University of Southern Queensland
School of Engineering

Use of Harvested Ash as Replacement for Fine Aggregate in Concrete

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Mr Drew Obst

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ABSTRACT

Many years of heavy reliance on coal combustion for energy production has resulted in the generation of large amounts of waste ash material. Some of this ash is commonly used for beneficial purposes, such as fly ash in concrete, but the coarser bottom ash is less frequently utilised and predominantly ends up in storage ponds.

This research project seeks to determine if coal bottom ash in these ponds can be harvested and used to replace a portion of fine aggregate in concrete. This possible use for harvested ash (HA) has been investigated in numerous studies from around the world with mixed results pertaining to how the incorporation of HA affects concrete performance. A key finding from review of the existing literature is that physical and chemical properties of HA vary significantly depending on the source of the ash. The literature review also reveals there is very limited research into replacing fine aggregate in concrete with ash from sources within Australia.

This project investigates how physical properties of concrete are impacted when a portion of the fine aggregate is replaced with HA from a power station in Millmerran, Queensland. The experimental programme involves the batching of five concrete mixes having fine aggregate replaced with HA at rates of 0%, 12.5%, 25%, 50% and 75% by volume. The concrete properties tested in this project include workability, concrete density, and compressive, splitting tensile and flexural strength. Material testing was also conducted on the HA to determine the properties required for mixing in concrete and to help characterise the ash from this specific source.

The results of the research suggest up to 25% of the fine aggregate in concrete can be replaced by HA without significantly affecting the concrete's strength performance. The testing also indicates the workability of concrete reduces significantly as the amount of HA replacement increases. Scanning electron microscope (SEM) analysis of the hardened concrete samples reveal negligible difference in the microstructure of concrete containing 25% HA while the 75% HA mix shows significantly less crystalline structure development.

The report concludes that replacing a portion of the fine aggregate in concrete with HA shows potential as a way of removing coal bottom ash from storage ponds and having a positive impact on the natural environment. While the results of this research project show significant promise, the report also suggests further research that would be required before the use of HA as fine aggregate in concrete is considered commercially viable.

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Drew Obst

Student number: [redacted]

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NOMENCLATURE

HA	Harvested ash
kN	Kilonewton
MPa	Megapascal
PSD	Particle size distribution
SEM	Scanning electron microscope
SG	Specific gravity
SSD	Saturated surface dry
WA	Water absorption

CHAPTER 1. INTRODUCTION

1.1 Introduction

Since the industrial revolution, global energy production has relied heavily on coal combustion to meet ever-increasing energy demands. Even with the recent world-wide ambitions to increase sustainable energy generation using renewable sources such as wind, hydro and solar, coal power plants are still one of the main energy contributors globally.

When coal is burned in these power plants, the non-combustible material within the coal results in the formation of ash. Approximately 80% of the ash produced in this process is a very fine and light material called fly ash which is extracted from the furnace using precipitators (Singh et al. 2016). This fly ash is used widely to reduce the amount of cement powder in concrete and also improve concrete properties such as workability, strength and durability. The remaining approximately 20% of ash is a heavier, coarser material that collects on the bottom of the furnace, leading to it commonly being referred to as bottom ash. This bottom ash is generally not viewed as being a useful product and is commonly transported into large holding ponds for storage.

Due to the long history of coal power generation, large quantities of bottom ash have built up in storage ponds all around the world. As global awareness of human impacts on the environment continues to gain momentum, there has been a shift in attitude to try and minimise these impacts. As a result, many researchers have begun looking into possible uses for, or ways to responsibly dispose of the large quantities of bottom ash that currently exist and continue to accumulate. Due to the beneficial properties gained by the addition of fly ash in concrete, researchers in places such as India, United States of America, Africa, and Asia are now investigating whether bottom ash could also provide similar benefits.

In Australia alone there is estimated to be approximately 400 million tonnes of bottom ash stored in ponds around the country (Millington 2019). This quantity is continuing to grow with nearly 1.2 million tonnes of bottom ash produced per year, approximately 60% of which is not used beneficially and transferred to storage (HBM Group Pty Ltd 2022). More locally based research into possible uses for bottom ash from Australian sources is required to increase the utilisation rate of this material and reduce the amount in storage.

1.2 The problem

Pond ash, coal bottom ash, furnace bottom ash. These are some of the terms used to describe the same thing, residual ash formed during the coal burning process at coal fired power plants. These various names derive from the fact this ash collects on the floor of the furnace and is pumped out in a slurry, to large storage ponds near the plant. The ash usually contains an assortment of heavy metals which pose a risk to the natural environment if they are allowed to leach or escape from the holding ponds. While these heavy metals are naturally occurring elements, they present a risk when they occur in high concentrations. Even with the current global trend to move away from coal fired power stations and toward more environmentally friendly alternatives, the abundant existing accumulations of pond ash will still continue to grow and be a source of concern for many years to come. Research needs to be conducted into ways to dispose of pond ash responsibly to try and reduce risks to the environment.

Concrete is the most widely used construction material in the world and each year Australia alone uses approximately 29 million cubic metres of pre-mixed concrete for construction projects (CCAA 2022). The four main components used to make conventional concrete are cement powder, water, coarse aggregate and fine aggregate. The process to create cement powder is hugely energy-intensive and there has been extensive research conducted into substituting a portion of the cement with more environmentally sustainable materials. The coarse and fine aggregates are usually crushed natural stone and clean river sand respectively. These materials typically make up the majority of the volume of concrete and keeping up with the demand puts a large strain on these limited natural resources. As a result, many studies have also been conducted into substituting the aggregate components of concrete with recycled or waste material. If pond ash could be proven to be a possible fine aggregate replacement in concrete it would provide a double benefit of:

- providing a useful place to dispose/store pond ash where it cannot harm the environment and,
- reducing the strain on natural fine aggregate sources.

1.3 Research objectives

The objective of this research is to investigate the feasibility of harvesting pond ash and incorporating it in concrete as a replacement for natural fine aggregate. If this can be done to produce a useable concrete mix without drastically impacting the concrete performance, it would offer huge environmental benefits.

The challenge with pond ash is it has different physical and chemical properties depending on the type of coal used in the plant and the way the plant operates. This means there is a large variation in the properties of pond ash from different sources. Similar studies have been conducted in the past, however there is very little research in this field for ash sourced in Australia. This project aims to fill this gap and perform testing on a range of concrete batches incorporating various amounts of HA sourced from a local power station in Millmerran, Queensland. A list of the specific objectives for this research is shown below.

1. Research existing literature that examines the utilisation of HA in concrete.
2. Determine the standard concrete component ratio for the control mix and identify a suitable range of substitution rates for the HA.
3. Obtain HA and perform laboratory analysis to characterise the ash being used.
4. Batch the range of concrete mixes and cast and cure test specimens as per the procedures detailed in AS1012.
5. Perform mechanical property testing (including compressive, flexural and tensile strength) on the cured concrete specimens at a range of specimen ages.
6. Perform Scanning Electron Microscope (SEM) analysis on test specimens.
7. Analyse the test results to determine the impact of the HA on the performance of the concrete specimens and identify the potential optimum ash ratio.
8. Complete and submit an acceptable thesis.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

This chapter contains a review of existing literature on the subject of replacing fine aggregate in concrete with HA. As previously mentioned, the ash material left behind after the combustion of coal at power plants is referred to by many different names in the literature. To avoid the confusion associated with using multiple names for the same product, this report will use the term HA to describe any coal ash product obtained either directly from the bottom of a furnace or from holding ponds where it is stored after removal from a furnace.

The literature review will reinforce the need to conduct research into the use of Millmerran HA as a replacement for fine aggregate in concrete. The review will provide insight into and explain how a suitable method of incorporating the HA into the concrete mixes can be developed. Furthermore, the review will provide examples of results from previous experimental trials that offer an understanding of the possible consequences of using HA in concrete and aid in the selection of appropriate testing methods for further research.

2.2 Properties of harvested ash

Harvested ash is not a material produced in a controlled manner. It is a by-product of the coal burning process used in power plants. This means that the properties of the ash vary significantly depending on the type and source of the coal, as well as the process and furnace used in the combustion process (Rafieizonooz et al. 2022). For this reason, these factors are a critical aspect to consider when considering the use of harvested ash for any purpose. The properties that vary can include particle size distribution (PSD), chemical composition, specific gravity (SG) and water absorption (WA). In an effort to help categorise HA used in testing, a summary of the observed results for these properties in a number of studies is included in this report.

2.2.1 Particle size

The most fundamental classification of HA is its physical appearance. It is usually dark grey in colour with individual particles described by Rafieizonooz et al. (2022) as being spherical and irregular in shape with porous textures. However, these properties can vary as observed in a study by Jung and Kwon (2013) that utilised HA from two different sources. They found that the HA that originated from bituminous coal had a smoother surface when compared to the HA from an anthracitic coal source that had a rougher texture.

Of particular importance with regard to the physical appearance of HA or any concrete component is the PSD. Concrete is a composite material made of coarse aggregate, fine aggregate, cement and water. Good concrete requires these materials to be spread consistently through the concrete to form a dense and homogeneous matrix. Knowing and controlling the particle size of the components assists in developing an appropriate concrete mix ratio to achieve these objectives.

While the PSD of HA varies from source to source, the HA used in many previous studies appears to consist predominately of particles smaller than 5 mm, lending itself to being a suitable replacement for the fine aggregate component of concrete. Studies conducted by Yimam et al. (2021), Yüksel et al. (2011) and Lal et al. (2019) all found their HA to have 100% of particles smaller than 5 mm. While other studies by Harle (2019), Kadam and Patil (2015) and Bai and Basheer (2003) all determined their HA to consist predominately of material smaller than 5 mm with 98.8%, 96% and 95% respectively, of the HA passing a 4.75 mm sieve.

Another important consideration in the PSD is the fine portion of the fine aggregate. For use in concrete. Standards Australia (2014a) recommend that a maximum of 25% of the fine aggregate be smaller than 0.15 mm. Studies by Kasemchaisiri and Tangtermsirikul (2008), Singh and Siddique (2014), Yimam et al. (2021), Lal et al. (2019), Abubakar and Baharudin (2012) and Jamaluddin et al. (2016) all found their HA to fall within this limit, with a range of 5.25% to 20% of material smaller than 0.15 mm.

There were instances observed when the amount of material smaller than 0.15 mm was found to be outside this limit such as Kou and Poon (2009), and Praveen Kumar and Radhakrishna (2020), who reported 41% and 48% respectively. In most cases the large amount of finer than 0.15 mm material was still incorporated in the concrete mixes. This may be because the finest particles in HA could contain some fly ash, which has pozzolanic properties and might contribute to increased strength gain in the concrete. There were also studies such as those conducted by Yimam et al. (2021), Kadam and Patil (2015) and Jung and Kwon (2013) where HA used in the concrete mixes was sieved to exclude any material smaller than 0.15 mm.

Figure 2-1 shows a graphical comparison of a selection of PSD results obtained in a range of studies. This figure clearly shows the amount of variation of particle size between HA from different sources.

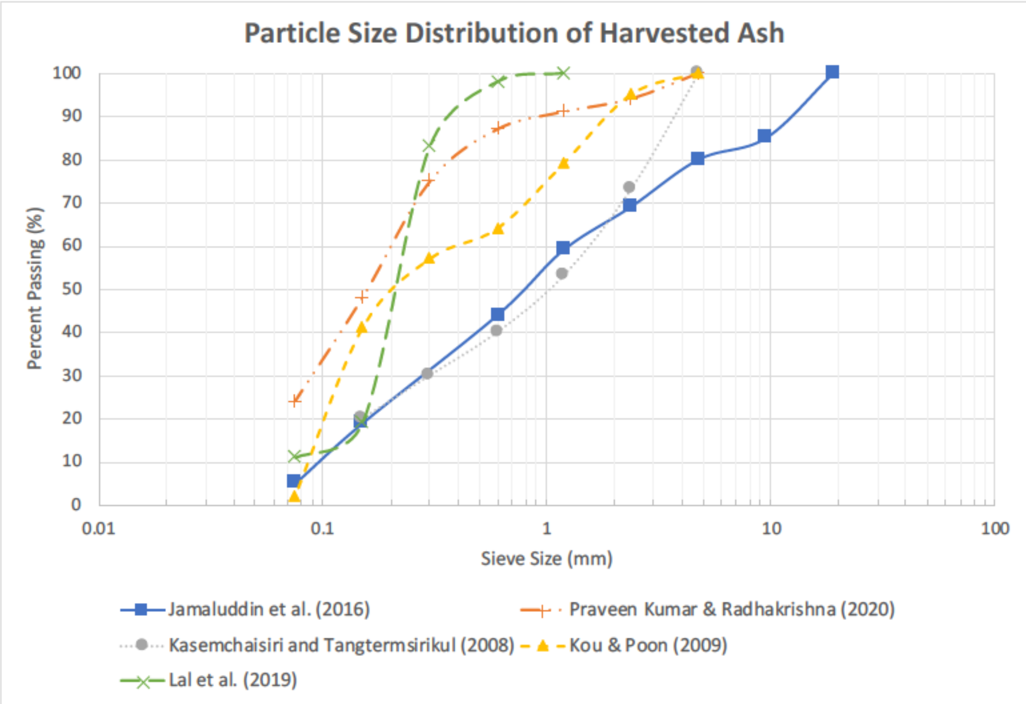

Figure 2-1: Graphical comparison showing variation in PSD results.

2.2.2 Water absorption

The water absorption (WA) of the aggregate is another important property to be aware of when considering an aggregate for use in concrete. The WA of an aggregate is a measure of the amount of water held in the permeable voids of particles after a period of soaking. It is a ratio, usually expressed as a percentage, of the mass of the absorbed water compared to the dry mass of the aggregate (Standards Australia 2000b). A major contributing factor to the final strength of a concrete mix is the water cement ratio (w/c), with higher water cement ratios resulting in lower strength concrete. For this reason, it is important to know the WA of all concrete components so that their impact on the w/c ratio of the mix can be determined.

The literature indicates that the WA varies greatly for HA from different sources, ranging from 1.97% to 32.2%. "The average absorption of natural aggregates is about 2%" (Standards Australia 2014a) and as can be seen in Table 2-1 the WA value for the majority of the HA used in a number studies is significantly greater than 2%. This is likely due to the porous texture of the HA particles that was observed in the studies. It is not certain what method was used to obtain the WA value for the HA in each study. While variation in test procedure could account for a small portion of the variation in results observed, the majority of the variation is most likely due to the differing sources and properties of the HA.

Table 2-1: Water absorption values observed in a number of studies.

Study	Water Absorption (%)
Kou & Poon (2009)	28.9
Singh (2015)	31.48
Singh & Siddique (2014)	31.58
Singh et al. (2016)	31.58
Bai & Basheer (2003)	30.4
Basheer & Bai (2005)	32.2
Praveen Kumar & Radhakrishna (2020)	5.4
Yimam et al. (2021)	1.97
Kadam & Patil (2015)	21.09
Yüksel et al. (2011)	6.1
Abubakar and Baharudin (2012)	19
Jung & Kwon (2013)	6.32
Jung & Kwon (2013)	3.32

2.2.3 Specific gravity

The aggregate in conventional concrete usually makes up around 80% of the total mass of the end product. It is therefore logical that any change in the density of the aggregate components will have a significant impact on the density of the concrete. The specific gravity (SG) is the commonly used way of representing the density of materials used in concrete. Also known as the relative density, it is the ratio of the density of one material to another, usually water. Given the density of water is 1000 kg/m^3, the SG of materials equates to the particle density of the material in t/m^3.

The SG of HA is another property that varies depending on the material source. A study of the existing literature reveals HA to have an SG in the range of 1.39 to 2.28, consistently less than the natural aggregates used (Muthusamy et al. 2020). Standards Australia (2014a) defines aggregate with a density between 0.5 t/m^3 and 2.1 t/m^3 as being lightweight aggregate. Table 2-2 shows the majority of the HA tested would fall within the lightweight aggregate category with three samples that would be classified as normal weight.

Table 2-2: Specific gravity values observed in a number of studies.

Study	SG
Kasemchaisiri and Tangtermsirikul (2008)	2.28
Siddique (2013)	1.93
Singh (2015)	1.39
Singh & Siddique (2014)	1.39
Singh et al. (2016)	1.39
Bai & Basheer (2003)	1.5
Basheer & Bai (2005)	1.58
Jamaluddin et al. (2016)	1.72
Praveen Kumar & Radhakrishna (2020)	1.85
Yimam et al. (2021)	1.7
Kadam & Patil (2015)	1.93
Yüksel et al. (2011)	1.39
Abubakar and Baharudin (2012)	1.9
Lal et al. (2019)	2.16
Jung & Kwon (2013)	2.12
Jung & Kwon (2013)	1.9

2.2.4 Chemical composition

One of the reasons that HA poses a risk to the environment is because of the chemical composition of the ash. HA can contain relatively high amounts of chemicals that could be harmful to the environment if the ash is not properly contained (Singh & Siddique 2014). The potential benefit of using HA in concrete is that it removes the ash from the ponds and safely encapsulates the harmful chemicals within hardened concrete. This theory is supported by research by Rafieizonooz et al. (2022) which tested various concrete mixes containing fly ash and HA for leaching. Using toxicity characteristic leaching procedure (TCLP) and semi-dynamic tank leaching procedure they found the heavy metals did not leach from the hardened concrete.

The chemical composition of solid materials is usually measured using X-ray fluorescence (XRF) analysis. The results of the XRF analysis on HA used in a number of studies is shown in Table 2-3. These results show the combined silicon dioxide, aluminium oxide and iron oxide (SiO_2, Al_2O_3 and Fe_2O_3) content makes up the vast majority of the HA in all cases. Again, it can be seen that there is significant variation in the individual component percentages across the different samples, further supporting the notion that that the ash source plays an important role in the properties of the ash (Rafieizonooz et al. 2022).

Table 2-3 also shows the loss on ignition (LOI) value for each HA sample. The LOI test consists of heating the ash for a prolonged period to burn away any organic or volatile substances (Mohebbi et al. 2015). The LOI value is the ratio of the mass lost during ignition to the total mass of the remaining sample expressed as a percent. The LOI for HA is shown to vary significantly for the different ash sources.

Table 2-3: Chemical composition of harvested observed from a number of studies

Study	Chemical component (%)								Loss on Ignition (%)
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	
Kasemchaisiri and Tangtermsirikul (2008)	38.64	21.15	11.96	13.80	2.75	0.61	0.90	2.06	7.24
Kou & Poon (2009)	60.70	18.30	6.56	3.25	1.28	0.82	0.89	2.12	4.13
Siddique (2013)	57.76	21.58	8.56	1.58	1.19	0.02	0.14	1.08	5.8
Singh (2015)	56.44	29.24	8.44	0.75	0.40	0.24	0.09	1.29	0.89
Singh & Siddique (2014)	47.53	20.69	5.99	4.17	0.82	1.00	0.33	0.76	0.89
Singh et al. (2016)	60.33	19.46	11.78	0.62	0.26	0.24	-	-	1
Bai & Basheer (2003)	61.80	17.80	6.97	3.19	1.34	0.79	0.95	2.00	3.61
Basheer & Bai (2005)	61.80	17.80	6.97	3.19	1.34	0.79	0.95	2.00	4.6
Jamaluddin et al. (2016)	68.90	18.70	6.50	1.61	0.53	-	0.24	1.52	2.68
Praveen Kumar & Radhakrishna (2020)	64.40	19.34	0.50	2.50	7.80	0.30	-	-	3.8
Yimam et al. (2021)	61.00	27.65	2.40	<0.01	<0.01	-	<0.01	<0.01	6.1
Kadam & Patil (2015)	60.63	-	-	1.09	0.40	0.58	0.45	-	6.04
Yüksel et al. (2011)	59.5	20.0	13.0	2.0	3.2	trace	-	-	2.4
Lal et al. (2019)	59.80	28.31	5.98	0.51	0.60	-	0.19	0.74	3.02
Jung & Kwon (2013) Source 1	53.47	28.25	3.65	1.99	0.72	-	0.65	2.88	0.27
Jung & Kwon (2013) Source 2	55.47	23.75	12.81	2.93	1.20	-	0.64	0.78	0.34

2.3 Mechanical properties of harvested ash concrete

There have been many experimental studies conducted that investigate the viability of incorporating HA into concrete. These studies have been conducted in many different places around the world such as India, Turkey, Africa, Korea, Thailand, Hong Kong and Ireland. Due to this the studies vary significantly in their focus, processes used and testing methods. Some studied the effect of HA on conventional concrete while others used highly workable self-compacting concrete or mortar. While the methods and materials vary considerably these studies all still provide a valuable data that can be used to guide the direction of further research into the subject.

