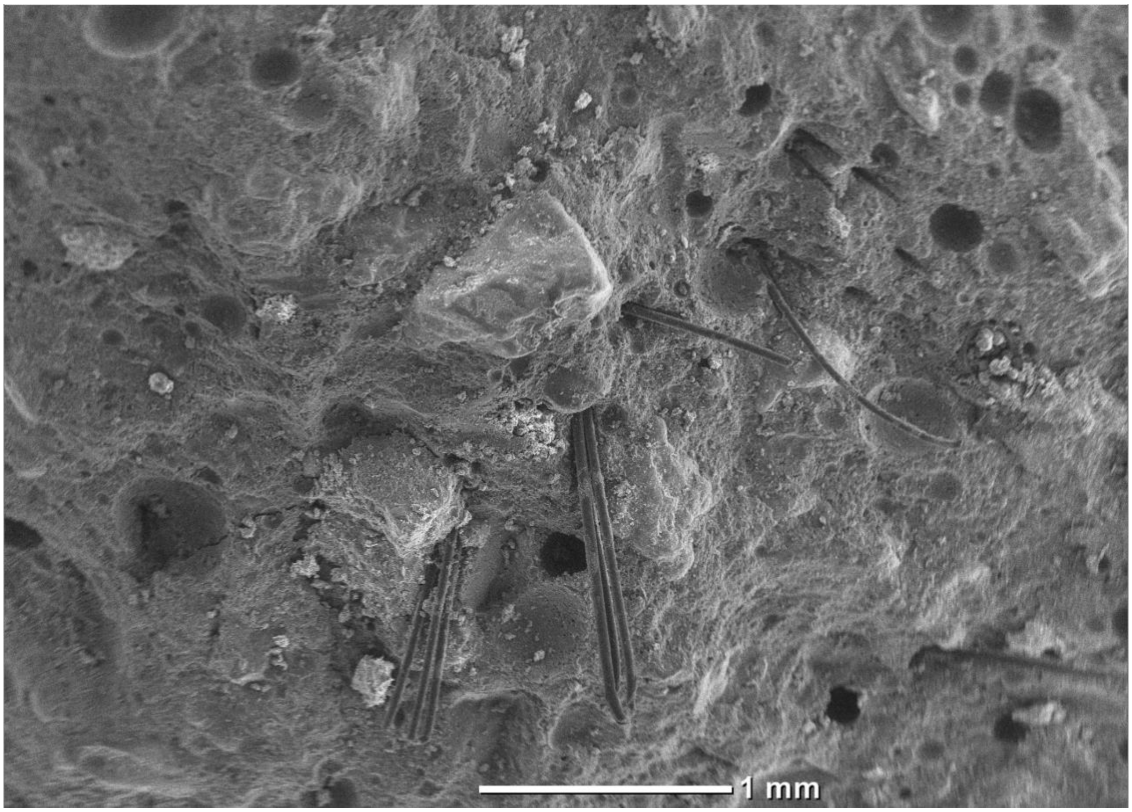

Figure 5-28 Voids and fibre distribution at 28 days (100% Replacement)