2.3.1 Workability (fresh concrete)

The workability of concrete describes the ease with which fresh concrete can be placed and compacted to fill the required formwork. Obviously, the less viscous a concrete mix is, the easier it will be to pour and fill all corners within a form. However, if a concrete mix is too fluid, it has increased risk of segregation, with the coarser particles falling to the bottom, reducing the performance of the concrete. The challenge with concrete is to achieve a workable mix that can be placed and compacted relatively easily while still achieving a dense and homogeneous final product.

A common way to measure the workability of conventional concrete is the slump test. This test involves filling and compacting fresh concrete into a conical mould, then lifting away the mould. Without the mould for support, the concrete will spread and reduce in height, and this reduction in height is measured and recorded as the slump of the concrete. Depending on the intended use of the concrete, the mix can be designed to have a slump ranging anywhere from 0 mm to over 150 mm. Given this is such a critical characteristic it is important to know how the addition of HA into a concrete mix could affect this property.

There have been many studies undertaken using HA as replacement for fine aggregate in concrete, and although the HA was from a variety of different sources there is a general consensus that the incorporation of HA affects the workability of the mix (Muthusamy et al. 2020).

Studies by Harle (2019), Singh and Siddique (2014), Abubakar and Baharudin (2012) and Jung and Kwon (2013) all observed a consistent decrease in the workability of the concrete as the amount of HA in the mix increased. Figure 2-2 shows a graph of the slump results obtained by Singh and Siddique (2014) for concrete mixes with a fixed w/c ratio. Praveen Kumar and Radhakrishna (2020) observed a similar trend in their study and prevented the reduction in workability by increasing the w/c ratio of the mix to maintain workability. This proved an effective means of maintaining workability however as previously mentioned, a higher w/c ratio also results in lower final strength of the concrete mix. Rather than combat the reduction in workability with increased water, other studies such as those conducted by Yimam et al. (2021) and Siddique (2013) incorporated plasticiser into the concrete mixes in increasing amounts as the amount of HA increased. A common theme from the studies that observed decreased workability as a result of HA inclusion is that they all mixed the HA into the concrete in an oven dry state (Muthusamy et al. 2020). Praveen Kumar and Radhakrishna (2020) propose that the decreased workability is due to these porous particles of the HA with high WA, soaking up the mixing water in the concrete leaving less free liquid to lubricate the particles.

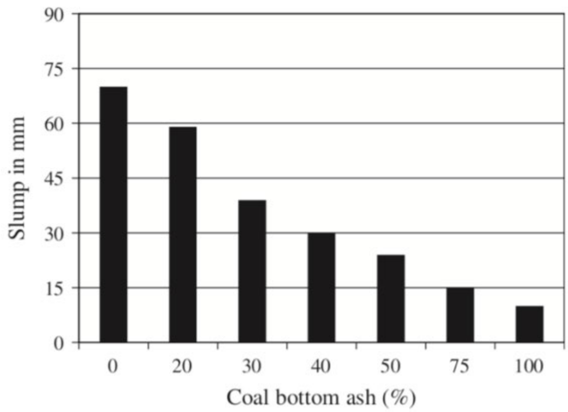

Figure 2-2: Effect of harvested ash on workability of concrete with a fixed w/c ratio (Singh & Siddique 2014).

There were also studies conducted that observed the opposite effect when HA was added to concrete as a replacement for fine aggregate. As shown in Figure 2-3, Bai and Basheer (2003) conducted trials with HA replacement rates of 0%, 30%, 50%, 70% and 100% and found that with a fixed w/c ratio, the slump of the concrete increased as the amount of HA in the mix increased. In a subsequent project, Basheer and Bai (2005) observed a similar trend while trying to maintain a constant slump for the concrete mixes. They found that in order to maintain a similar slump, the concrete mixes required less free water as the amount of HA in the mix increased. Kou and Poon (2009) conducted experiments using both the fixed w/c ratio and fixed slump range as described above and achieved very similar results with respect to increased workability as the HA content increased. While these results appear to contradict the other results, it is worth noting that in these studies the HA was either prepared to saturated surface dry SSD state prior to mixing or the water added to the concrete mix was adjusted to account for the water absorption of the HA. This meant that all of the permeable voids in the HA were filled with water so the HA did not absorb any water from the concrete mix, leaving more of the mixing water available as free water within the mix.

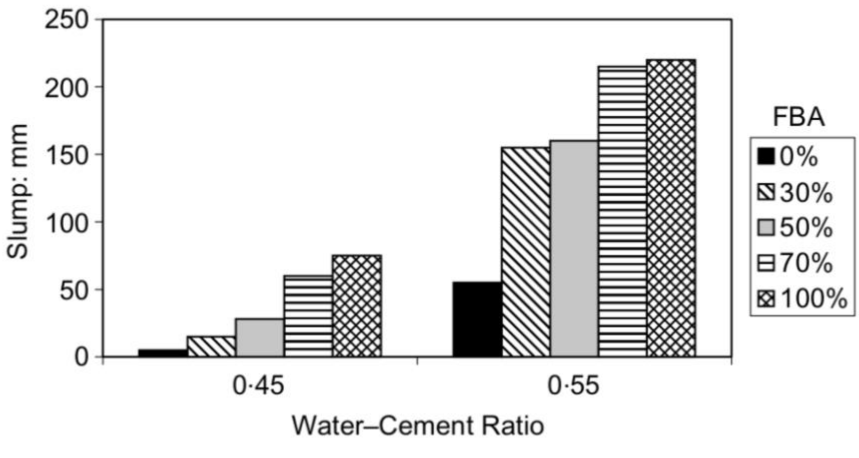

Figure 2-3: Influence of harvested ash on the workability of concrete (Bai & Basheer 2003).

2.3.2 Compressive strength

One of the properties that make concrete such an appealing and widely used construction material is its high compressive strength. Concrete is typically graded by suppliers based on its characteristic compressive strength (CCAA 2020), with mix grades ranging from 10 MPa to over 120 MPa for high performance concrete. Depending on the intended purpose of the concrete consumers can order from a range of different grades to suit the specific job requirements. These concrete grades will also need to meet other specific criteria such as workability and aggregate size limits (CCAA 2020), but the compressive strength is the base requirement and as a result it is one of the most commonly tested parameters.

The characteristic compressive strength of a concrete mix is the strength achieved by the concrete at 28 days of age (CCAA 2020). The strength testing is usually conducted on either cylindrical or cube test specimens sampled and cast from the concrete mix while fresh. The specimens are usually demoulded then cured in a moist environment until the required test age (Siddique 2013), at which point they are loaded in a compression machine until failure. The specifics of the testing process can vary depending on the local standards and requirements but the end result in MPa or N/mm^2 reflect the ultimate force the specimen can withstand over the area of the specimen.

Being such a critical parameter of concrete, nearly all studies involving the addition of HA as replacement for fine aggregate in concrete include compressive strength testing, providing a large source of data to evaluate. Given the wide variety of sources for this data there is significant variation in the materials, batching and test methods used, resulting in a range of different conclusions regarding the impact of HA on concrete compressive strength (Muthusamy et al. 2020).

There are a number of studies that conclude the addition of HA to concrete results in a decrease in compressive strength. In their study Harle (2019) used 150 mm cube specimens tested at seven days of age and found that all concrete mixes with HA achieved lower compressive strength than the control mix. The achieved compressive strength of the HA mixes displayed reductions ranging between 23% and 51% of the control. The research by Siddique (2013) also used 150 mm cubes and observed a decrease in strength at all test ages, for all HA concrete samples compared to control. In another study conducted by Kou and Poon (2009), their HA concrete batches mixed using a consistent w/c ratio displayed reduction in compressive strength for all concrete mixes that included HA. They did however notice that the batch with 25% HA replacement achieved compressive strength results comparable to the control mix.

These results are backed up by the research of Yüksel et al. (2011) and Praveen Kumar and Radhakrishna (2020) who consistently observed lower strength results for the HA concrete mixes using 70 mm cube specimens. Yüksel et al. (2011) observed the strength of concrete reduced consistently as the amount of HA in the concrete mix increased. An interesting observation regarding the strength development over time was determined in the research of Praveen Kumar and Radhakrishna (2020). In their research, the control mix achieved 71% of its 28-day strength at 7 days, whereas the HA mixes achieved approximately 50% of 28-day strength at 7 days. This shows a trend for slower strength gain in HA concrete compared to normal aggregate concrete.

There are examples of research in this area that have achieved more promising results, such as the study by Basheer and Bai (2005) who observed higher compressive strength in HA concrete in nearly all test mixes at all ages tested. They used 100 mm cube specimens and tested mixes with 0, 30%, 50%, 70% and 100% HA replacement at ages of 3, 7, 28, 91 and 150 days. The results in Figure 2-4 show the strength increase is more pronounced the at the later test ages.

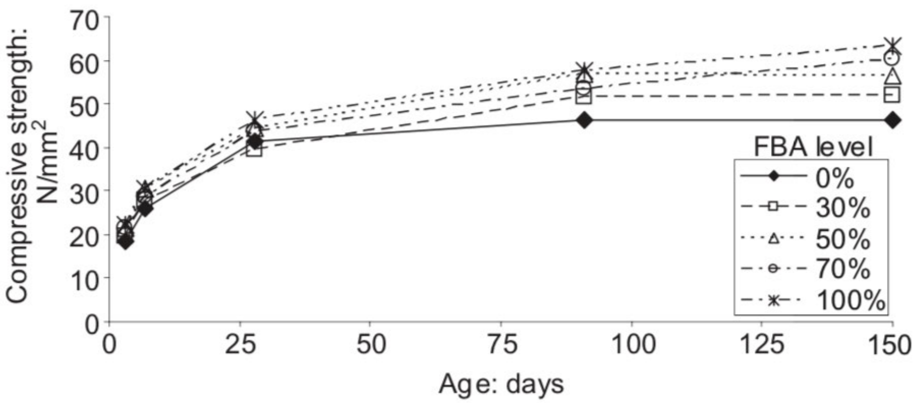

Figure 2-4: Compressive strength for slump range 30-60 mm (Basheer & Bai 2005).

Research by Abubakar and Baharudin (2012) achieved similar positive compressive strength results that also showed a tendency for slower strength development. Using 150 mm cubes they observed the 7 and 28 day strength results were similar to the control sample, then at 56 and 90 days the strength was significantly higher as the amount of HA in the mix increased. Kou and Poon (2009) used 100 mm cubes for compressive strength testing at 3, 7, 28 and 90 days of age. Their series 2 batches were mixed to achieve a constant slump range and showed compressive strength improvement for all replacement rates of HA.

In the majority of the research, the effect of the HA on the strength of concrete is not as clear cut. There are many instances where within a single research project, there are signs of increased strength as well as reduced strength as a result of the inclusion of HA. Singh and Siddique (2014) used 150 mm cubes for compressive strength test found that at 7 days, compressive strength was lower than control for most HA rates. At 28 days of age the compressive strength results for all levels of HA replacement were similar to the control sample. They found that at 90 and 180 day test ages, the strength was equal or better than the control batch for all HA replacement rates. Singh and Siddique (2015) backed this research up by achieving similar results in a subsequent study. While this study showed increased strength at 90 days, it also showed that the difference between the results of the control and the HA mixes had reduced to a maximum of 5.6% by 365 days of age. Other research by Singh et al. (2016) appears to support these findings and suggest that the compressive strength performance of the HA concrete appears to be linked with the test age of the specimens.

Other studies suggest that the performance of HA concrete is more closely related to the amount of HA replacement in the mix (Muthusamy et al. 2020). Yimam et al. (2021) found that for the mixes with HA replacement of 5% and 10% achieved higher strength at 14 and 28 days of age. For all HA replacement rates beyond 10% the compressive strength results decreased as the amount of HA increased (see Figure 2-5). Kadam and Patil (2015) and Lal et al. (2019) observed similar trends in their research except the compressive strength started decreasing at 30% and 40% HA replacement rates respectively.

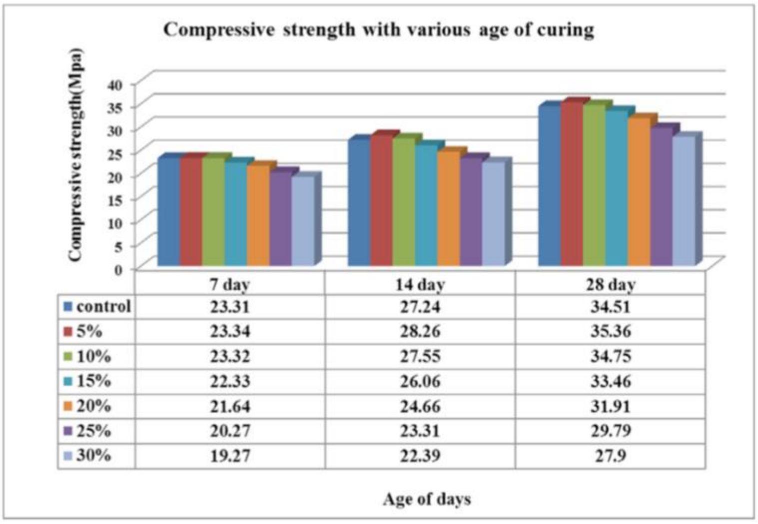

Figure 2-5: The effect of harvested ash and test age on compressive strength (Yimam et al. 2021).

Research conducted by Bai and Basheer (2003) suggest that the amount of HA and the test age are both factors that can affect the strength achieved. They replaced natural fine aggregate with HA at rates of 0, 30%, 50%, 70% and 100% and observed increased strength at 28 days for 30% and 50% replacement rates only. They also noted that by 365 days, all mixes with HA had exceeded the strength of the control mix.

Adding further variability to the performance of HA concrete is the research of Jung and Kwon (2013). They conducted research using two different sources of HA, one derived from anthracitic coal and one from bituminous coal. They found that over a range of HA replacement contents, the anthracitic coal HA had minimal impact to compressive strength whereas the HA from bituminous coal source generally reduced the concrete strength.

On review of the existing literature, it can be seen that the effect of HA on compressive strength of concrete can be extremely varied. This variation is likely due to the many different factors (Muthusamy et al. 2020) such as HA replacement rates, test methods, and how the HA is incorporated into the concrete mix (e.g. oven dry, SSD, constant w/c ratio, constant slump range). One observation that was made in most studies is that concrete with HA generally shows slower strength gain which continues for a long period of time.

2.3.3 Tensile strength

Concrete is known for and utilised primarily for its compressive strength and is relatively weak in resisting tension forces. As a result, most concrete structures incorporate steel reinforcement to resist the tensile forces leaving the concrete to resist the compressive forces. As well as carrying the compressive load, the concrete also plays an important part in protecting the steel reinforcement from the environment, preventing premature deterioration. This means that cracking of concrete can be extremely detrimental to the performance and lifespan of concrete structures and is why concrete is also tested for its tensile strength. The splitting tensile strength of concrete is a test used to determine the tensile load at which concrete will start cracking.

The effect of HA on the splitting tensile strength of concrete is not as thoroughly covered in the existing literature as the compressive strength but there has been some research conducted on this property of concrete. In their study of self-compacting concrete (SCC) incorporating HA as replacement for fine aggregate, Siddique (2013) found that for all ages tested the splitting tensile strength of the concrete decreased as the amount of HA increased. They produced four batches of concrete with HA replacement of 0, 10%, 20% and 30% and observed a maximum reduction in tensile strength of 21% at 28 days for the 30% HA mix.

Singh and Siddique (2014) performed splitting tensile strength testing on concrete mixes with 0, 20%, 30%, 40%, 50% and 100% HA incorporation. As can be seen in Figure 2-6, the splitting tensile strength results are very similar or slightly higher for all HA replacement rates in this study. Singh and Siddique (2014) suggest this is the case because tensile strength is more affected by the quality of cement paste and propose that the HA possibly has pozzolanic properties that improve paste quality.

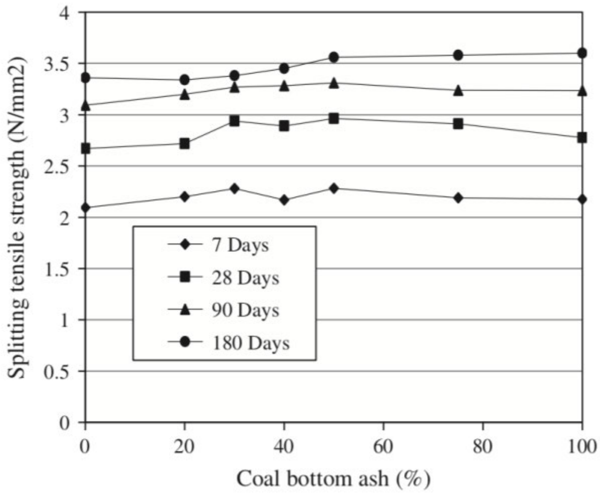

Figure 2-6: Splitting tensile strength of concrete with harvested ash (Singh & Siddique 2014).

In their research Kadam and Patil (2015) performed testing on concrete mixes containing HA in proportions of 0 to 100%, in 10% increments. They found the tensile strength to follow very similar trend to their compressive strength testing and observed either equal or better tensile strength results at all test ages for HA replacement up to and including 30%. From 40% to 100% HA replacement content, the strength reduced as the amount of HA increased.

2.3.4 Flexural strength

The flexural strength, also known as the modulus of rupture of concrete is another property that gives an indication of the tensile strength of concrete. This method is different from the splitting tensile strength because it uses long rectangular beam specimens and applies the test load to a simply supported test specimen.

In conventional concrete, there is a consistent relationship between the compressive strength and flexural strength of concrete. A good approximation of the flexural strength of concrete is $0.6\sqrt{f'c}$, where f'c is the characteristic compressive strength of the concrete (Standards Australia 2018). The existing literature considering the effect of HA on flexural strength of concrete appears to indicate that even with HA included in concrete, this close relationship between the compressive strength and flexural strength remains (Muthusamy et al. 2020).

In testing conducted by Kadam and Patil (2015) they used 100 mm x 100 mm x 500 mm beam specimens to test for flexural strength using two-point loading. They tested specimens at 7, 28, 56 and 112 days for HA replacement from 0-100% in 10% increments. They achieved flexural strength results very similar to the control sample for the 10% and 20% replacement rates, then observed a decrease in strength as the replacement rate increased beyond that. This demonstrates a very similar trend in results to the compressive strength testing conducted as part of this research.

In research conducted by Lal et al. (2019) they tested mortar incorporating HA replacement from 0-100% in 10% increments at 28 days of age. When tested for flexural strength the 160 mm x 40 mm x 40 mm prisms, achieved a slight increase in flexural strength for 10% HA replacement. At 20% and 30% HA the flexural strength was slightly lower than the control sample and from 40% HA the strength decreased significantly.

2.3.5 Modulus of elasticity

The modulus of elasticity is the measurement a material's resistance to deformation when under an applied load. This is an important property because it represents the stiffness of concrete and how a concrete structure will deform during service. The modulus of elasticity of conventional concrete also has a close relationship with the compressive strength and is therefore likely to be affected by the addition of HA.

In their research Singh and Siddique (2014) conducted modulus of elasticity testing on cylinder specimens at 28, 90 and 180 days of age. As can be seen in Figure 2-7 the results of their testing showed an almost linear decrease in the modulus of elasticity with respect to the increase in HA content. Interestingly the compressive strength results for this project did not show a drop in strength for the 90 and 180 day meaning the modulus of elasticity behaved independently from the compressive strength in this experimentation.

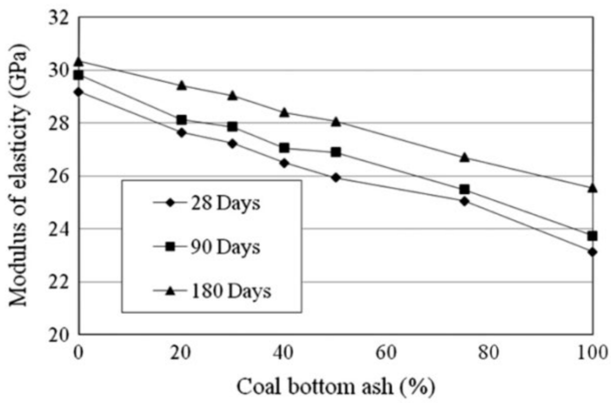

Figure 2-7: The effect of harvested ash on the modulus of elasticity (Singh & Siddique 2014).

Yüksel et al. (2011) used ultrasonic pulse velocity to determine the dynamic modulus of elasticity on 70 mm cube specimens. They also observed a consistent decrease in the modulus of elasticity of the concrete as the amount of HA increased. The maximum drop in modulus of elasticity was approximately 30% when compared to the control mix. The maximum decrease in modulus of elasticity corresponded to the maximum amount of HA replacement of 50%. Yüksel et al. (2011) also observed that the modulus of elasticity results did not conform with the behaviour of the compressive strength results. From the limited literature found including modulus of elasticity testing, it appears that the modulus of elasticity is significantly reduced by the addition of HA in concrete. This conclusion was also reached by Muthusamy et al. (2020) after their research.

2.3.6 Concrete density

Given the porous nature of most HA particles it is usually a lower density material when compared to the natural aggregates typically used in concrete. Because this natural aggregate is being replaced with less dense HA it is a fair assumption that the resulting concrete would have a lower density. This occurrence was observed in studies by Kadam and Patil (2015) and Bai and Basheer (2003) with reductions in density for 100% HA replacement to be 14% and 5% respectively. In apparent contradiction to these findings, Basheer and Bai (2005) observed no significant change to the concrete density when HA was included. They attributed this to the finer HA particles filling more voids and the increased the amount of coarse aggregate in HA mixes.

2.4 Durability properties of harvested ash concrete

2.4.1 Drying shrinkage

The drying shrinkage is an important durability characteristic of concrete because if concrete shrinks excessively during the drying process it can result in substantial cracking which reduces the lifespan of the concrete structure. The drying shrinkage of concrete can be tested by casting long prismatic beams with measuring nodes cast into each end. The beams can then be measured at regular intervals over an extended period of time to determine the reduction in length of the specimen.

A number of different studies have included investigation of the effect of HA on the drying shrinkage of concrete and the common conclusion is that the HA produces reduced drying shrinkage Muthusamy et al. (2020). Singh et al. (2016) observed a consistent reduction in the drying shrinkage of concrete mixes as the amount of HA increased. This finding was supported by Kou and Poon (2009) who tested 2 different concrete series, one using a constant w/c ratio and the other using constant slump range to batch the concrete. In the constant slump mixes they observed an almost linear decrease in drying shrinkage as the amount of HA increased. The constant w/c ratio mixes produced less shrinkage for all batches except 100% HA which showed a 5% increase.

The research of Basheer and Bai (2005) achieved different results which suggest HA is not always beneficial to the drying shrinkage of concrete. In their research they observed increases in drying shrinkage for nearly all HA replacement rates with a maximum increase of approximately 130% for the 50% HA mix at 150 days of age. They did find that the 30% HA concrete batch performed very similarly to the control mix with a maximum increase in shrinkage of approximately 5% at 150 days of age.

2.4.2 Abrasion resistance

Abrasion resistance is an important property for concrete because many concrete structures are subjected to repeated traffic that can gradually wear away the surface, reducing the structural integrity, appearance or performance of the structure. As such, high abrasion resistance, which equates to shallower abrasion depth over a fixed period of time is desirable for concrete. Based on their study, Muthusamy et al. (2020) suggest that abrasion depth for HA concrete increases as the HA replacement rate increases. This is supported by the research of Siddique (2013) and Singh and Siddique (2015) who observed a distinct correlation where the abrasion depth during testing increased as the amount of HA in the mix increased. The results obtained by Siddique (2013) for 60 minutes of abrasion show a maximum increase in wear depth of approximately 17% for the peak HA replacement rate of 30%. Singh and Siddique (2015) achieved results showing an approximate increase in wear depth of 44% for a 15-minute abrasion test.

In a study that achieved the opposite results Basheer and Bai (2005) observed a reduction in abrasion depth for most mixes that contained HA. There appeared to be no consistent trend in the results that linked this reduced abrasion with the amount of HA in the mixes. Basheer and Bai (2005) instead suggest that the reduced w/c ratio in the HA concrete mixes may have been the contributing factor in the better abrasion resistance.

2.4.3 Chemical resistance

For concrete to be durable it needs to be able to resist excessive deterioration caused by different chemicals that it may be exposed to in the environment. The types of chemicals concrete might be exposed to are numerous and varied and may be due to natural features such as salt water or manmade causes such as heavy industrial environments. Testing the chemical resistance of concrete is therefore also quite varied and some of the more common tests are chloride ion penetration resistance and resistance to sulphate attack.

There are a number of studies that investigate the resistance to chloride ion penetration for concrete incorporating HA. Studies by Singh et al. (2016), Bai and Basheer (2003) and Basheer and Bai (2005) used differing test methods but all observed that the resistance to chloride ion penetration improved as the amount of HA in the concrete increased. Kou and Poon (2009) observed varied results with their series 1 batches showing decreased resistivity while the series 2 batches showed a nearly linearly increasing resistance as the HA replacement increased. They proposed that the higher effective free water content in the fixed w/c ratio may have caused the reduced resistivity in series 1 mixes. While the results obtained by Siddique (2013) exhibited a reduction in chloride penetration resistance as the amount of HA increased in the concrete, they noted that the results were still very low.

The experimental work of Singh et al. (2016) showed that after immersion in sulphate solution, while mass loss of HA concrete was less than that of the control sample, the HA concrete suffered a greater reduction in compressive strength than the control. The loss in compressive strength was insignificant and after 365 days of emersion the strength loss had improved to less than the control sample. Muthusamy et al. (2020) also observed that the sulphate attack resistance of HA concrete is generally similar to control samples but suggested that more research is needed in this field.

2.4.4 Water penetration/permeability

Water penetration resistance is another property that affects the durability of concrete. If water can easily penetrate the concrete, then it can lead to premature deterioration of steel reinforcement and structural failure. In their experimentation Singh et al. (2016), Singh and Siddique (2014 & 2015) and Siddique (2013) observed the water absorption of concrete increased as the amount of harvested ash increased compared to the control concrete. They also noted that the water absorption decreased as the concrete aged, with Singh and Siddique (2015) finding that at 365 days of age the HA concrete had less absorption than the control samples.

Bai and Basheer (2003) and Basheer and Bai (2005) tested HA concrete for air permeability and water absorption and found that HA concrete generally performed worse for both properties. Kadam and Patil (2015) performed water permeability testing on concrete in a pressurised test apparatus and found that the water penetration was less for concrete with HA replacement up to 30%. From 40% to 100% replacement, the water penetration began increasing as the amount of HA increased.

CHAPTER 3. METHODOLOGY

3.1 Concrete testing

For this research it is essential that the concrete mixing, sampling and testing is done in a consistent way so the only variable in each mix is the amount of HA. This way, any differences observed in test results can be attributed only to the amount of HA in the concrete. It is also important to use standard procedures so the testing can be reproduced if further research is conducted in this field in the future.

3.1.1 Laboratory mixing and sampling

For this research the laboratory mixing and sampling of the concrete was conducted in a consistent manner to limit the variation not attributed to the presence of HA within the mixes.

Before mixing commenced for each batch of concrete, the appropriate amount of each ingredient was prepared and set aside, ready for use. The coarse and fine aggregates, including HA where applicable, were then added to the 120 litre electric cement mixer. The aggregates were mixed until all of the aggregates had combined to create a consistent blend. The cement powder was then added to the cement mixer and the mixer was run again until the cement powder had mixed thoroughly with the aggregates to create a blend that was consistent in colour. The mixing water was the last ingredient to be incorporated into the mixer and was added while the mixer was running. After all mixing water was added, the mixture was watched to determine the point when all aggregate had been thoroughly incorporated. Once this point had been observed, the mixer was run for a further 2 minutes of mixing. At the completion of the final 2 minutes of mixing, the mixer was shut down and the mixture was transferred to a wheelbarrow for testing.

3.1.2 Workability

The workability of the concrete is a vital fresh concrete characteristic and for this research it was tested using the slump test method as per AS 1012.3.1. This test method involves filling a conical mould with concrete, removing the mould, and measuring the vertical subsidence of the concrete. The testing procedure used for this project is summarised below and follows the requirements detailed in AS 1012.3.1.

- The clean mould and levelled baseplate were moistened using a damp cloth immediately prior to the test.
- The conical mould was placed on the baseplate and firm pressure was maintained on the mould to ensure it did not move throughout the filling and rodding process.
- The freshly mixed concrete was added to the mould in 3 layers of equal height, rodding each layer with 25 strokes of the 16 mm diameter tamping rod.
- The top layer was slightly overfilled and once rodding was complete, the concrete was levelled to the top of the mould, and excess concrete was cleared from around the base of the mould.
- Immediately after levelling and clearing the concrete, the mould was raised slowly in a vertical direction avoiding any lateral or torsional movement of the concrete.
- The slump was measured immediately after removal of the cone as ‘the difference between the height of the mould (300 mm) and the average height of the top surface of the concrete’ (Standards Australia 2014b, p. 3).
- The slump value was recorded to the nearest 5 mm for slump values of 100 mm or less and to the nearest 10 mm for values greater than 100 mm.

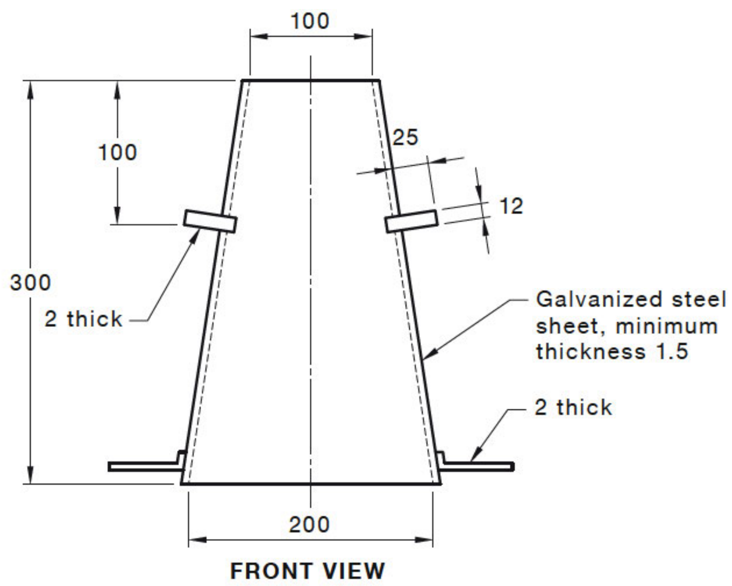

Figure 3-1. Dimensions of a typical slump cone for testing to AS 1012.3.1 (Standards Australia 2014b).

3.1.3 Casting of test specimens

It is essential in concrete testing that the test specimens are cast in a consistent way that achieves a properly compacted and homogeneous specimen. The test specimens used for this experimental research were cast using AS 1012.8.1 for the cylindrical compressive strength, tensile strength and modulus of elasticity specimens. The cylindrical moulds used for this research had nominal internal dimensions of 100 mm in diameter and 200 mm in height. This produced test specimens that met the shape and size requirements set out in AS 1012.8.1. The procedure used to cast the test specimens is summarised below.

- Internal surfaces of the moulds were oiled to prevent concrete sticking to the moulds.
- The bulk concrete sample was mixed by hand to ensure a consistent mix.
- All moulds were filled with concrete to approximately half height and the concrete was compacted using 25 strokes of a 16 mm diameter rod, spread evenly over the cross section of the mould.
- After rodding, each mould was tapped with a rubber mallet to close any remaining surface holes in the concrete.
- The moulds were then filled with the final layer of concrete to a level slightly over the top of the mould.
- The final layer of concrete for each test specimen was then compacted by rodding and using a rubber mallet similar to the first layer.
- A steel trowel was then used to strike off and smooth the surface of each test specimen.

The beam test specimens for flexural strength or modulus of rupture testing were cast using the procedure documented in AS 1012.8.2. The beam moulds used for this research had nominal internal dimensions of 100 mm by 100 mm by 350 mm to produce test specimens meeting the shape and size requirements set out in AS 1012.8.2. The procedure used to cast the beam test specimens followed the same steps applied for the cylinders except the beams were compacted with 55 strokes of the rod for each layer of concrete.

Once the casting of all test specimens in a batch was complete, the test specimens were carefully moved to a flat, rigid surface in the lab for initial curing. This area in the lab was such that it limited the risk of disturbance to the specimens during initial curing of between 18 and 36 hours. Each batch was stored in a separate area with a tag for traceability of specimens, and to ensure specimens from different batches were not mixed up.

3.1.4 Curing

Curing of concrete can have a large impact on the performance of the hardened concrete, particularly the concrete durability. For this research the concrete was cured in standard tropical zone curing conditions as per the requirements detailed in AS 1012.8.1. The curing environment consisted of a fog room with a constant temperature of 27ºC ± 2ºC and humidity of 86%. After initial curing was complete, between 18 and 36 hours from moulding, the test specimens were carefully removed from their moulds. The specimens from each batch were marked with a uniquely identifying label to ensure traceability for future testing. The specimens were then placed in the standard moist curing environment until the time of testing.

3.1.5 Compressive strength

One of the principal properties that makes concrete so widely used is its compressive strength. For this research the compressive strength has been determined using the procedure detailed in AS 1012. 9. To be tested to this method, the specimens must first be checked for physical defects that are liable to affect the test results. If any apparent defects are observed they must be noted on the test report and if they are too severe, the specimen may be rejected from testing.

To account for minor imperfections in the non-formed end of the test cylinders, the specimens are usually capped before testing. AS 1012.9 specifies either moulded capping using one of a range of materials, or a restrained natural rubber capping system. Because the predicted strength of concrete for this research project was between 10 MPa and 80 MPa, it was decided the restrained natural rubber capping system would be suitable. This system consists of a rubber pad with a Shore A Durometer hardness of 50 to 65, and a uniform thickness of 12 mm to 15 mm. The rubber pad is inserted into a steel restraining device and the device is applied to the non-formed end of the test cylinder immediately before compression testing.

The process for compressive strength testing is summarised below.

- Remove test specimens from curing environment.
- Test each specimen in a wet condition. Wipe surplus water from test specimens.
- Inspect specimens for apparent defects.
- Measure and record the diameter and height of each test specimen.
- Place capped test specimens on the clean platens of the compression machine taking care to align each cylinder centrally to the platens and capping system.
- Apply force to each specimen without shock and increase at a rate of 20 ±2 MPa per minute until failure of the specimen.
- The maximum force applied is recorded as the failure load.

The compression testing machine used for this research was an IMPACT automatic console with 2000 kN capacity. This machine automatically controlled the application of force during compression testing to ensure it stayed within the 20 ±2 MPa per minute limit.

The compressive strength of each specimen was calculated as the failure load divided by the cross-sectional area of the specimen.

3.1.6 Flexural strength

While compressive strength of concrete is generally the characteristic that receives more focus, the flexural strength of concrete is also important. The procedure used for this research to determine the flexural strength, also known as modulus of rupture, was AS 1012.11. Similar to compressive strength testing, the flexural beam specimens must be checked for defects that could make them liable for rejection. Possible defects include chipped edges, surface cracks, honeycombing or out of plane test surfaces.

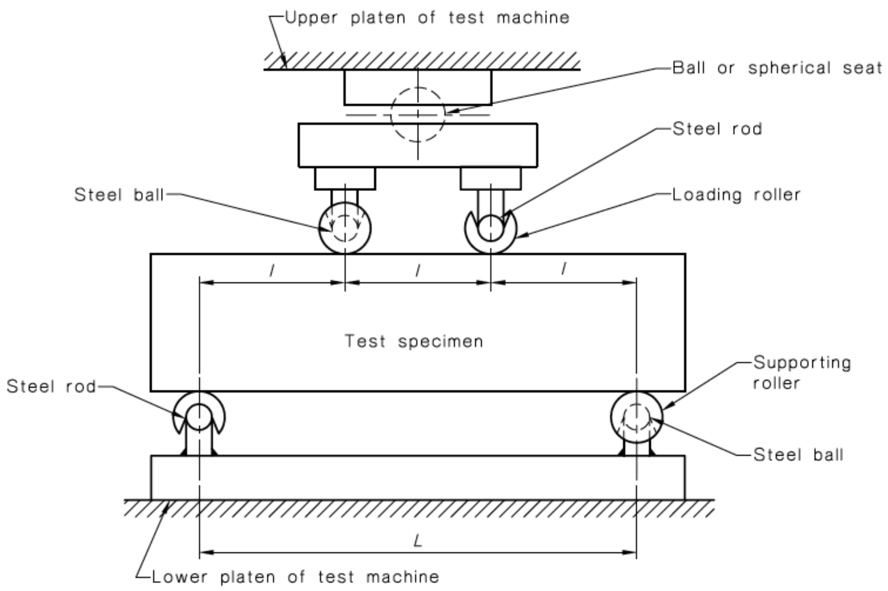

Figure 3-2. Suitable arrangement for flexure loading apparatus (Standards Australia 2000a).

The flexure testing machine must have an apparatus that applies the force to the specimen through two supporting rollers and two loading rollers. A typical loading frame arrangement is shown in Figure 3-2, where for 100 mm by 100 mm nominal size specimens:

- L = 300 +8, -3 mm and
- l = $^{L}/_{3} \pm 1$ mm.

The process for flexural strength or modulus of rupture testing is summarised below.

- Remove test specimens from curing environment.
- Test each specimen in a wet condition. Wipe surplus water from test specimens.
- Place each test specimen on its side in respect to its position as moulded, centrally on the supporting rollers.
- Apply force to each specimen without shock and increase at a rate of 1 ±0.1 MPa per minute until failure of the specimen.
- Record the maximum force applied to each specimen.
- Measure and record, to the nearest 1 mm, the average width and depth of each specimen at the section of failure.
- If the fracture occurs outside the middle third of the span length, the modulus of rupture must not be calculated for that specimen.

Due to the limitations of the compression machine used for this project, the rate the specimens were loaded at differed to the rate specified in the method. The minimum rate the machine could operate at was 0.5 kN/second. For the dimensions of the specimens used this equates to a loading rate of 9 MPa/minute which is significantly faster than the specified loading rate.

The modulus of rupture of the test specimen is calculated by the following equation:

$$f_{cf} = \frac{PL \times 1000}{BD^2}$$

Where

f_{cf} = modulus of rupture in MPa

P = maximum applied force in kN

L = span length in mm

B = average width of specimen at section of failure in mm

D = average depth of specimen at section of failure in mm

3.1.7 Tensile strength

While concrete is not typically relied on for its tensile strength, it is still important to consider how this property will be affected by the addition of HA. Testing for this project used the test procedure detailed in AS 1012.10 to determine the indirect tensile strength of concrete cylinder specimens.

The tensile strength test requires a compression machine complying with the same requirements as for compressive strength testing, however test specimens are tested in a horizontal position.

To test the cylinders in the horizontal position, an appropriate testing jig may be used to ensure the specimen is located centrally and force is applied in a vertical plane through the axis of the specimen. The testing jig requires two plane bearing surfaces that are parallel to within 1 degree and must not constrain the specimen or any other part of the compression apparatus when load is applied. For this project no testing jig was available, so the test specimen was manually aligned and held in place on the bearing strips until sufficient load was applied to hold the specimen in place.

The process used for tensile strength testing is summarised below.

- Remove test specimens from curing environment.
- Wipe surplus water from test specimens.
- Measure and record the diameter and length of test specimens to the nearest 0.2 mm and 1 mm respectively.
- Align each specimen centrally in the compression machine with the hardboard bearing strips between the upper and lower bearing plates.
- Apply force to each specimen without shock and increase at a rate of 1.5 ±0.15 MPa per minute until failure of each specimen.
- Record the maximum force applied to test specimens.

The indirect tensile strength of the test specimen is calculated by the following equation:

$$T = \frac{2000P}{\pi LD}$$

Where

T = indirect tensile strength in MPa

P = maximum applied force in kN

L = test specimen length in mm

D = average specimen diameter in mm

3.1.8 Modulus of elasticity

The modulus of elasticity is a parameter used to define the stiffness of concrete and is determined by the relationship between stress and strain. For this research the static chord modulus of elasticity has been determined using the procedure detailed in AS 1012.17. This procedure requires the measurement of the strain of test specimens while being subjected to a compressive force. The maximum compressive force applied is defined as the test load and is 40% of the characteristic concrete strength. The characteristic strength adopted for this testing was the average 28-day compressive strength achieved by the companion specimens for each batch.

During testing, the cylinder specimens must have a suitable deformation measuring device attached symmetrically about the mid-height of the specimen. The measuring device must measure deformation along at least two opposing gauge lines. The compression machine used for this testing must comply with the same requirements used for compressive strength testing.

The process for testing the static chord modulus of elasticity is summarised below.

- Remove test specimens from curing environment. Complete testing within 30 minutes of removal from curing environment.
- Test specimens in a wet condition. Wipe surplus water from test specimens.
- Inspect specimens for apparent defects.
- Measure and record diameter and height of each test specimen.
- Attach the deformation measuring device to each specimen and place the specimen centrally on the compression machine platen.
- Load each specimen three times, with the initial loading used primarily for testing gauge operation. Record the second and third loading cycles only. Calculate final results based on the average values recorded in these cycles.
- Apply force to each specimen without shock and increase at a rate of 15 ±2 MPa per minute.
- Record the load when the deformation is equal to a strain of 50 x 10^{-6} m/m and the deformation achieved at the test load.
- Once the test load is achieved, reduce the load to zero at approximately the same rate as loading was applied.