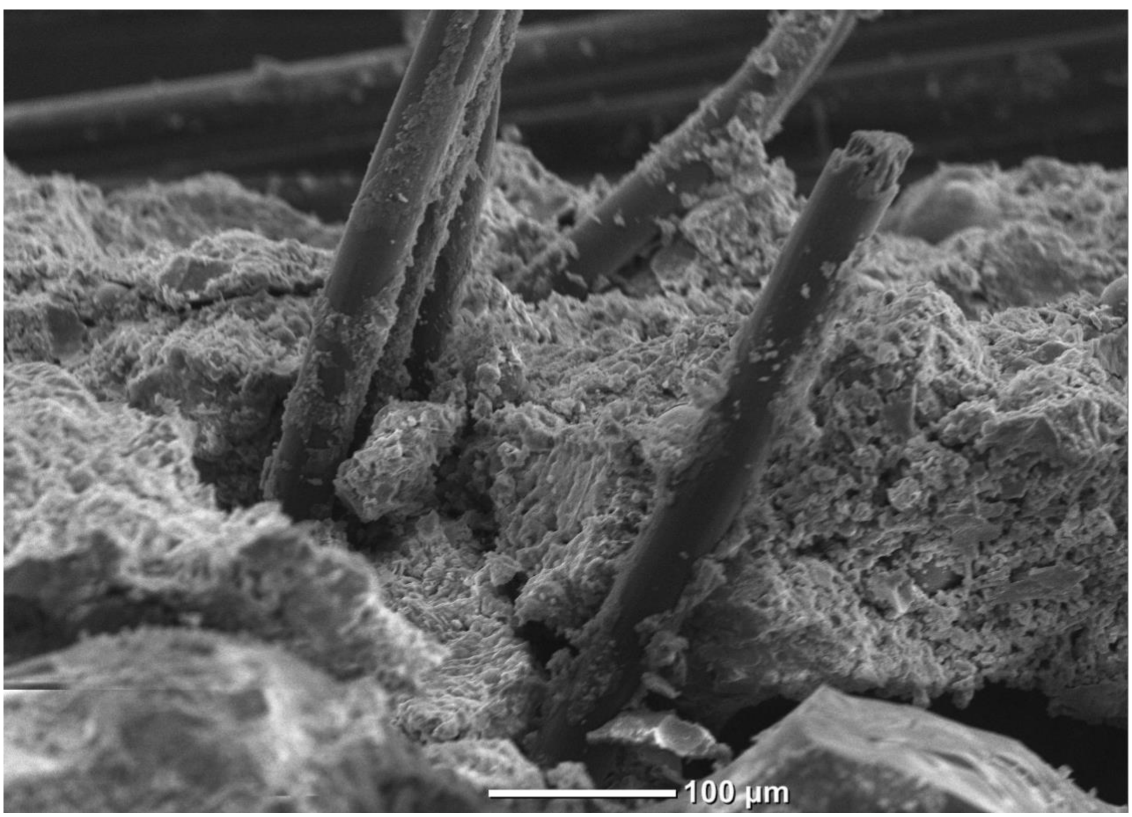

Figure 5-29 Fibre matrix at 28 days (100% Replacement)

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

This research has investigated the performance of ECC containing 25%, 50% and 100% pond ash replacement of fly ash by volume. Extensive testing focused on determining the effects on compressive, flexural and tensile strength of various specimens cast from the ECC mix.

Based on the results the following conclusions have been made:

1. Locally sourced pond ash can be successfully used in ECC mix design as a partial substitution to fly ash. While the mechanical performance of locally sourced pond ash ECC generally presented higher compressive, flexural and tensile strength, the consistency of pond ash sources can vary.

2. Fresh mortar testing indicated a decrease in both yield stress and plastic viscosity as pond ash replacement increases. Density of ECC specimens increased by 4.7%, 4.8% and 3.3% from 1707 kg/m^3 as pond ash content increased. Tailoring of the ECC mix and superplasticiser may present more favourable fresh mortar rheological properties.

3. The compressive strength of ECC was significantly higher with an 88% and 68% strength increase at 25% pond ash replacement of fly ash at 7 and 28 days respectively. Notable strength gains of 43% and 22% from the control strength of 23 MPa was also observed at 50% and 100% replacement of fly ash respectively.

4. The flexural strength results did not follow the same trend as compressive strength testing at 28 days. Generally flexural strength did not present any noticeable changes as pond ash content increased within the ECC mix. When outliers from the data were removed all results for flexural strength ranged from 4.62 MPa to 5.27 MPa with no obvious trend. 50% pond ash replacement presented the most favourable flexural strength results.

5. Similar to the results from the compressive strength testing, uniaxial tensile testing demonstrated optimal pond ash replacement of fly ash occurring at 25% with a 10.5% strength increase. Decreasing strength occurs when exceeding 25% pond ash replacement with a 15.8% and 52.4% decrease from control strength at 50% and 100% pond ash replacement, respectively.

6. Poor tensile strength results for 100% pond ash replacement may be attributed to the high presence of voids seen within the SEM imaging for this mix.

This project has added to the collective knowledge of pond ash and its ability to be utilised as a sustainable alternative to fly ash in ECC. This research has contributed to filling the gap surrounding existing pond ash research while its success acts to improve confidence in pursuing further research on adopting this material into the construction industry. Results, particularly at 25% replacement, demonstrate cause for future research of lightweight pond ash ECC to continue. As this project took a broad approach, beginning the research on pond ash ECC, there are a plethora of areas yet to investigate and optimise to utilise this waste material most effectively.

6.2 Future Research

To determine the full potential of pond ash ECC, the following is a list of identified research opportunities. List items have been determined from results of this project along with research presented during the literature review and therefore should not be considered exhaustive.

1. Optimising the mix design to suit pond ash ECC should be investigated, particularly through identifying mix designs that achieve desirable rheological fresh mortar properties. This may require specialist mixing equipment but would act to improve confidence in the mixing quality control and may improve results.

2. Jung & Kwon (2013) demonstrated that the source of pond ash has a significant effect on the performance of pond ash replacement in ordinary concrete. An investigation into the source of pond ash and the effect on pond ash ECC should be investigated before this material can be confidently adopted for use. Further analysis into the contributing factors

causing the performance variations should also be considered so pond ash sources may be optimised for higher quality product.

3. Research should be undertaken to ensure the desirable ECC qualities such as ductility, cracking behaviour and durability are maintained or improved with the addition of pond ash replacement in ECC.

4. Pond ash replacement of alternative ECC constituents such as fine aggregate or cement should be investigated. This will contribute to determining alternative methods to achieve sustainable ECC options with pond ash.

5. Investigate the use of different types of fibres and dosage on the mechanical properties, ductility and cracking behaviours of pond ash ECC. Different fibre types may impact the optimal mix design, methods and ultimately the performance of the ECC.

6. Validate the use of briquette specimens for uniaxial tensile strength testing of ECC as per ASTM C307.

7. Building on the findings of this study, testing of intermediate replacement percentages between the control and 25% pond ash replacement is recommended. Based on past literature of pond ash replacement of fine aggregate or cement, optimal values were found within the range of 0% to 20% replacement. Results from this project demonstrate cause to explore if a more optimal replacement percentage may exist outside the values tested within this research.

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Appendix A – Project Specification

ENG4111/4112 Research Project

Project Specification

For: Mitchell Parke

Title: Mechanical Performance of Engineered Cementitious Composites (ECC) with Substitution of Fly Ash by Pond Ash

Major: Civil Engineering

Supervisor: Weena Lokuge

Enrolment: ENG4111 – EXT S1, 2023
ENG4112 – EXT S2, 2023

Project Aim: This project aims to evaluate the mechanical properties of Engineered Cementitious Composites (ECC) if fly ash is partially substituted by volume with pond ash. To determine the performance the project will test fly ash replacement with 25%, 50% and 100% by pond ash.

Programme: Version 3, 22nd July 2023

1. Conduct initial background research on the mechanical properties and behaviour of concrete, fly ash, pond ash and ECC. Evaluate the effects of pond ash in ordinary concrete.

2. Develop suitable ECC mix design, testing methodology and source required materials.

3. Prepare ECC test samples. Conduct mechanical testing after 7 and 28 days as per AS 1012 and collect results.

4. Analyse and evaluate test results to determine the effects of various pond ash substitution levels. Confirm the most optimal pond ash substitution percentage in ECC mix design.

5. Compare results with control samples and provide an initial analysis on the suitability and potential application to sustainable ECC materials.

6. Present results at the ENG4903 project conference and submit USQ project dissertation.

Appendix B – Risk Management

Risk management seeks to identify foreseeable hazards or incidents that may accompany activities required to complete a project. By identifying potential hazards in advance, control measures can be implemented to mitigate the likelihood of risks occurring or reduce the severity of the consequences. The risk management plan is determined by completing the following tasks:

1. Identify possible risks that may occur in each activity required to complete the project.
2. Assess the likelihood of each risk event occurring.
3. Assess the consequences if a risk event was to occur.
4. Develop control measures to reduce the likelihood or consequences of risk events.
5. Re-evaluate the risk and determine if the activity is at a safe and acceptable level.

Table B- 1 Risk matrix

		Consequence					
		Safety	No injuries. Minor delays	First Aid required. Small spill gas release easily contained within work area	Medical treatment required. Large/spill gas release contained on campus	Medical attention and hospitalisation required, permanent severe health effects	One or more deaths. Toxic substance, genetically modified organism escapes or biosafety critical incidents
			Insignificant	Minor	Moderate	Major	Catastrophic
Likelihood	1 in 2	Almost Certain	High	High	High	Extreme	Extreme
	1 in 100	Likely	Medium	Medium	High	High	Extreme
	1 in 1,000	Possible	Low	Medium	Medium	High	High
	1 in 10,000	Unlikely	Very Low	Low	Medium	Medium	Medium
	1 in 1,000,000	Rare	Very Low	Very Low	Low	Low	Medium

Table B- 2 Experimental risk assessment

NUMBER	RISK DESCRIPTION	TREND	CURRENT	RESIDUAL
2562	Testing mechanical properties of ECC with pond ash replacement of fly ash		Low	Low

DOCUMENTS REFERENCED
SDS for bottom ash SDS for fly ash SDS for PVA fibre SDS for cement