The static chord modulus of elasticity is calculated by the following equation:

$$E = \frac{G_2 - G_1}{\varepsilon_2 - 0.00005}$$

Where

E = static chord modulus of elasticity in MPa

G_1 = the average load applied at strain of 50 x 10^{-6} in MPa

G_2 = test load in MPa

ε_2 = the average strain at test load

3.1.9 Scanning Electron Microscope (SEM) analysis

Scanning electron microscopy is a technique that uses a focused high energy electron beam to obtain highly detailed images of the surface characteristics of materials. The imagery can provide information about topography, morphology, composition, chemistry, orientation of grains and crystallographic information (Akhtar et al. 2018). Significant training and experience is required to decipher and extract the large amount of information available in SEM images. Due to time and resource requirements, the SEM analysis conducted for this research is relatively low detail and focuses on the topography and morphology of the HA concrete samples compared to the control mix.

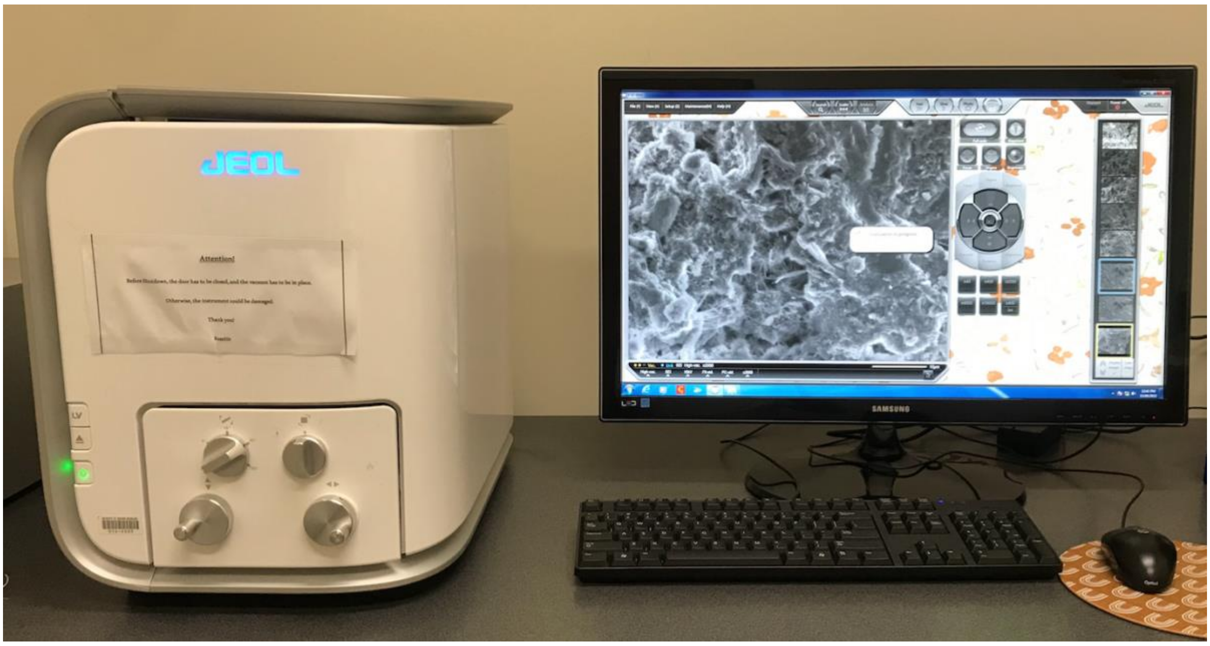

Figure 3-3. JEOL NeoScope JCM6000Plus scanning electron microscope used for this project.

The instrument used for this research was a JEOL NeoScope JCM6000Plus benchtop SEM shown in Figure 3-3. Due to concrete being a non-conductive material, the test specimens required application of a thin conductive coating. This was achieved by using a JEOL Smart Coater to apply a gold sputter coating to the specimens as seen in Figure 3-4.

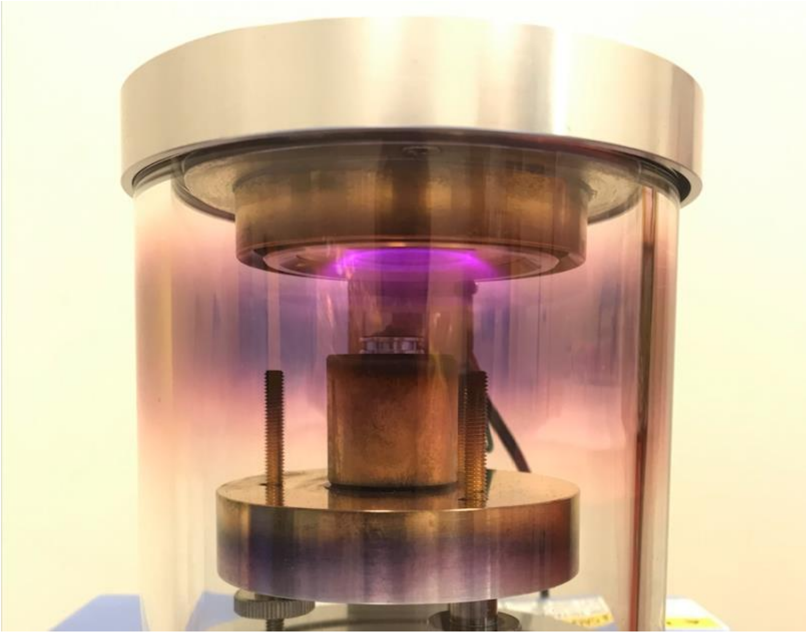

Figure 3-4. Mounted test specimen receiving gold sputter coat in the JEOL Smart Coater.

The procedure used to conduct the SEM analysis for this project is detailed below.

- Small fragments of concrete from broken compressive strength test samples were obtained and dried out in ambient conditions.
- All preparation of test specimens for SEM analysis was conducted while wearing powder free gloves.
- Using tweezers, a small fragment from each concrete batch was mounted on a stage using double-sided adhesive carbon tape.
- Each prepared specimen was mounted on a labelled board to ensure sample traceability.
- Each of the mounted test specimens were placed in the Smart Coater for a one-minute cycle to achieve sufficient gold coating.
- A gold-coated specimen was loaded into the SEM and the specimen chamber was closed to ensure the vacuum could be developed.
- SEM images were obtained for each test specimen using the JCM6000 software, beginning at low magnification and working toward higher magnification.

Figure 3-5. Mounted and gold sputter coated specimens ready for SEM analysis.

CHAPTER 4. EXPERIMENTAL PROGRAM

4.1 Outline

A brief overview of the methodology utilised for the project is listed below.

1. Obtain concrete constituent materials (i.e. typical fine and coarse natural aggregates, cement and HA).
2. Test the physical properties of aggregates and HA (PSD, WA, SG).
3. Design a control concrete batch mix that is comparable to standard conventional concrete.
4. Prepare five batches of concrete (one control batch and four with a varying amount of HA to replace sand).
5. Perform a slump test for each batch of concrete.
6. Cast multiple test specimens for each batch of concrete (compressive strength, tensile strength, flexural strength and modulus of elasticity).
7. Perform strength tests for each batch of concrete over a range of test ages (7, 28 and 56 days).
8. Perform SEM analysis of hardened concrete specimens from each different batch at 56 days of age.
9. Analyse the test results to determine the impact HA has on the strength properties of concrete.

4.2 Assumptions

It is assumed the HA provided for use in this study is a representative sample of HA from Millmerran power station and the material properties observed are representative of the typical HA properties from that source

4.3 Materials

The aggregates used in concrete usually have very stringent limits for physical properties such as PSD, WA, SG, and a range of strength and durability properties. The natural aggregates used in the experiment will be comparable to typical concrete aggregates used in the local area. Due to time constraints, only a limited number of tests could be conducted on the natural aggregates and

HA. The tests were selected for this research to assist in concrete mix design and with the intention of characterising the HA from Millmerran power station for comparison against other sources.

Figure 4-1. 10 mm basalt aggregate used for this research project.

Figure 4-2. 7 mm basalt aggregate used in this research project.

Figure 4-3. Natural fine aggregate used in this research project.

Figure 4-4. Harvested ash from Millmerran power station used in this research project.

4.3.1 Particle size distribution

PSD testing was undertaken on all aggregates that were to be used in the concrete mixes. The coarse and natural fine aggregates (NFA) were tested to see how they compare to the grading limits recommended in AS 2758.1. These limits are based on grading envelopes that have proven successful in the past and are provided for guidance only (Standards Australia 2014a). The PSD was conducted on the HA sample to help characterise ash from the project source and to see how it compares to the natural fine aggregate it is replacing. The PSD testing was conducted on the aggregates as per the procedure specified in AS 1141.11.1.

The coarse aggregates used in the concrete mixes consisted of 7 mm and 10 mm nominal single-size aggregates and the typical fine aggregate was a natural washed sand. The HA from Millmerran had already been screened at the power station to exclude all material larger than 7 mm. Samples of these materials are shown in Figure 4-1 to Figure 4-4.

Table 4-1. Particle size distribution for concrete aggregates.

Sieve aperture (mm)	HA	NFA	7 mm	10 mm
	Percent passing			
13.2	-	-	-	100
9.5	100	-	100	85
6.7	99	-	94	11
4.75	96	100	27	1.0
2.36	88	99	2.7	0.7
1.18	82	95	2.0	-
0.6	78	83	-	-
0.425	74	64	-	-
0.3	70	41	-	-
0.15	51	8.7	-	-
0.075	23	2.4	0.6	0.2

The numerical results of the PSD testing are shown in Table 4-1. The sieves used for each test were selected based on the grading requirements specified for each particular material type. When comparing the numerical results of the HA and NFA it can be seen that the HA has significantly higher percentages passing the finer sieves (from 0.425 mm and below). This indicates the HA has a larger proportion of fine sand particles than the NFA. Figure 4-5 to Figure 4-8 show the results for the relevant sieves plotted against the limits recommended in AS 2758.1.

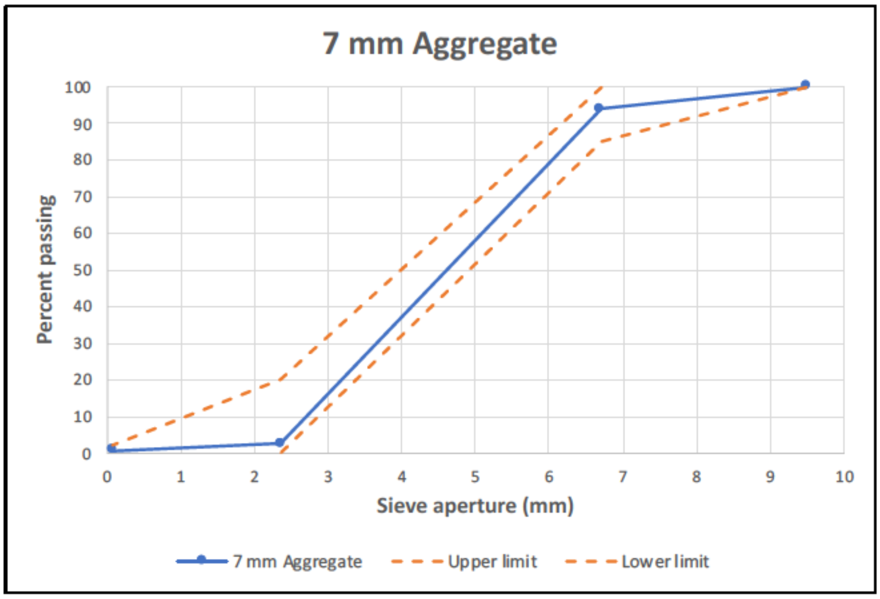

Figure 4-5. Plot of particle size distribution results for 7 mm aggregate.

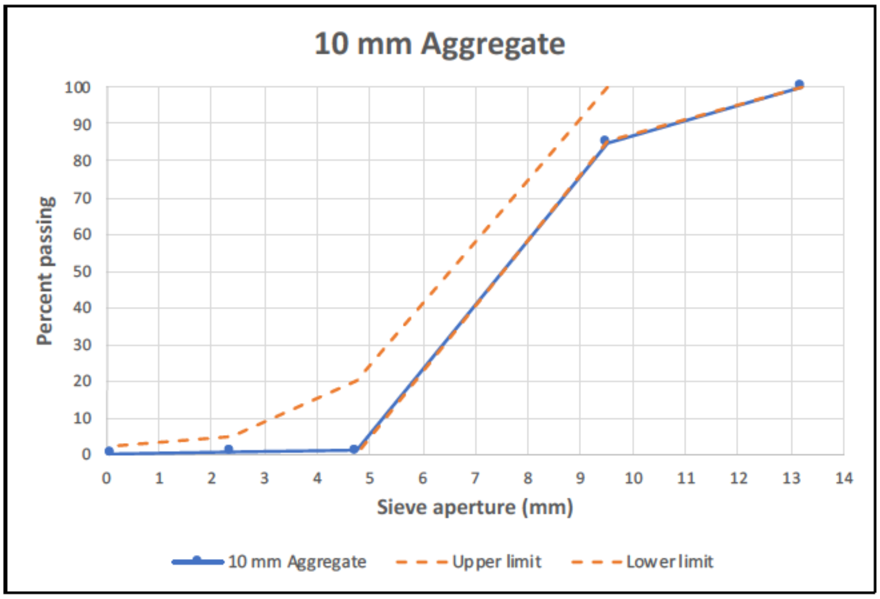

Figure 4-6. Plot of particle size distribution results for 10 mm aggregate.

The plotted results show the 7 mm aggregate falls comfortably within the recommended grading limits and the 10 mm aggregate matches the lower limit.

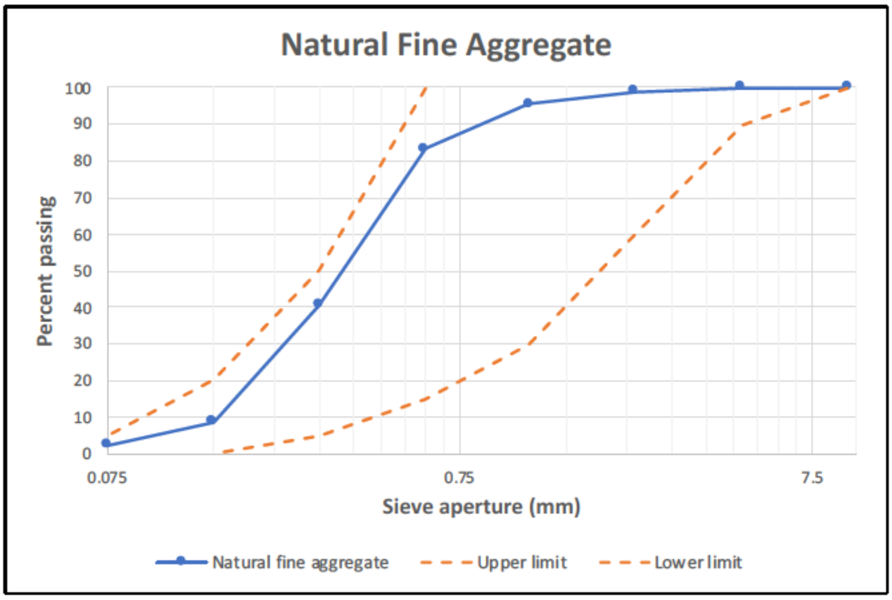

Figure 4-7. Plot of particle size distribution results of natural fine aggregate.

The plot of the NFA test results shows it is well within the recommended grading limits. The PSD results for the HA and NFA are plotted on a log scale to more clearly depict the data at the small sieve apertures.

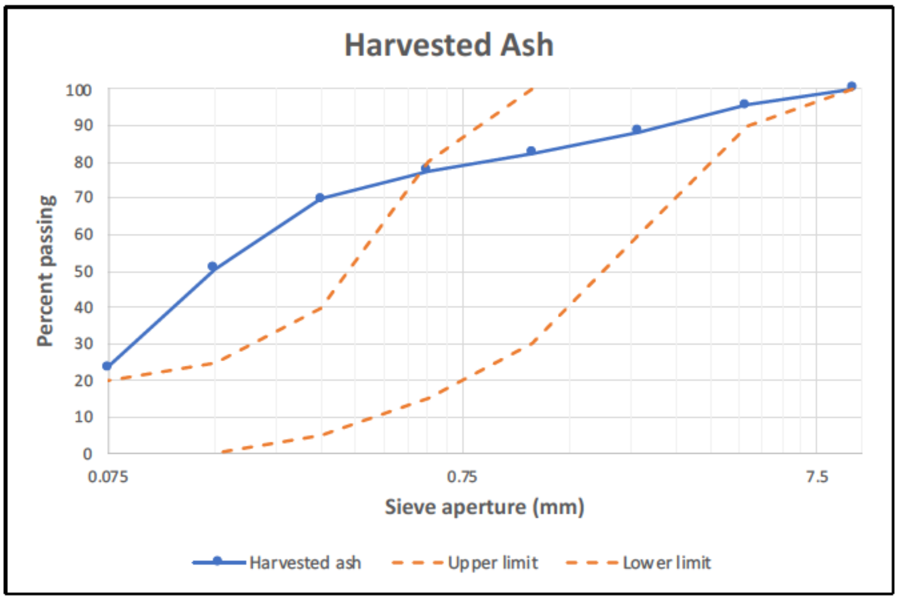

Figure 4-8. Plot of particle size distribution results for HA.

Because the HA sample has higher proportion of fine particles, it has been plotted against the recommended limits for a manufactured fine aggregate. These limits allow for a higher amount of fine material, but it can be seen in Figure 4-8 that the grading is still well outside these recommended limits. The plot clearly shows the HA is within the limits for sieve sizes of 0.6 mm and greater, and for sieve sizes smaller than 0.6 mm falls well outside the upper limit.

Despite falling outside the recommended grading limits, the HA was used in its received state with no modification of the particle size distribution. It is important that this project demonstrates whether the HA is usable in its natural state because supplementary preparation or treatment of HA would reduce the practicality of using it as a fine aggregate in concrete.

Figure 4-9 to Figure 4-12 illustrate the particle size distribution of the concrete aggregates and HA by showing each material split into individual size fractions after sieve analysis.

Figure 4-9. The 10 mm aggregate split into individual size fractions.

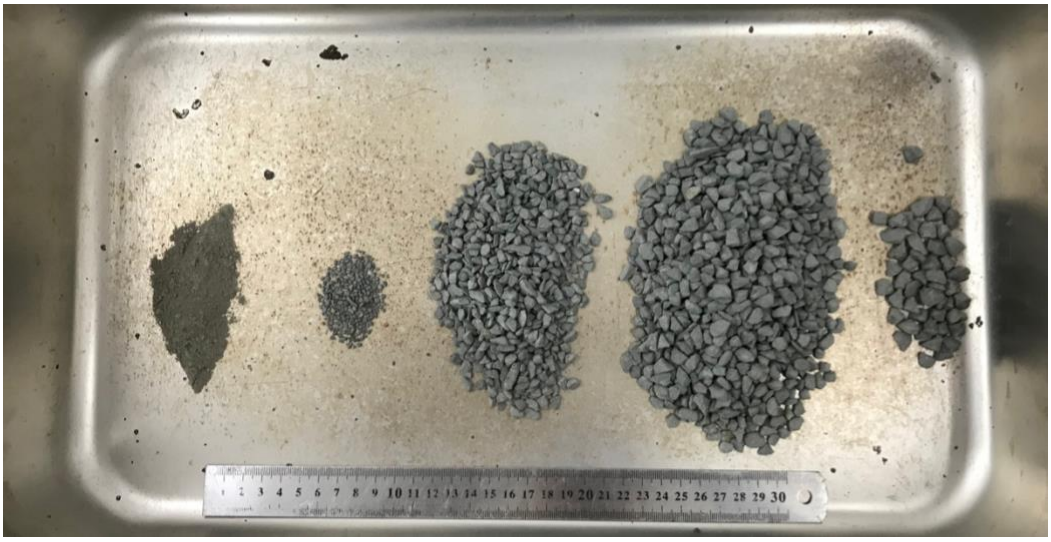

Figure 4-10. The 7 mm aggregate split into individual size fractions.

Figure 4-11. The natural fine aggregate split into individual size fractions.

Figure 4-12. The Millmerran harvested ash split into individual size fractions.

4.3.2 Water absorption

The water absorption of an aggregate is a term used to describe the amount of water that can be held within the permeable voids of the aggregate particles when at the saturated surface dry (SSD) state (Standards Australia 2000b). The water absorption value is expressed as a percentage and is calculated by the mass of water held at SSD condition divided by the mass of the oven dry aggregate. This water absorption value is important to know for concrete aggregates because it gives an indication of how much water the aggregate is likely to absorb when the concrete is being mixed and how it will affect the water cement ratio. Given that the water cement ratio of a concrete mix is a significant contributing factor in the final concrete performance, anything that could alter the ratio in the mix should be managed to minimise its effect.

The water absorption testing for this project was conducted to methods AS 1141.5 for fine aggregate and AS 1141.6.1 for coarse aggregates. The water absorption values achieved for the aggregates are shown in Table 4-2. These values were used in the concrete batching calculations to determine any adjustments required to the amount of mixing water added to each mix.

Table 4-2. Water absorption values determined for aggregates used in this project.

Material	Natural fine aggregate	7 mm aggregate	10 mm aggregate	Harvested Ash
Water Absorption (%)	0.8	1.6	1.4	24.4

The HA was tested using the AS 1141.5 method in the same manner as the fine natural aggregate, however the test proved difficult to perform. The test procedure involved soaking the material for 24 hours then drying it back until it reaches a free-flowing state, at which point it is deemed to have reached SSD state. The trouble encountered with the HA sample was that it reached a free-flowing state when the moisture content of the material was 0.2%. This very low water absorption value is questionable when considering the highly porous nature of HA particles as illustrated in Figure 4-13 and Figure 4-14. It is also significantly lower than any other value determined for HA from other sources in the existing literature.

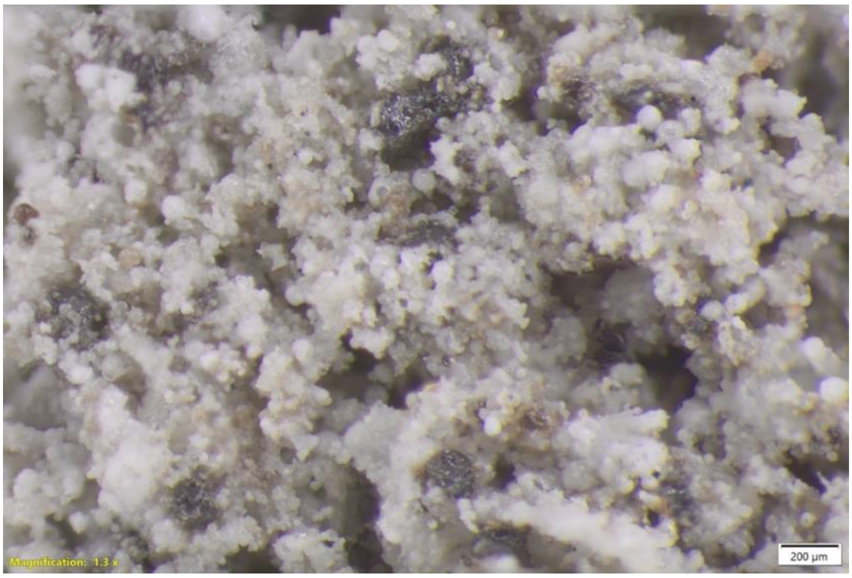

Figure 4-13. Stereo microscope image of a washed HA particle.

The questionable result could possibly be due to the high proportion of very fine particles in the material making a free-flowing state difficult to achieve and not an accurate representation of the SSD state. Other contributing factors could be the very low density or the highly irregular and angular shapes of the particles.

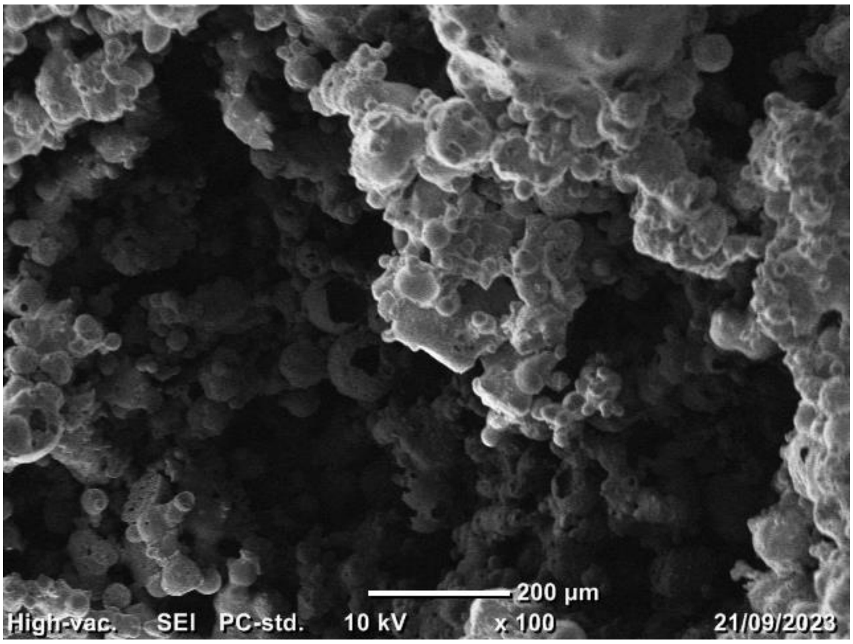

Figure 4-14. SEM image of a washed HA particle.

After conducting research into possible alternate methods for determining water absorption, a second attempt at testing the HA was conducted. Gentilini et al. (2015) suggest that when porous aggregates are dried at a constant temperature, the evaporation rate consists of three phases. The phases as defined by Mechling et al. (2003) are a transition phase, a constant phase, and a decreasing phase. Gentilini et al. (2015) proposes that during the constant phase the surface water is evaporating and in the decreasing phase the absorbed water in the aggregate is evaporating. As such the SSD state of a porous aggregate occurs at the point when the constant phase changes to the decreasing phase as shown in Figure 4-15.

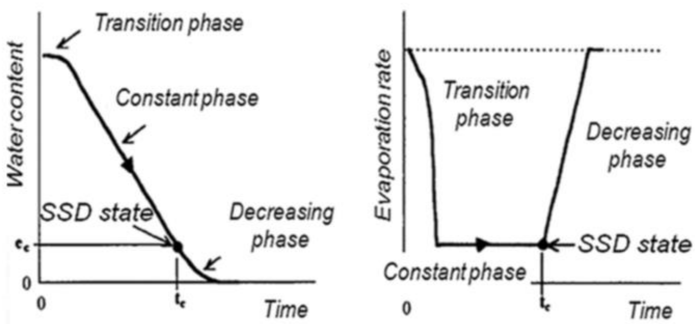

Figure 4-15. Drying phases of a porous material (Mechling et al. 2003).

The procedure for the second attempt at determining SSD state for the HA consisted of drying a soaked portion of HA at 40ºC with periodic weight measurements taken to determine the evaporation rate. This drying was conducted in a thermogravimetric analyser which automatically recorded mass readings at 0.5 second intervals. The moisture content with respect to time was calculated and plotted and a line was drawn along the constant phase as shown in Figure 4-16. From this plot it was difficult to determine a definite transition point from the constant phase to the decreasing phase.

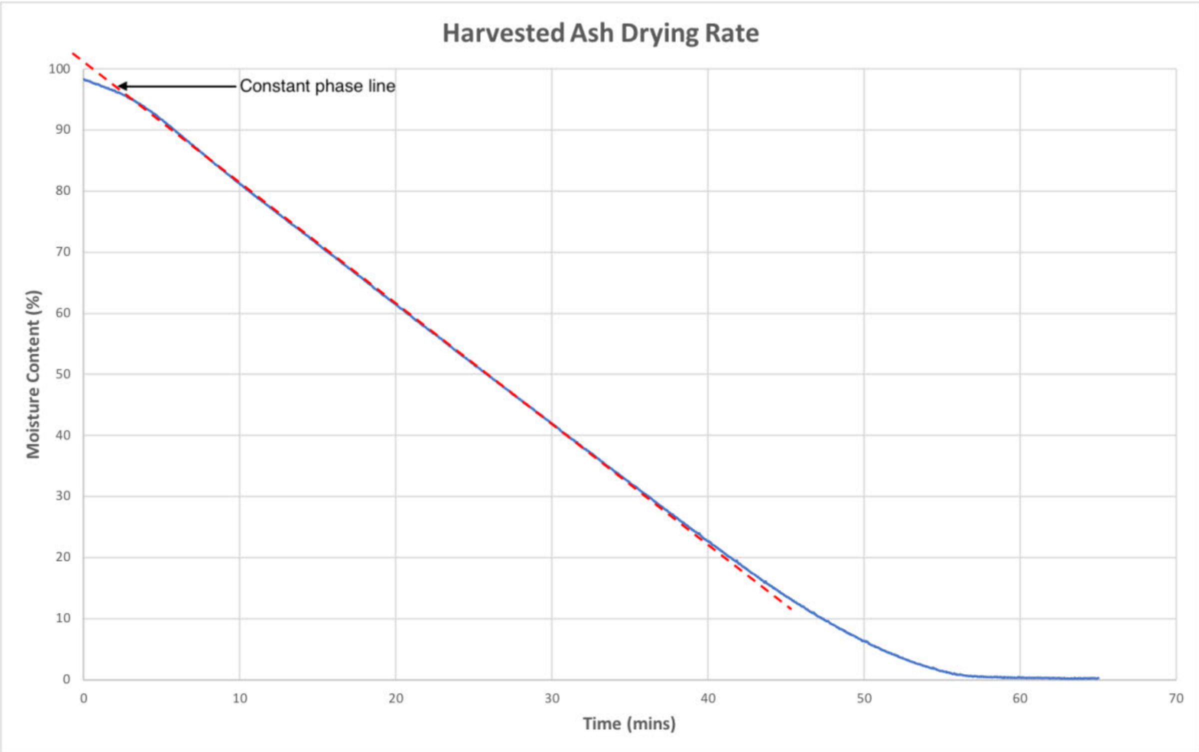

Figure 4-16. Plot of moisture content versus time for Harvested Ash.

To help determine the point of change, the derivative of weight, with respect to time, was plotted for the same data. Due to the extremely small reading intervals the data showed substantial fluctuations. To give a clearer view of the data the plot was smoothed by determining a moving average of every 250 readings and a line was then drawn on the plot to represent the constant phase. The point where the smoothed data line diverges from the constant phase line was determined to be the time at which the HA was at SSD state. Figure 4-17 shows the plot used to determine the SSD point for the HA. From this plot it was determined the HA reached SSD state at approximately the 39th minute of the test which also appears to fit with the data shown in Figure 4-16. The corresponding moisture content at this time was 24.4% which was adopted as the assumed water absorption value for the HA.

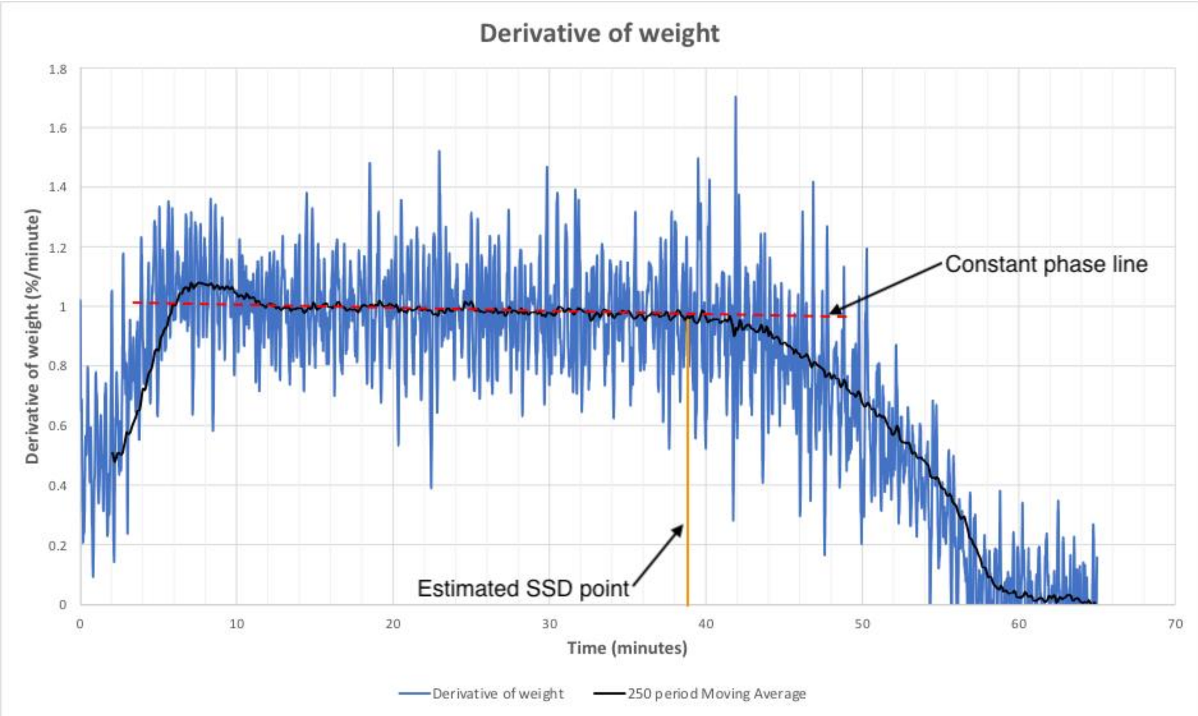

Figure 4-17. Plot of derivative of weight against time with approximate SSD point marked.

4.3.3 Particle density

The particle density is relevant for concrete aggregates because aggregates make up a large portion of the concrete, meaning the density of the concrete will be affected by the particle density of the aggregates. It is also important for this project because the design concrete mix ratio was developed based on volume, but the batches were mixed by weight for each component. Knowing the density of each concrete component material enabled the conversion of the required volume of each aggregate into masses that could be measured accurately.

A review of the existing literature shows the density of HA is typically substantially lower than that of natural fine aggregate and it was possible this would be the case for the HA used in this study. Therefore, it was especially important to determine if this is the case for HA from Millmerran so the amount of HA used to replace the natural aggregate could be calculated to ensure it was equal to the volume of aggregate it was replacing.

The particle density of the aggregates used in this research was determined along with the water absorption using test procedures AS 1141.5 and AS 1141.6.1 for fine and coarse aggregates respectively. The results of the particle density testing are compiled in Table 4-3 and it can be seen that the density of the HA was lower than that of the natural fine aggregate as expected. The results also show that the particle density of the 7 mm and 10 mm aggregates are very similar. This is to be expected because the coarse aggregates were different sizes of the same source rock.

Table 4-3. Particle density of aggregates used in concrete for this project.

Material	HA	Natural fine aggregate	7 mm aggregate	10 mm aggregate
Particle density - Dry (t/m^3)	1.77	2.59	2.81	2.82

4.4 Mix design

The proportions of base materials in concrete mixes vary significantly depending on the characteristics of the base materials used and the proposed use of the concrete itself. Mixes can be adjusted to meet a wide range of design strengths and workability criteria. The aim for the control mix for this project was to closely replicate a commonly used commercial concrete of 32 MPa characteristic strength and 80 mm slump.

The mix ratio selected to achieve this was 1 part cement to 1.5 parts fine aggregate to 3 parts coarse aggregate by volume (1:1.5:3). The coarse aggregate portion would be made up of equal quantities of 7 mm and 10 mm aggregate. The chosen water cement ratio for the mix was 0.5 on a by mass basis, meaning the mass of water added to the mix was equivalent to half the mass of the cement powder. The specific gravity of the cement powder used for this research was listed as 2.8 to 3.2 in the material safety data sheet. For quantity calculations, the average was taken to be an SG of 3.0, equating to 3000 kg/m^3.

4.4.1 Concrete mix proportions

The design concrete mix ratio was determined in relation to the volume of the cement and aggregate components however during batching the components for each mix were measured by mass to ensure accuracy. This meant appropriate masses had to be determined for each component to maintain the proposed mix ratio for each batch. The aggregate components all contained various moisture content in relation to their SSD state. The mixing water was therefore also adjusted for each mix to account for the presence of free water or absorption capacity of the aggregates and maintain a constant water cement ratio. Due to difficulties in determining the water absorption capacity of HA, the water adjustment was not calculated for the HA portion of each mix.

The following procedure was used to determine the mass required for each component in each concrete batch.

- A representative portion of each aggregate was sampled and the moisture content was determined by drying to a constant mass in an oven at 105ºC.
- The volume of each component required per cubic metre of concrete was calculated by dividing the number of parts of that component by the total number of parts. For the mix ratio of 0.5:1:1.5:3 the total number of parts is 6.
- The dry mass of each component required per m^3 was determined by multiplying the volume required per m^3 by the dry density of each component in t/m^3.
- The dry mass required for each component was determined by multiplying the dry mass per m^3 by the size of the batch (approximately 0.035 m^3).
- The wet mass required for each component was determined by multiplying the dry mass by the relevant predetermined moisture content (in percent) plus 1.
- The SSD mass required for each aggregate was determined by multiplying the dry mass by the relevant water absorption moisture content (in percent) plus 1.
- The difference between the wet mass required and the SSD mass required was calculated and the mixing water for each batch was adjusted to account for this difference.

Due to the time constraints of the project and the curing times required for test specimens, the batching and casting had to be conducted before a water absorption value had been determined for the HA. As previously stated, difficulties were experienced when trying to determine the SSD state for HA and despite multiple test attempts, a conclusive water absorption value could not be determined before batching commenced. As a result, it was decided to use the HA in the concrete mixes at the moisture content at which it was received with no adjustment to the mixing water in each batch.

After batching had been completed further testing of the HA was conducted and determined a possible water absorption value. This water absorption value was slightly higher than the moisture content of the HA, meaning the ash would have absorbed mixing water during the concrete batching. This means the effective free water for the concrete batches incorporating HA would have decreased as the amount of HA in the mixes increased, meaning the water cement ratio would have been affected. Based on the water absorption value determined for HA after batching was complete, the corrected water cement ratio for each batch was calculated to account for the variation. The corrected water cement ratio and mix proportions for each batch are shown in Table 4-4.

Table 4-4. Concrete mix proportions.

Mixture	Cement (kg/m³)	W/C ratio	Natural fine aggregate (kg/m³)	Harvested Ash (kg/m³)	7 mm aggregate (kg/m³)	10 mm Aggregate (kg/m³)
Control	500	0.500	648.50	0.00	702.00	704.00
12.5% HA	500	0.499	567.44	55.25	702.00	704.00
25% HA	500	0.495	486.38	110.50	702.00	704.00
50% HA	500	0.490	324.25	221.00	702.00	704.00
75% HA	500	0.486	162.13	331.50	702.00	704.00

4.5 Sample preparation

Prior to mixing each concrete batch, the required number of test specimen moulds were cleaned, oiled and arranged to allow easy access during the compaction process. All compaction tools such as tamping rod, rubber mallet, and trowel were arranged close to the moulds for easy access. This allowed for speedy and efficient casting of the test specimens which was completed within 50 minutes of the batch time for each batch.

Due to the effect of the high HA content, the concrete mix that had 75% HA replacement had a slump of 5 mm. According to Standards Australia (2014c) concrete with a slump value less than 40 mm should not be compacted using rodding method, it should be compacted using external or internal vibration. It was decided that maintaining consistency in compaction method for all batches would be preferable to minimise the variables between concrete specimens from different batches. As such, the compaction for the 75% HA batch was conducted using rodding the same as with all other batches.

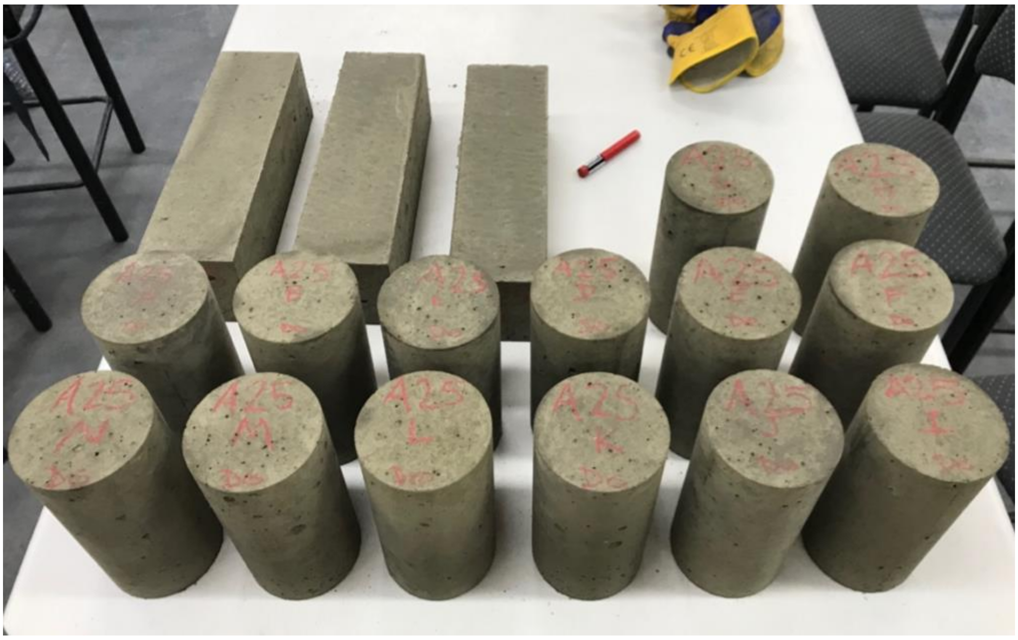

Figure 4-18. Demoulded and labelled specimens for 25% HA mix prior to moist curing.