RISK OWNER	RISK IDENTIFIED ON	LAST REVIEWED ON	NEXT SCHEDULED REVIEW
Mitchell Parke	07/06/2023	07/06/2023	N/A

RISK FACTOR(S)	EXISTING CONTROL(S)	PROPOSED CONTROL(S)	OWNER
Manual handling of ECC materials, specimens and testing equipment. Risks include strains or sprains or cuts and abrasions.	**Control:** Gloves Steel cap Boots **Control:** Use trolleys and lifting aids where possible for transporting large or heavy objects. **Control:** ECC is a lighter than ordinary concrete which reduces potential risks. **Control:** Use correct lifting techniques. Lab induction before completing any tasks. Become familiar with equipment before operating. Complete work under the supervision of staff.	**No Control Required**	
Working with ECC materials which may cause irritation or damage to skin, eyes or lungs.	**Control:** Shower and eye wash station provided on site to wash skin or eyes if required. Complete work under the supervision of staff. Obey procedures in SDS.	**No Control Required**	

	Control: Wear appropriate PPE (gloves, safety glasses and mask where required)	
Moving components of cement mixer may cause injury.	**Control:** Keep area surrounding the mixer clear of materials or people to prevent accidents occurring around it. **Control:** Safety cutoff switch on machine. **Control:** Ensure machine is fit for use before using. **Control:** Wear gloves, eye protection and mask.	**No Control Required**
Testing ECC specimens in compression, tension and flexural bending presents crushing/pinching points and potential projectiles.	**Control:** Ensure safety measures and guards are in place before operating machines. **Control:** Ensure machines are checked and is fit for use before operating. Follow operating procedure for equipment. Complete work under the supervision of staff. **Control:** Wear gloves and safety glasses.	**No Control Required**
Other students and staff may be in the work area. Potential injury due to trips or slips.	**Control:** Wear safety boots. **Control:** Ensure area is kept tidy with materials and equipment stored safely and out of the way. Clean up spills immediately. Complete work under the supervision of staff. Power cables to be kept out of walkways.	**No Control Required**

Table B- 3 Project risk assessment

Risk Factor(s)	Current Risk Level	Control(s)	New Risk Level
Computer related injuries from extended use.	Medium	• Take regular breaks. • Implement good office ergonomics. • Regular exercise.	Low
Technical issues or illness resulting in delays.	Medium	• Ensure time management schedule allows for unforeseen delays.	Low
Lab booking or equipment issues.	High	• Ensure time management schedule allows for unforeseen delays. • Organise access to the most suitable equipment as soon as possible.	Medium
Loss of work documents or experimental data	High	• Ensure all work is backed up online or on a hard drive after every session. • Ensure samples are labelled and stored correctly as per UniSQ requires.	Low
Materials are not easily accessible or available.	High	• Secure required materials as early as possible to allow time to source alternatives as required.	Medium
Lack of time to effectively analyse experimental results.	Medium	• Implement good time management skills throughout the life of the project.	Low
Lack of time to prepare of presentation.	Medium	• Implement good time management skills throughout the life of the project. • Summarise key points from project to suit desired presentation length.	Low

Appendix C – Consequences and Ethics

This project seeks to provide foundational knowledge in the development of sustainable alternative materials for use in ECC. Successful testing results may lead to further testing on the effects of pond ash ECC, where positive results could ultimately allow companies to adopt a more environmentally friendly, high performance construction material. This would simultaneously aid in the reduction of hazardous material entering landfill which has been identified as a large contributor to landfill, particularly within India.

As a future engineering professional, the Engineers Australia's Code of Ethics provides a framework with key professional values and principles that act as a guideline for sound judgement and decision making.

While it is recognised that this list is not exhaustive, professional conduct for engineering practice should:

1. Demonstrate integrity
2. Practice competently
3. Exercise leadership
4. Promote sustainability (Engineers Australia 2022)

Where previous research by others has been drawn on and contributed to this project, their work has been properly recognised. All results, conclusions and recommendations are as a result of the author's own work. Testing has been carried out in a professional manner in controlled laboratory settings with guidance from experienced professionals to ensure reliable and genuine data.

This project has been carried out by the author, acting within their field of study and developing suitable methodology and testing procedures using past literature and guidance from relevant professionals. Collection and interpretation of data will be carried out by the author and should be recognised as the work of a student engineer.

To promote sustainability, this project aims to encourage and build on the existing knowledge base of sustainable building materials to contribute to reducing the environmental impact of the construction industry. While it is hopeful that testing will provide results that support the use of pond ash, the project is being carried out without bias and objectively to truthfully evaluate the mechanical performance of pond ash ECC.