Figure 4-19 shows the flexural strength beam test specimens for the 75% HA and 12.5% HA mixes. This image clearly shows increased presence of air pockets in the outer surface of the 75% HA test specimens caused by the low workability of the mix. While these specimens appear very poorly compacted from the outside, when inspecting the fractured surfaces of the specimens after testing, large air voids were not obviously noticeable in the interior of the specimens indicating suitable compaction was achieved.

Figure 4-19. Flexural strength beam specimens from the 75% (left) and 12.5% (right) HA concrete mixes.

CHAPTER 5. RESULTS AND DISCUSSION

5.1 Slump testing

The control batch of concrete was the first batch to be mixed and tested during the project. This mix produced a slump of 170 mm, which is significantly higher than the intended slump for the control mix. While this was an unintended result, it ended up being beneficial because all of the concrete batches containing HA displayed a tendency for the slump to decrease as the amount of HA increased. This allowed concrete mixes of up to 75% HA replacement to be produced while still maintaining enough workability to cast suitable test specimens.

Table 5-1. Slump results for concrete mixes.

Concrete mix	Slump (mm)
Control	170
12.5% HA	95
25% HA	85
50% HA	55
75% HA	5

The original intention was to increase the amount of HA in each concrete mix in 25% increments up to 100% replacement of natural fine aggregate. As can be seen from the slump values shown in Table 5-1, the HA caused a significant drop in the slump value achieved. The 75% HA mix achieved a slump of 5 mm meaning the concrete was very stiff and had barely enough workability to cast the test specimens adequately. This raised a concern that making a batch containing 100% HA had a high risk of producing totally unworkable concrete. As a result, it was decided the 100% HA mix would be abandoned and replaced with a different replacement amount. A mix with 12.5% HA replacement was chosen as a suitable mix intended to provide another data point between 0% and 25% due to the large drop in slump over that range. Figure 5-1 and Figure 5-2 show the drastic difference in slump between the 12.5% HA and 75% HA concrete mixes.

Figure 5-1. Photo of slump test for 12.5% HA concrete mix.

Figure 5-2. Photo of slump test for 75% HA concrete mix.

Figure 5-3 presents the slump values achieved plotted against the percent of HA in each mix. The plotted results show an approximately linear decreasing relationship between the amount of HA in the concrete mix and the slump achieved. The R^2 value of approximately 0.9 for the trendline plotted in Figure 5-3, indicates the linear relationship displays a good approximation of the expected slump for different HA replacement amounts.

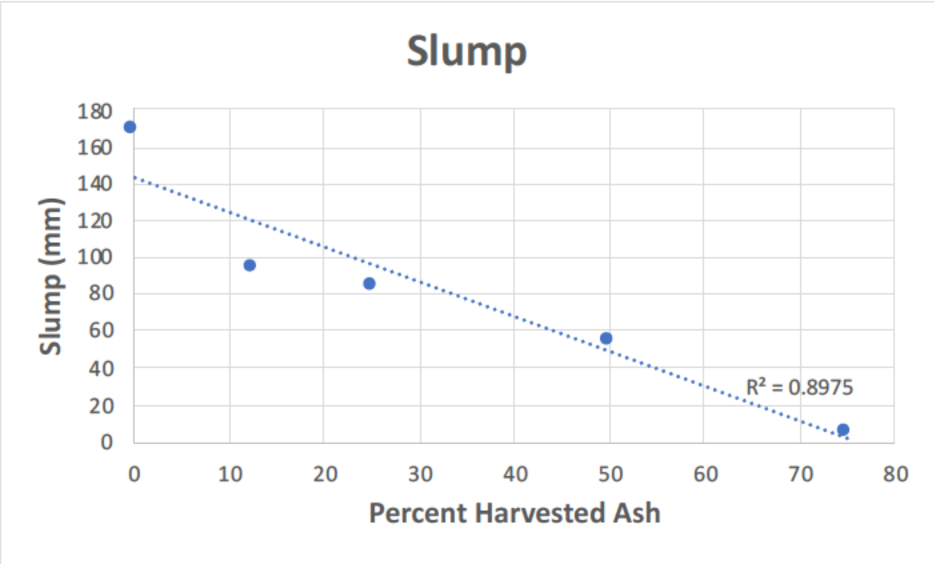

Figure 5-3. Plot of slump values against percent of HA replacement.

Having a moisture content of 22.2%, the HA used in the concrete mixes was 2.2% drier than to the water absorption value. This means the absorption of mixing water by the HA particles may contribute to a small reduction in slump but is most likely not the sole reason. This leads to the assumption that some other properties of the HA are contributing to the reduced workability.

It is possible the reduction in slump could have been caused by the irregular shape and rough texture of the HA particles as suggested by Singh and Siddique (2014). The much rougher surface of the HA as shown in Figure 5-4, may have increased the friction between particles in the mix when compared to the smoother and more rounded natural fine aggregate particles. The HA particles were also less dense than the natural fine aggregate meaning the concrete mixes containing HA were less dense overall. This factor could also have contributed to the HA concrete mixes slumping less.

Figure 5-4. Photo of washed HA particles showing rough and angular surface texture.

Most previous studies have suggested that the main contributing factor to the reduced slump is the water absorption capacity of the porous HA particles. This could suggest the water absorption value determined for the HA used in this research is incorrect. Given the method used to determine the SSD state for the HA was experimental, it should be considered a possibility that this is the case, and the HA may have been significantly drier than SSD state. This would have resulted in the ash absorbing mixing water from the concrete batches in increasing amounts as the HA increased and as a result, reducing the workability.

5.2 Concrete density

The hardened concrete density at SSD state was calculated for each cylinder specimen cast for this project. The density was determined by dividing the mass by the volume for each specimen. The volume of each specimen was calculated using dimensions measured as per the procedure detailed in AS 1012.12.1.

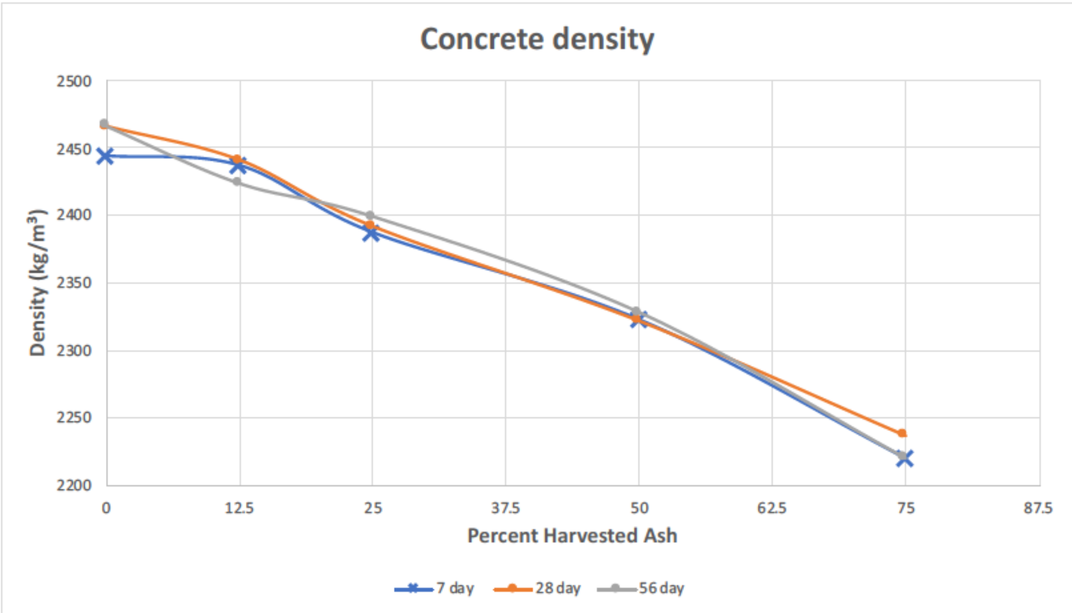

Figure 5-5. Plot of average concrete density in relation to HA replacement rate at 7, 28 and 56 days of age.

The data plotted in Figure 5-5 shows a very linear relationship between the amount of HA replacement and the density of the concrete with the density decreasing as the amount of HA increases. The change in density for concrete at 7 days of age was insignificant at 12.5% HA replacement but from there, density steadily decreases to an approximately 9% reduction at 75% HA replacement. For the concrete at 28 and 56 days, the density decreased linearly from 0% HA to an approximately 9% reduction at 75% HA replacement.

The reduction in concrete density as a result of HA replacement was also observed in studies by Kadam and Patil (2015) and Bai and Basheer (2003). This is most likely due to the HA having a significantly lower density than the natural fine aggregate that it replaced. It should also be taken into consideration that the low workability of the 75% HA concrete mix may have contributed to the reduction in density for that batch. The rodding method used for compaction of the test specimens was not suited to concrete of such low workability and as a result additional small air voids were present in the concrete, resulting in lower density. In Figure 5-6 larger smooth air voids caused by low workability can be seen as well as smaller irregular air voids caused by the porous ash particles.

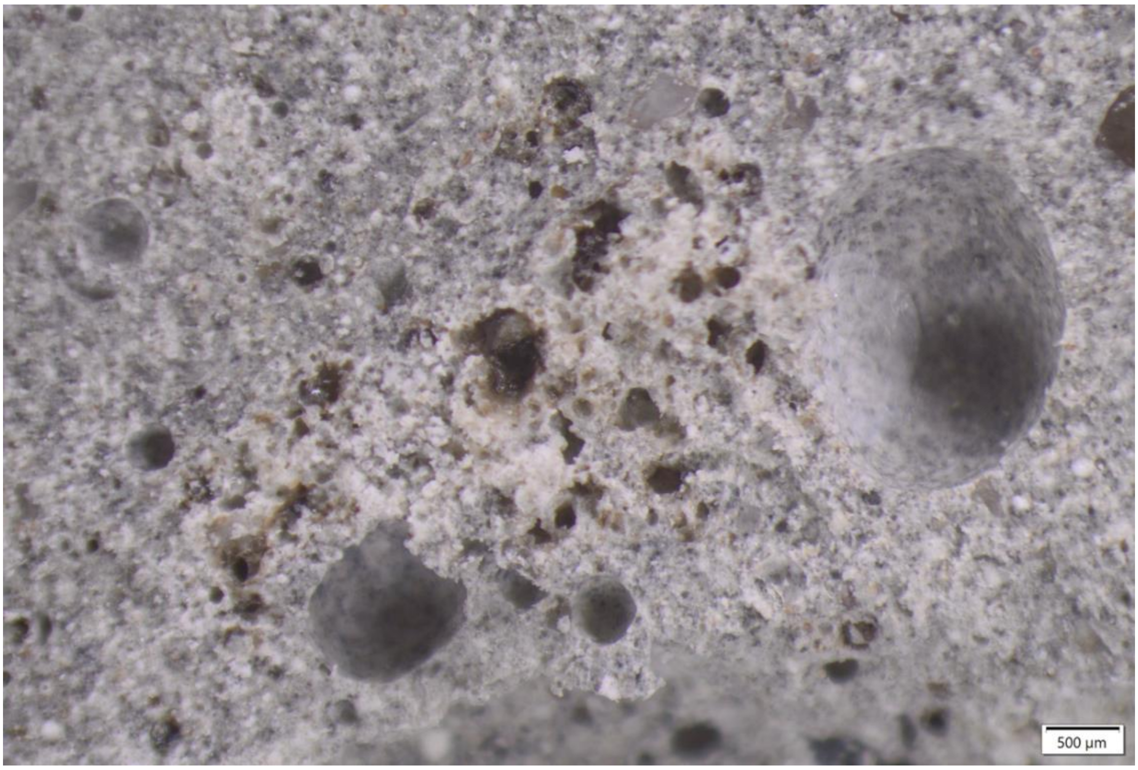

Figure 5-6. Stereo microscope image of 75% HA concrete showing voids in concrete caused by low workability and porous HA particles.

It can also be seen from Figure 5-5 that the control mix shows a definite increase in density from 7 to 28 days of age. While this increase in density amounts to less than 1% of the total density it is interesting to note that this change was considerably reduced or not apparent for most HA replacement mixes. The 75% HA replacement mix was the only one to show any substantial increase in density from 7 to 28 days of age, however at 56 days this increase had reversed.

Table 5-2. Average density of test specimens at various ages.

Concrete mix	Average density at age (kg/m^3)		
	7 days	28 days	56 days
Control	2445	2466	2467
12.5% HA	2437	2441	2424
25% HA	2388	2392	2400
50% HA	2323	2322	2329
75% HA	2220	2237	2220

The change in concrete density with respect age appears inconsistent from the results and is of such a small scale it could be deemed negligible. However, the results do display a definite trend in the reduction of concrete density as the amount of HA replacement increases.

5.3 Compressive strength

Compressive strength testing was conducted on each batch of concrete at 7, 28 and 56 days of age using the procedure detailed in section 3.1.5. The testing was conducted at this range of ages to enable analysis of the effect of HA on concrete strength development over time, in addition to the overall strength compared to the control sample. Figure 5-7 shows one of the compression test samples in the compression machine with the restrained natural rubber capping system in place.

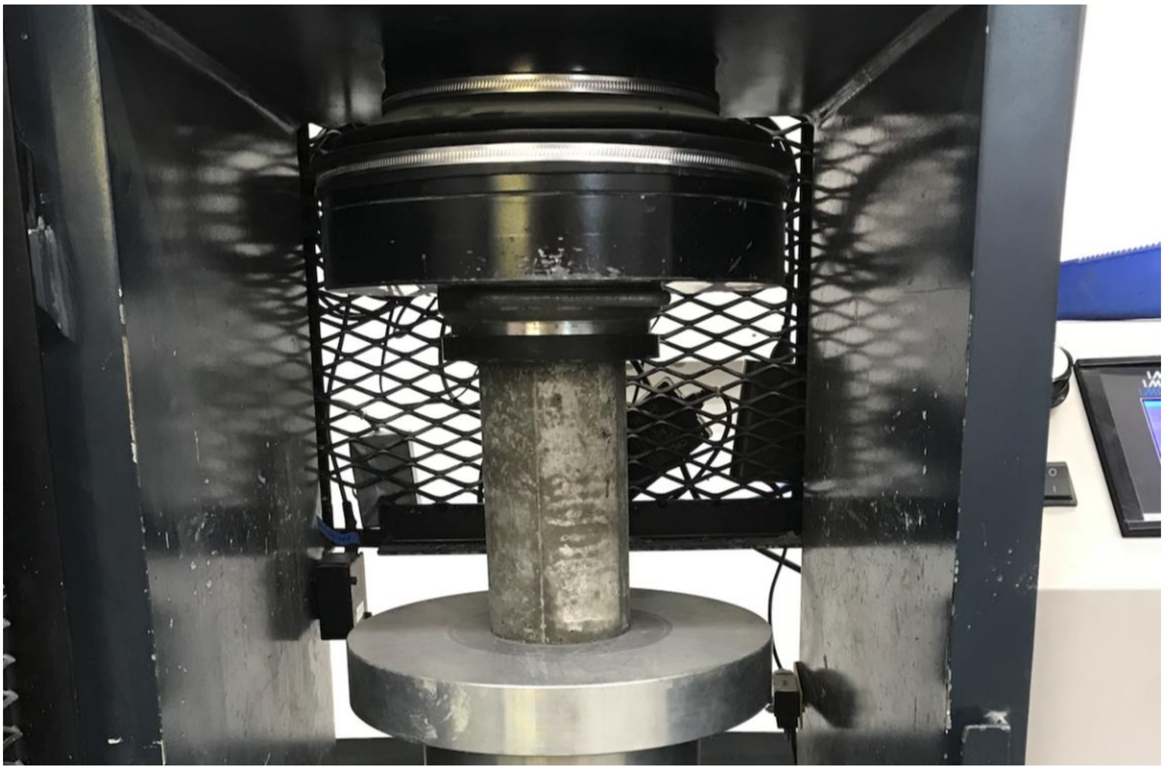

Figure 5-7. Compression test specimen from control batch in compression machine ready for testing.

In general, the compression test specimens failed in a similar manner. Most of the test cylinders failed with a crack forming in the top face of the cylinder, the rubber cap end. The crack spread down from the top face towards the side of the cylinder, shearing off a portion of the cylinder. The broken cylinder specimens in Figure 5-8 show examples of typical compression test failures observed in this research.

Close inspection of the fractured surfaces of the 28-day test specimens revealed that for the control sample and 12.5% HA mixes, the plane of failure tended to shear through the aggregate. As the amount of HA increased from 25% to 75% replacement, the plane of failure showed an increased tendency to pass around the aggregate rather than shearing through it. Figure 5-8 provides an example of this showing failure planes of compression test specimens with sheared aggregates circled in red and non-sheared aggregates circled in blue for a 12.5% HA and 75% HA specimen. This demonstrates that the bond between the aggregate and cement paste gets weaker as the HA replacement amount increases.

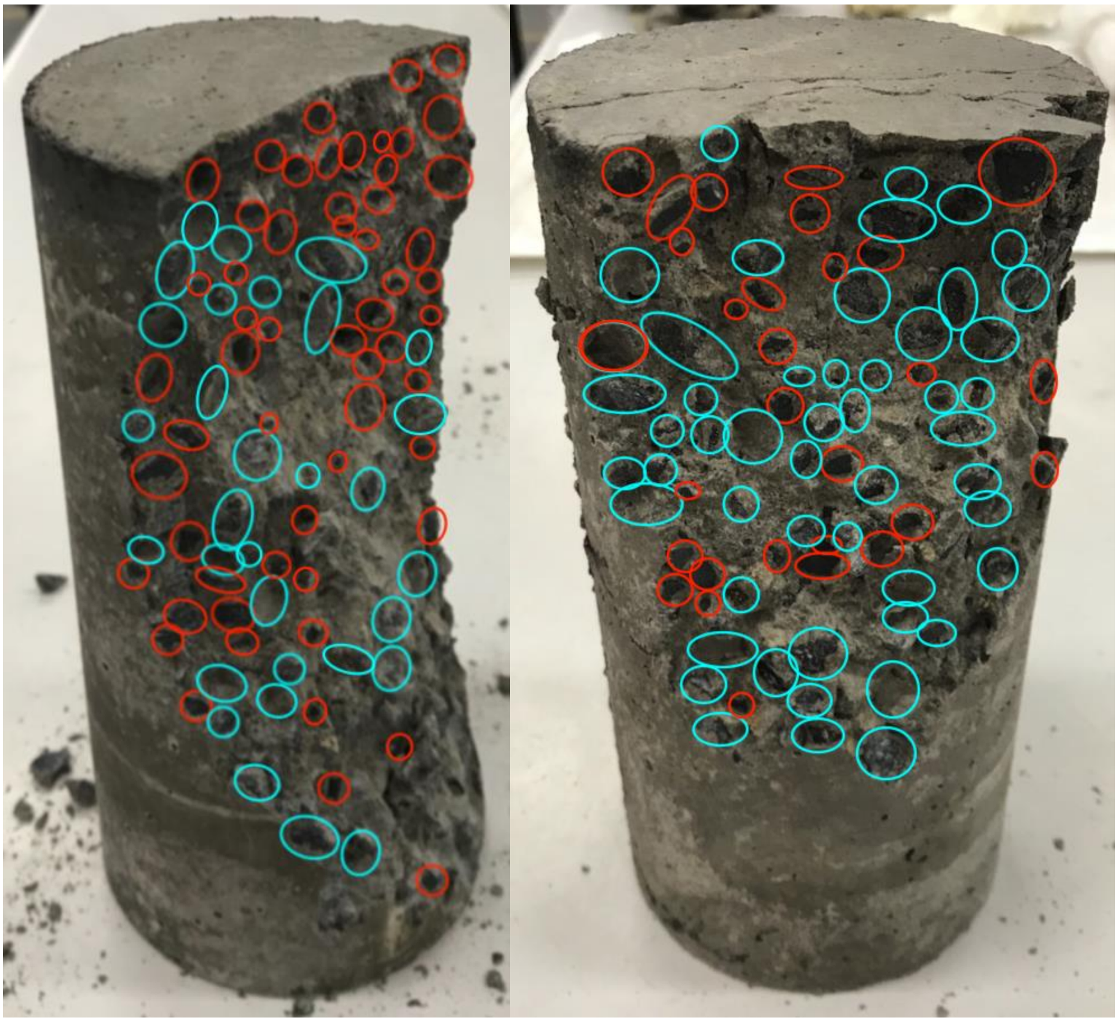

Figure 5-8. Comparison of failure planes for 12.5% HA (left) and 75% HA (right) compression test specimens.

The compression tests were conducted in triplicate for each concrete mix at each test age and the average of the three results was used for comparison. The results of the compressive strength testing are shown in Figure 5-9.

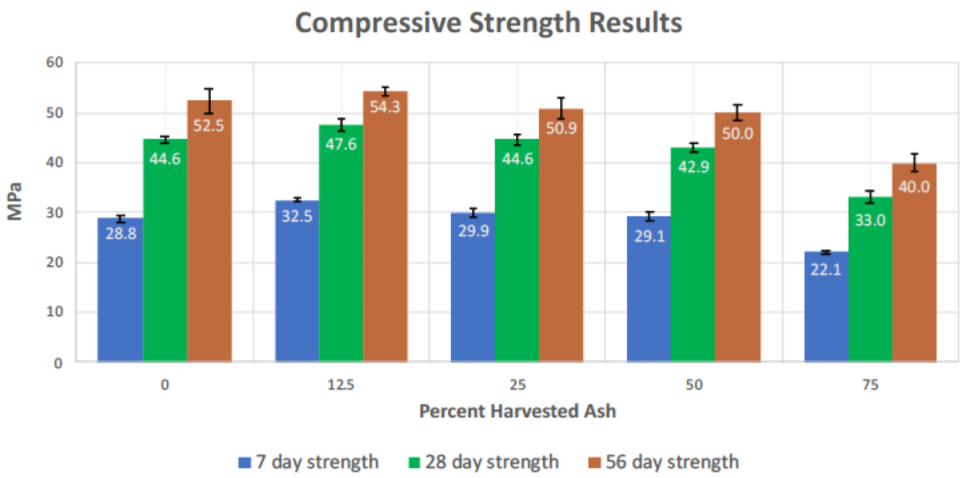

Figure 5-9. Compressive strength testing results.

The characteristic compressive strength for a concrete mix is typically based on 28-day strength. Therefore, this value represents a good point for comparison when determining the effect of HA on the strength of concrete with respect to the control sample. The results of the testing shown in Figure 5-9 reveal that the concrete mix with 12.5% HA replacement achieved a 6.7% increase in strength with respect to the control mix, while the 25% HA mix achieved the same compressive strength. The 50% HA replacement mix experienced a 3.7% reduction and the compressive strength of the 75% HA mix reduced by 26% when compared to the control mix. These results back up findings by Kadam and Patil (2015) and Lal et al. (2019) that suggest a loss of strength occurs when HA replacement in concrete is approximately 35% and higher. Figure 5-10 illustrates that the 7 and 56-day test results for each batch follow a very similar trend to the 28-day results.

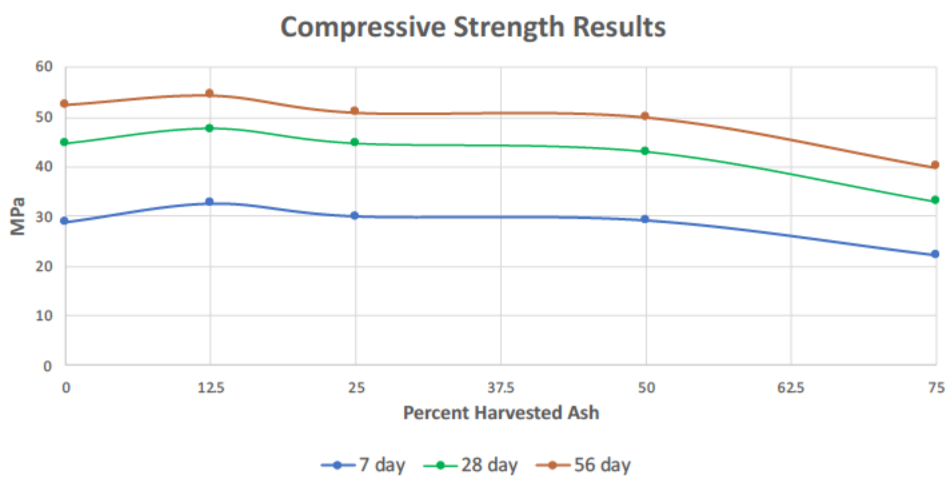

Figure 5-10. Plot of average compressive strength results for varying amounts of HA replacement.

Table 5-3 shows the increase or reduction in compressive strength for each mix at each test age with respect to the control mix. The results in this table show that at 7 days of age, the 75% HA replacement mix was the only mix to achieve lower strength results than the control batch. At 28 days of age the 50% and 75% HA mixes both showed decreases in strength and at 56 days the 25%, 50% and 75% mixes showed strength reduction in comparison to the control sample.

Table 5-3. Compressive strength increase/reduction when compared to the control mix

Concrete mix	Compressive Strength Increase/Reduction (%)		
	7 day	28 day	56 day
Control	0	0	0
12.5% HA	12.9	6.7	3.5
25% HA	4.0	0.0	-3.0
50% HA	1.2	-3.7	-4.8
75% HA	-23.1	-26.0	-23.8

This suggests that the HA concrete mixes experienced faster initial strength gain when compared to the control sample, which contradicts the findings of Abubakar and Baharudin (2012). Table 5-4 provides further detail on the rate of strength gain by presenting the 7 and 56-day strength expressed as a percentage of the 28-day strength for each mix. As can be seen in Table 5-4, all concrete mixes containing HA replacement achieved 67.1% to 68.3% of their 28-day strength after 7 days, whereas the control mix achieved 64.6%. The strength gain after 28 days shows inconsistent results with the 12.5%, 25% and 50% HA mixes showing less strength gain than the control mix. Conversely, the 75% HA mix showed higher strength gain than the control mix from 28 to 56 days.

Table 5-4. Compressive strength at 7 and 56 days expressed as a percent of 28-day strength.

Concrete mix	Compressive Strength Gain (%)	
	7 day	56 day
Control	64.6	117.7
12.5% HA	68.3	114.2
25% HA	67.1	114.1
50% HA	67.8	116.4
75% HA	67.1	121.1

Overall, the compressive strength results show that the rate of strength gain for HA concrete mixes is faster in the early stages of curing and generally slows after 28 days with respect to the control sample. The maximum strength results achieved show that mixes incorporating up to 25% HA can achieve similar of better compressive strength results than the control mix. This could suggest that HA has a small degree of pozzolanic properties that improved the strength gain when added in small amounts. It is possible that once the amount of ash increases past an optimum replacement amount, the strength gain provided by the pozzolanic reaction is offset by the ash beginning to act more as a filler. The observation of the failure planes tending to pass around the aggregate more as the amount of HA increased could support the theory that the HA acted as a filler above 12.5% replacement.

5.4 Tensile strength

The splitting tensile strength test was conducted on three test specimens from each concrete mix at 28 days of age using the procedure detailed in section 3.1.7. Figure 5-11 shows a test specimen from the control batch of concrete set up in the compression machine ready for testing.

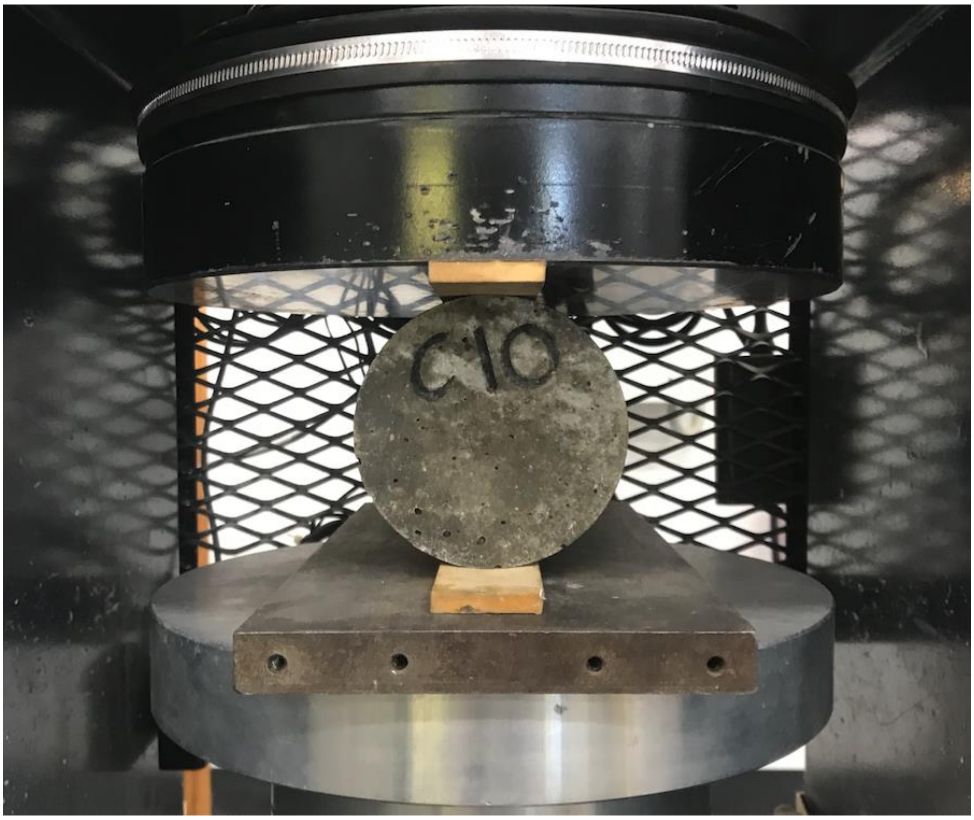

Figure 5-11. Splitting tensile test specimen ready for testing in compression machine.

Test specimens from all concrete batches behaved in a very similar manner during testing and failed with a single longitudinal split up the centre of the specimen. Examples of test specimens after testing are shown in Figure 5-12 and Figure 5-13. These figures clearly illustrate the clean split along the centre of the specimens. Figure 5-13 also clearly depicts the effect of HA on the concrete giving it a lighter overall colour than the control mix and larger individual light grey ash particles can be seen in the split.

The tensile specimens presented in Figure 5-12 and Figure 5-13 are from the control batch and the 75% HA batch. These images clearly show that the large air voids observed in the outer surface of the 75% HA test specimens were not obvious throughout the entire specimen.

Figure 5-12. Control mix tensile strength specimen after testing.

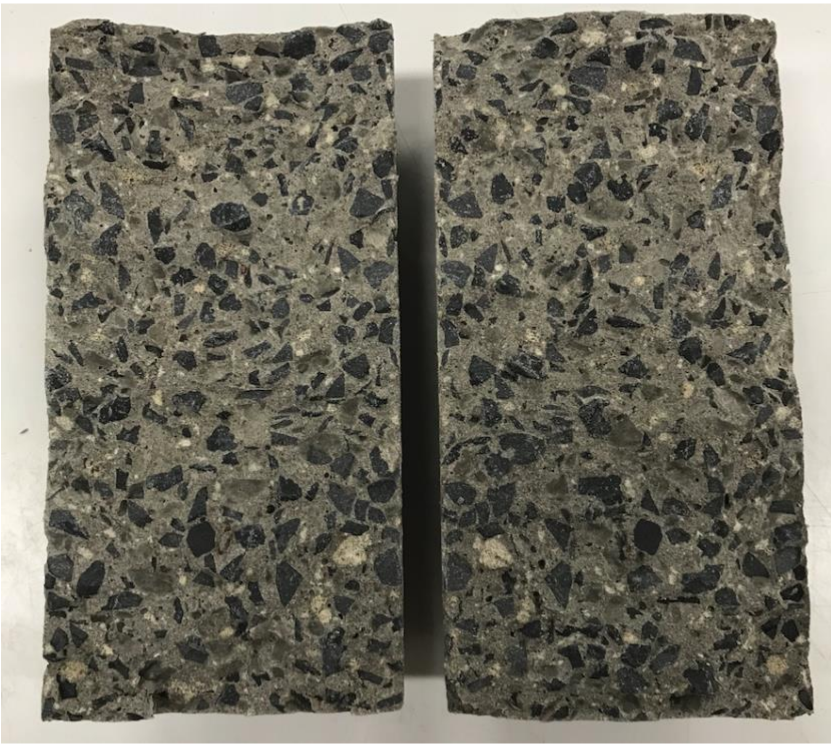

Figure 5-13. 75% HA replacement mix tensile strength specimen after testing.

Results for the splitting tensile strength tests are shown in Figure 5-14. The results show there was good agreement between the three test specimens for each concrete mix and therefore the average of the three results from each batch were calculated for comparison and are shown in Figure 5-15.

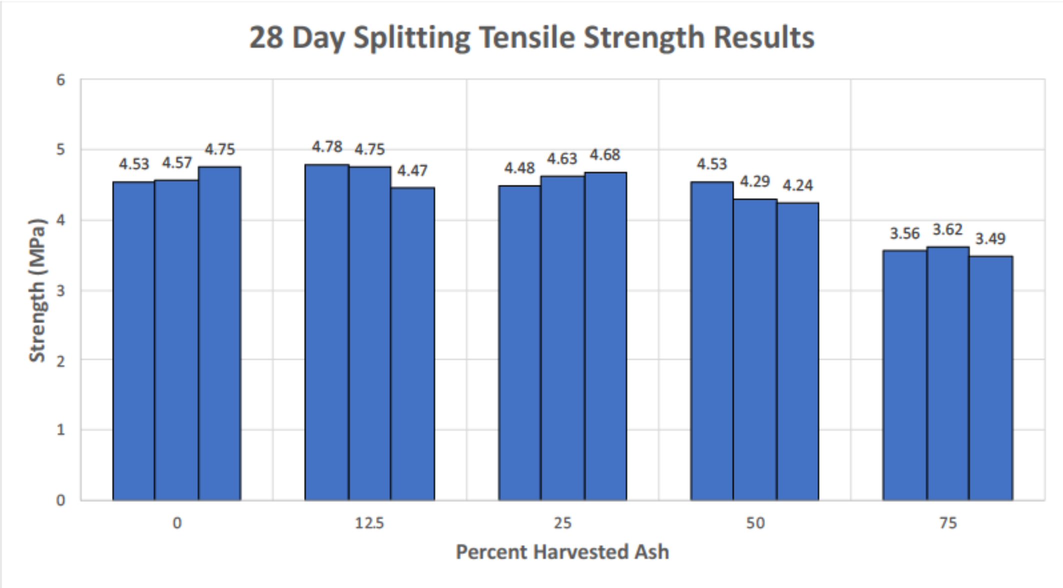

Figure 5-14. Results of splitting tensile strength testing for each concrete mix.

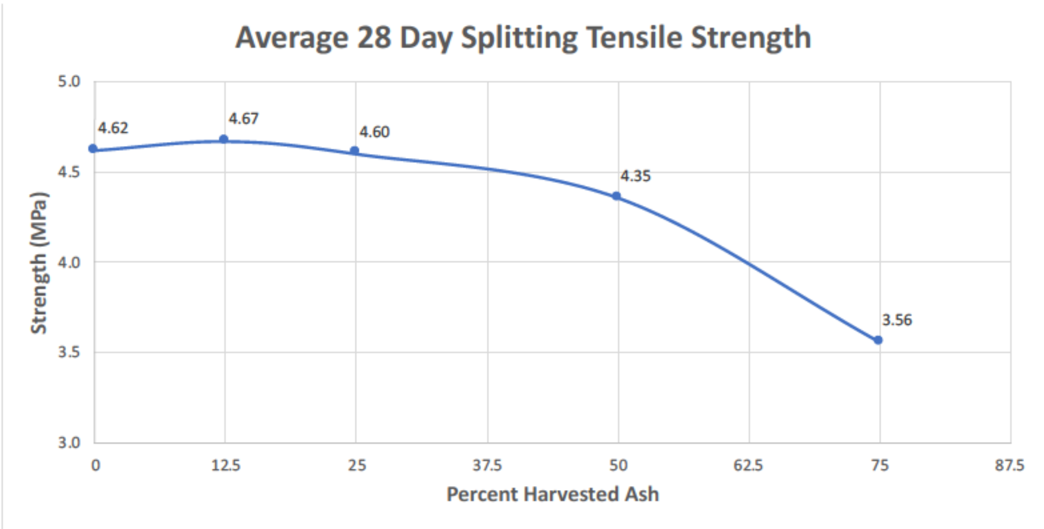

Figure 5-15. Plot of average splitting tensile strength for each mix in relation to HA content.

Figure 5-15 shows the relationship between HA content and tensile strength follows a very similar relationship to the 28-day compressive strength results. This is the same trend as was observed in the study by Kadam and Patil (2015). When compared to the control mix, the tensile strength for the 12.5% HA mix achieved a slight increase in strength, the 25% HA mix had very little change, and the strength decreased progressively from 50% HA to 75%. The strength reduction or increase for each mix as a percentage of the control batch strength is shown in Table 5-5. Given these results appear very closely related to the compressive strength results it is likely the factors related to HA that impacted compressive strength had the same effect on the tensile strength.

Table 5-5. Splitting tensile strength increase/reduction when compared to the control mix.

Concrete mix	Splitting Tensile Strength Increase/Reduction (%)
Control	0
12.5% HA	1.1
25% HA	-0.4
50% HA	-5.7
75% HA	-23.0

5.5 Flexural strength

The 28-day flexural strength testing was also conducted in triplicate to ensure representative results were obtained for each concrete mix. Figure 5-16 shows a 100 mm x 100 mm x 350 mm beam specimen ready to be tested as per the procedure detailed in section 3.1.6.

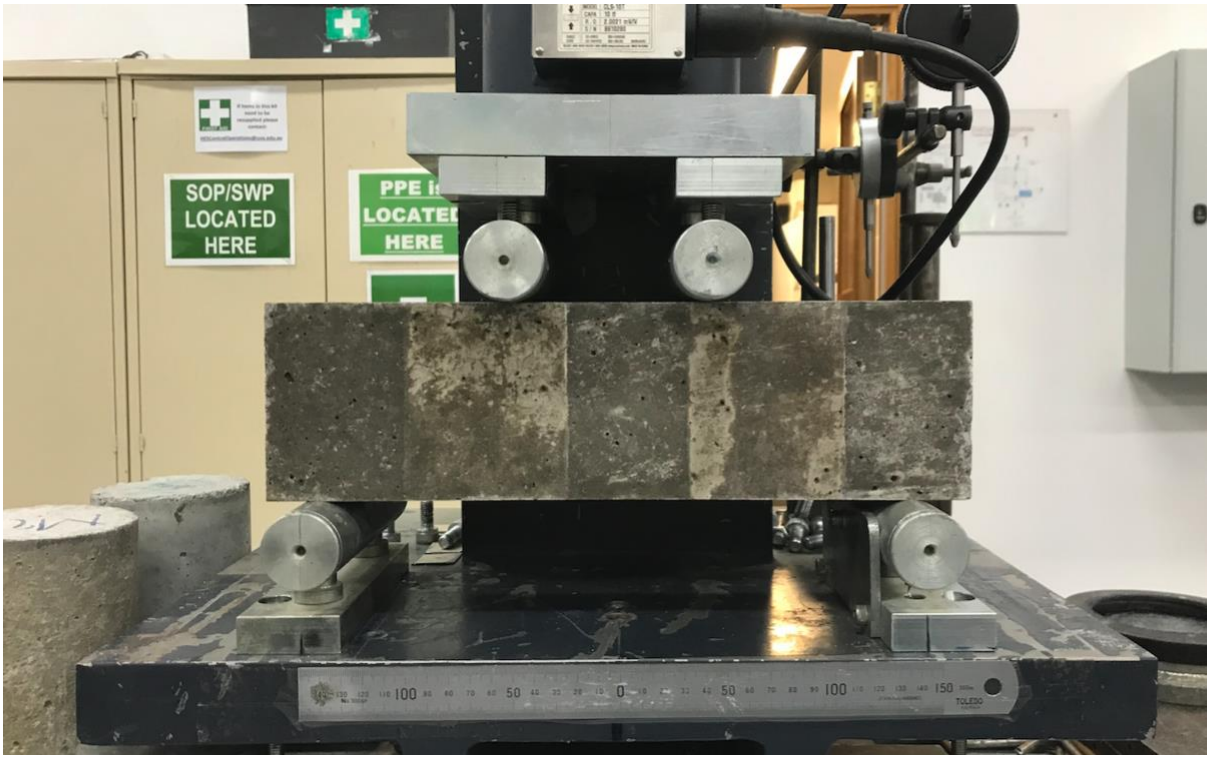

Figure 5-16. Flexural strength test specimen ready for testing in compression machine.

All of the flexural beam specimens ruptured in a very consistent manner during the testing for this project. The beams repeatedly failed due to a single fracture in the central third of the specimen toward the left-hand loading roller. Figure 5-17 and Figure 5-18 show examples of fractured flexural strength test specimens from the 25% HA and 50% HA mixes respectively.

Figure 5-17. Fractured flexural strength specimen from the 25% HA mix.

Figure 5-18. Fractured flexural strength specimen from the 50% HA mix.

The individual flexural strength results for all test specimens are shown in Figure 5-19. This data shows the three specimens from each batch achieved consistent results and therefore, the average of the three specimens from each batch was calculated. Figure 5-20 shows a plot of the average flexural strength results for each concrete mix for comparison.