Appendix D – Experimental Data

Table D- 1 Fresh mortar testing

Batch	Mini Slump (mm)		Cone Flow Time (s)
Control	d1	142	**20 (Stuck)**
	d2	140	
	d3	128	
	d4	140	
25%	d1	130	**7.33**
	d2	129	
	d3	132	
	d4	134	
50%	d1	150	**1.63**
	d2	158	
	d3	167	
	d4	166	
100%	d1	167	**1.16**
	d2	161	
	d3	180	
	d4	180	

Table D- 2 Compressive cube properties

Batch	Cube ID	Length (mm)	Width (mm)	Height (mm)	Weight (kg)	Density (kg/m3)
Control	C-01	50	50	49	0.22	1796
	C-02	50	50	49	0.20	1633
	C-03	50	50	49	0.20	1633
25%	25-01	50	50	49	0.23	1878
	25-02	50	50	49	0.23	1878
	25-03	50	50	49	0.23	1878
50%	50-01	50	50	49	0.22	1796
	50-02	50	50	48	0.22	1833
	50-03	50	50	48	0.22	1833
100%	100-01	50	50	46	0.21	1826
	100-02	50	50	46	0.21	1826
	100-03	50	50	46	0.21	1826

Table D- 3 Compressive cube test data

Batch	Cube ID	Ultimate Load (kN)	Max Compressive Strength (MPa)	Average Compressive Strength (MPa)	Standard Deviation
Control	C-01	55.07	22.48	23.43	2.25
	C-02	52.14	21.28		
	C-03	65.03	26.54		
25%	25-01	86.36	35.25	39.34	3.31
	25-02	106.20	43.35		
	25-03	96.61	39.43		
50%	50-01	73.09	29.83	33.57	3.35
	50-02	91.10	37.96		
	50-03	79.00	32.92		
100%	100-01	64.71	28.13	28.59	0.34
	100-02	65.92	28.66		
	100-03	66.61	28.96		

Table D- 4 Uniaxial dogbone properties

Batch	Cube ID	Length (mm)	Waist Width (mm)	Height (mm)
Control	C-01	75	22	25
	C-02	75	22	25
	C-03	75	22	25
25%	25-01	75	22	25
	25-02	75	22	25
	25-03	75	22	25
50%	50-01	75	22	25
	50-02	75	22	25
	50-03	75	22	25
100%	100-01	75	22	24
	100-02	75	22	24
	100-03	75	22	24

Table D- 5 Uniaxial dogbone test data

Batch	Cube ID	Ultimate Load (N)	Uniaxial Tensile Strength (MPa)	Average Uniaxial Tensile Strength (MPa)	Standard Deviation
Control	C-01	1455.00	2.76	2.60	0.62
	C-02	1722.00	3.26		
	C-03	935.00	1.77		
25%	25-01	1702.00	3.09	2.75	0.32
	25-02	1566.00	2.85		
	25-03	1277.00	2.32		
50%	50-01	1303.50	2.37	2.10	0.19
	50-02	1073.08	1.95		
	50-03	1083.67	1.97		
100%	100-01	720.75	1.37	1.19	0.18
	100-02	532.42	1.01		
	100-03	Defecive	Defective		

Table D- 6 Flexural beam properties

Batch	Cube ID	Length (mm)	Width (mm)	Height (mm)	Weight (kg)	Density (kg/m3)
Control	C-01	305	76	38	1.61	1828
	C-02	305	76	38	1.50	1703
	C-03	305	76	38	1.40	1589
25%	25-01	305	76	38	1.61	1828
	25-02	305	76	38	1.58	1794
	25-03	305	76	38	1.53	1737
50%	50-01	305	76	38	1.65	1873
	50-02	305	76	38	1.67	1896
	50-03	305	76	39	1.67	1847
100%	100-01	305	76	37	1.55	1807
	100-02	305	76	36	1.54	1845
	100-03	305	76	38	1.57	1782

Table D- 7 Flexural beam test data

Batch	Cube ID	Ultimate Load (N)	Max Modulus of Rupture (MPa)	Average Modulus of Rupture (MPa)	Standard Deviation
Control	C-01	1584.00	5.63	4.71	0.84
	C-02	1382.00	4.91		
	C-03	1010.10	3.59		
25%	25-01	1500.00	5.33	4.83	0.38
	25-02	1333.80	4.74		
	25-03	1308.50	4.41		
50%	50-01	1522.90	5.41	5.65	0.61
	50-02	1825.00	6.49		
	50-03	1500.60	5.06		
100%	100-01	1159.00	4.34	4.62	0.21
	100-02	1175.70	4.66		
	100-03	1366.00	4.85		

Appendix E – Project Plan