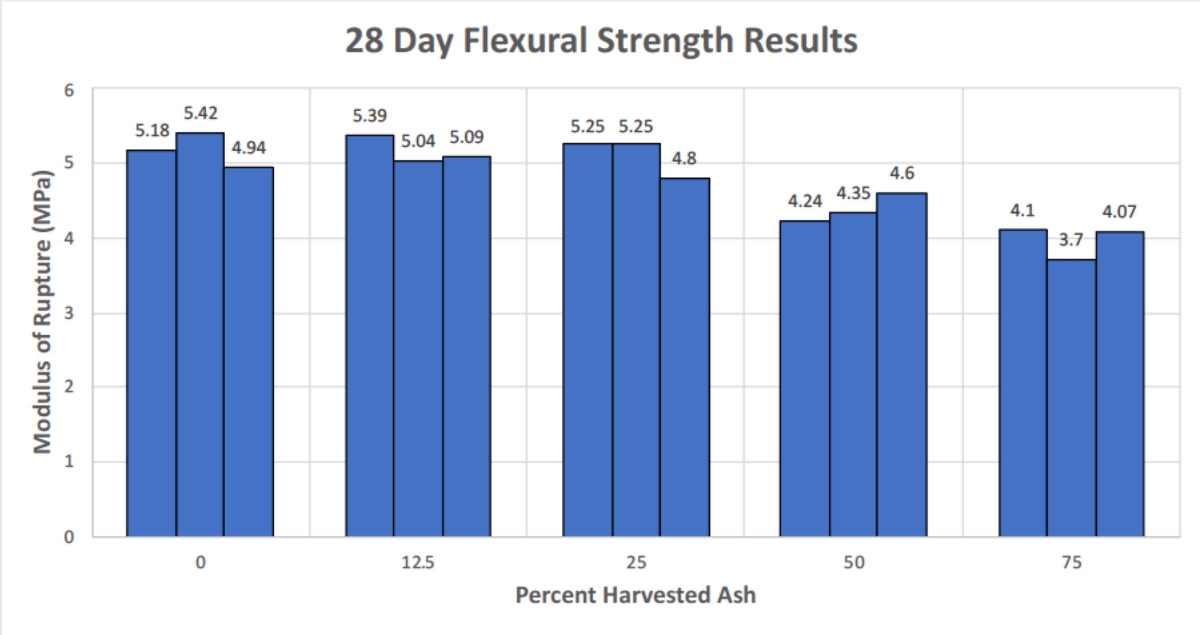

Figure 5-19. Results of flexural strength testing for each concrete mix.

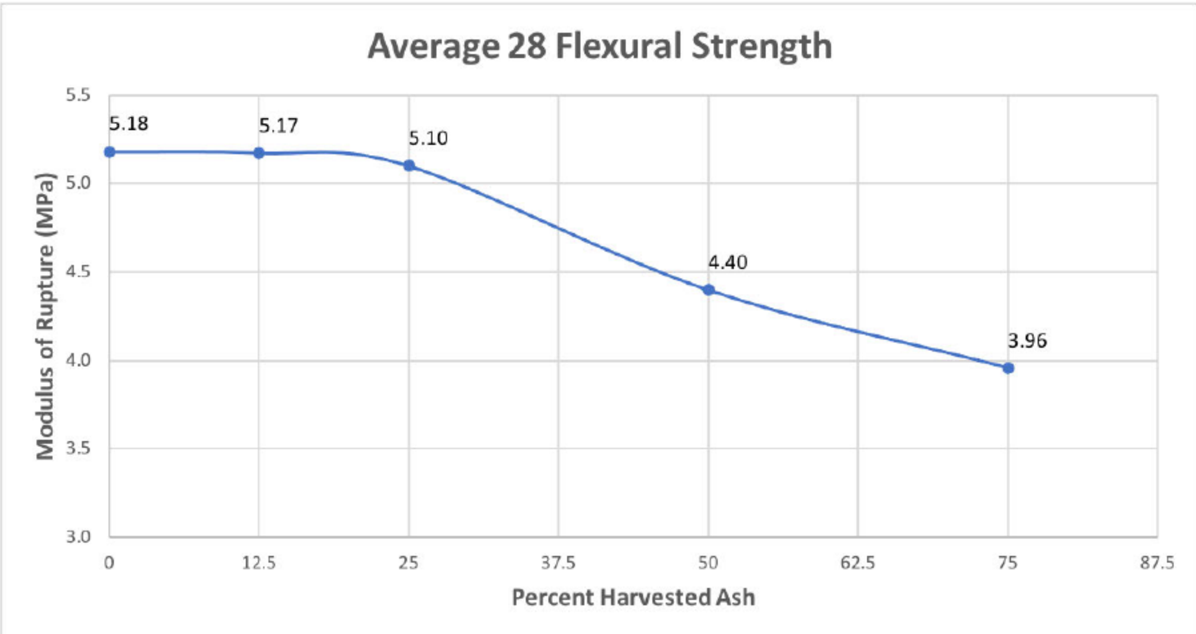

Figure 5-20. Plot of average flexural strength for each mix in relation to HA content.

It can be seen from Figure 5-20 that the flexural strength of concrete containing HA behaves differently to the compressive and tensile strength properties. The 12.5% and 25% HA mixes achieved very similar results to the control mix but neither of them showed any increase in flexural strength. These results support the research of Kadam and Patil (2015) who observed that the flexural strength was not significantly affected in concrete mixes with up to 20% HA replacement.

The flexural strength of the 50% HA mix was considerably lower than the control mix with a strength reduction of 15.1%. This reduction in noticeably larger than the reduction observed for the 50% HA mix for compression and tensile strength testing. However, the reduction in flexural strength of the concrete mix with the highest HA replacement amount was consistent with the reductions observed for the compressive and tensile strength tests of the same HA amount. A summary of the flexural strength reduction for all of the mixes is shown in Table 5-6.

Table 5-6. Flexural strength increase/reduction when compared to the control mix.

Concrete mix	Modulus of Rupture Increase/Reduction (%)
Control	0
12.5% HA	-0.1
25% HA	-1.5
50% HA	-15.1
75% HA	-23.6

According to Standards Australia (2018), the flexural strength of concrete can be estimated using the 28-day compressive strength and the following equation:

$$f'_{ct.f} = 0.6\sqrt{f'_c} \qquad \textbf{(5.1)}$$

Where:

$f'_{ct.f}$ = characteristic flexural strength (MPa)

f'_c = characteristic compressive strength of concrete at 28 days.

Equation 5.1 was used to calculate the flexural strength for each concrete mix based on the 28-day compressive strength results achieved. The value calculated by the formula was then compared to the experimental result to determine if this relationship is affected by the addition of HA. The results of this comparison are documented in Table 5-7. It can be seen that the flexural strength test results from this research were consistently higher than the values calculated based on the compressive strength. This may be due to the estimation formula coming from a concrete design standard, where it is only intended for use when more accurate test data is not available. This means the formula is most likely derived to determine a conservative flexural strength value to add an additional safety factor into designs.

Table 5-7. Comparison of experimental flexural strength results to values calculated by empirical formula.

Concrete mix	Tested flexural strength (Mpa)	Calculated flexural strength (Mpa)	Variation (%)
Control	5.18	4.01	29.3
12.5% HA	5.17	4.14	24.9
25% HA	5.10	4.01	27.3
50% HA	4.40	3.93	11.9
75% HA	3.96	3.45	14.9

The data in Table 5-7 shows that the relationship between flexural strength and compressive strength is reasonably consistent for the control mix, 12.5% HA and 25% HA mixes. These mixes all achieved experimental test values from 24.9 to 29.3 percent higher than the calculated estimates. It appears the relationship begins to change beyond 25% HA as shown by the variations of 11.9% and 14.9% achieved by the 50% HA and 75% HA replacement mixes respectively.

5.6 Modulus of elasticity

Due to resource requirements and time constraints, the modulus of elasticity testing was conducted on two samples for each batch of concrete at 28 days of age. The testing was conducted as per the procedure detailed in section 3.1.8. The deformation measuring device used for this testing was equipped with an electronic linear displacement transducer (LDT) that recorded the displacement readings at 0.1 second intervals. This displacement data could be viewed with the corresponding applied loads at the required test points. The data from the test points was converted to stress and strain, then used to calculate the static chord modulus of elasticity.

Figure 5-21. 12.5% HA test specimen with displacement measuring device attached.

The load displacement device used for testing is shown in Figure 5-21 attached to a test specimen. It can be seen from this figure that the device has a pivot point on one side of the concrete specimen and the LDT on the opposite side, with the attachment to the test specimen in the middle. Due to the geometry of this system, displacement readings recorded by the LDT had to be halved to determine the actual displacement of the test specimen to be used for calculations.

Table 5-8. Static chord modulus of elasticity test results.

Concrete mix	Modulus of Elasticity (Mpa)			
	Test 1	Test 2	Average	Standard deviation
Control	33476	34521	33999	523
12.5% HA	33110	44314	38712	5602
25% HA	27752	50340	39046	11294
50% HA	28324	26398	27361	963
75% HA	26037	26604	26321	284

The calculated results for the modulus of elasticity testing are shown in Table 5-8. On initial inspection of the test results, large standard deviations were observed for the 12.5% and 25% HA test specimens. This prompted a closer inspection of the test data for all test specimens to try and determine the cause of the inconsistent results. Reviewing the stress versus strain plots for each test on each specimen revealed that some samples exhibited inconsistent strain development as the stress increased. All results for the control mix and the 75% HA mix showed an approximately linear strain increase for the entire test and when the load was reduced back to zero, the strain reduced back to zero in a similar linear fashion. A number of the results from the 12.5%, 25% and 50% HA mixes showed irregular periods when stress increased and strain did not, resulting in non-linear strain gain throughout the test. The inverse was also observed when the load was lowered back to zero.

This irregular strain development resulted in the inconsistency in the results. These irregular strain readings may have been caused by slippage of the displacement apparatus during the test. During the test, every effort was made to ensure the test apparatus was firmly fixed in place but there is a chance the bolts holding it in place were not tight enough. Given the displacement measured during the test is in terms of hundredths of a millimetre, this means that the slightest slip would be enough to affect the results.

For the purpose of this research it was deemed appropriate to disregard the modulus of elasticity results for the 12.5%, 25% and 50% HA concrete mixes. A limited analysis was conducted on the results for the remaining concrete mixes by comparing the achieved results to results calculated using existing empirical formulas for elastic modulus of concrete.

According to Standards Australia (2018) the modulus of elasticity can be calculated for concrete using the following equations:

$$E_{cj} = \rho^{1.5} \times \left(0.043\sqrt{f_{cmi}}\right) \qquad \text{when } f_{cmi} \leq 40 \text{ MPa} \qquad \textbf{(5.2)}$$

$$E_{cj} = \rho^{1.5} \times \left(0.024\sqrt{f_{cmi}} + 0.12\right) \qquad \text{when } f_{cmi} > 40 \text{ MPa} \qquad \textbf{(5.3)}$$

Where:

E_{cj} = modulus of elasticity at the appropriate age (MPa)

f_{cmi} = mean in situ compressive strength (MPa)

ρ = density of concrete (kg/m^3).

Based on the compressive strength results achieved at 28 days of age, equation 5.2 was used to calculate the modulus of elasticity for 75% HA mix and equation 5.3 was used for the control mix. The calculated and tested elastic modulus results are shown in Table 5-9. It can be seen from these results that the tested modulus of elasticity for the control sample is in good agreement with the calculated modulus of elasticity with 0.9% variation between the two values. The results for the 75% HA replacement mix also show good agreement with 0.7% variation between the tested and calculated results.

Table 5-9. Comparison of tested elastic modulus results to elastic modulus calculated using method AS 3600.

Concrete mix	Tested Modulus of Elasticity (Mpa)	Calculated Modulus of Elasticity (Mpa)	Variation (%)
Control	33999	34323	-0.9
75% HA	26321	26135	0.7

This data possibly indicates the relationship between modulus of elasticity, density and compressive strength was not affected by the addition of HA in the concrete. However, due to the limited valid test data it has not been established conclusively. This observation contradicts the findings of Yüksel et al. (2011) and Singh and Siddique (2014) that suggest the modulus of elasticity of HA concrete is not directly related to the compressive strength. This contradiction to existing literature introduces further doubt on the validity of the modulus of elasticity testing for this project.

5.7 SEM analysis

Due to time constraints the SEM analysis was conducted on concrete specimens for the control batch, 25% HA and 75% HA mixes only. These three concrete mixes were chosen to provide information on the effect of mid-level and high-level ash replacement when compared to the control sample. The SEM analysis was conducted on the concrete mixes at 56 days of age.

The analysis of the control mix found that the concrete was generally densely packed with a low proportion of air voids. As can be seen in Figure 5-22, most air voids that were present have been nearly filled with what appears to be needle-like ettringite crystal. These crystals typically form in concrete that is exposed to water for a long period of time when the primary ettringite dissolves then reforms in voids or microcracks (PCA 2001). Larger plate-like crystals that were possibly calcium hydroxide were also observed in the control mix. These calcium hydroxide crystals typically present as hexagonal plate-like structures in SEM imaging (Belkowitz 2009).

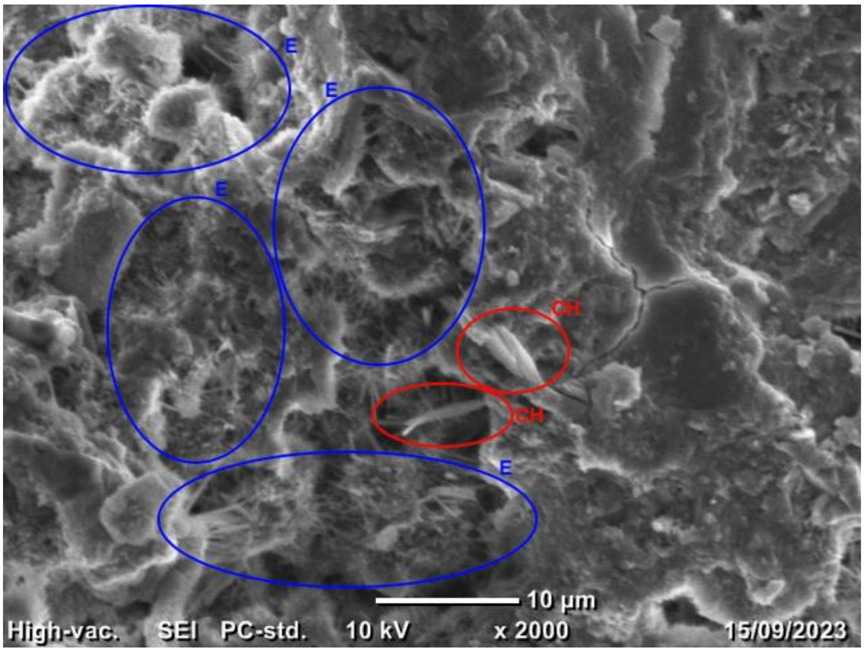

Figure 5-22. SEM image of control sample with ettringite (E) and calcium hydroxide (CH) crystals marked.

The SEM analysis of the 25% HA concrete displayed similar characteristics to the control mix. As can be seen in Figure 5-23, the concrete was still generally densely packed with most voids containing large amounts of ettringite crystals. The 25% HA concrete differed to the control sample in that calcium hydroxide crystals were less common throughout the concrete sample. It was also possible to locate the more porous HA particles within the concrete as shown in Figure 5-23.

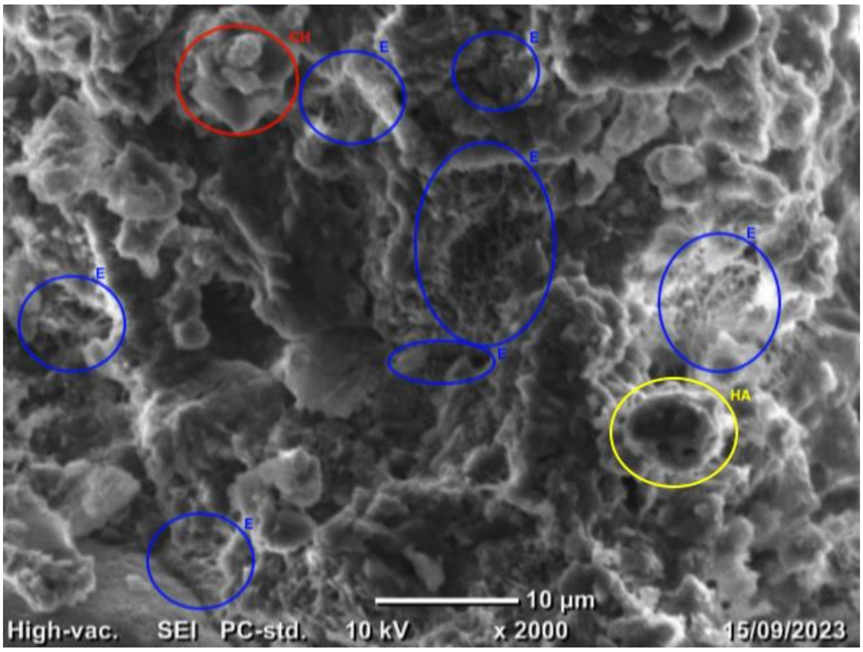

Figure 5-23. SEM image of 25% HA concrete specimen with ettringite (E), calcium hydroxide (CH) and harvested ash (HA) marked.

The microstructure of the 75% HA concrete mix was visibly different to the other concrete mixes when analysed using the SEM. There were significantly more air voids present in the concrete mix and obvious concentrations of porous HA particles. The voids contained very little ettringite crystal formation and calcium hydrate crystals were not apparent. Figure 5-24 clearly shows the increased air voids in 75% HA concrete and the lack of ettringite crystals.

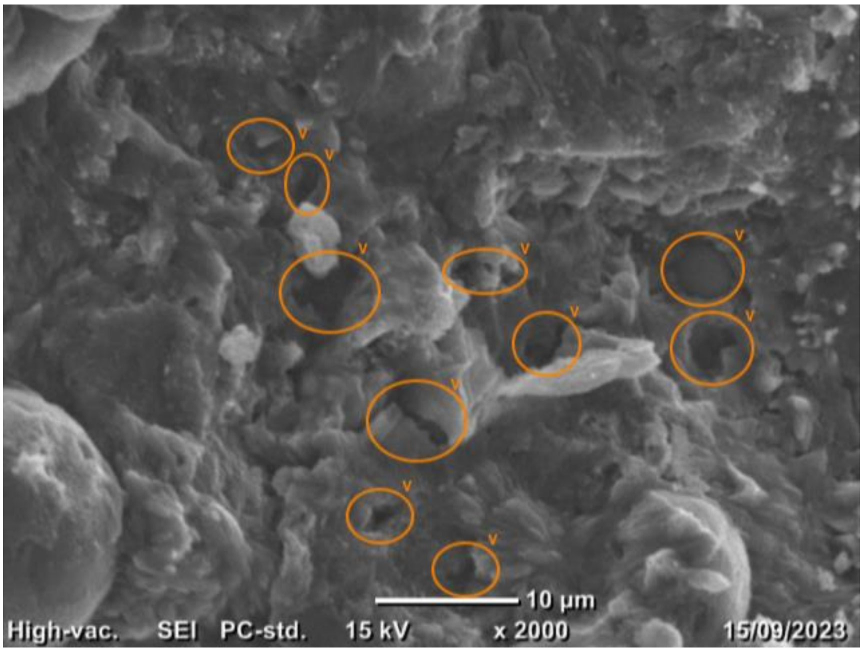

Figure 5-24. SEM image of 75% HA concrete specimen with voids lacking ettringite (V) marked.

CHAPTER 6. CONCLUSIONS AND FUTURE RECOMMENDATIONS

6.1 Conclusions

This project has explored the impact on the physical properties of concrete when HA is used as a replacement for a portion of fine aggregate. The research used a conventional concrete mix as a control sample and compared results with concrete mixes containing 12.5%, 25%, 50% and 75% HA replacement rates. The following specific conclusions can be drawn from the results of this research:

1. The HA from Millmerran power station has a higher proportion of fine particles than the common natural fine aggregate and does not fit the recommended particle size distribution for fine concrete aggregate according to AS 2758.1. The Millmerran ash is also extremely porous resulting in a high water absorption value of 24.4%. The porosity of the ash also contributes to a particle density of 1.77 t/m^3 which is approximately 32% lower than the natural fine aggregate.
2. The incorporation of HA in the concrete mixes had a significant impact on the workability of the concrete mix. The tested slump of the concrete mixes decreased almost linearly as the amount of HA increased, resulting in almost zero slump for the mix with 75% HA replacement.
3. Up to 25% of the natural fine aggregate can be replaced with HA with no negative impact on the 28-day compressive strength. Beyond 25% HA incorporation, the compressive strength of the concrete decreased with respect to the control mix as the amount of HA increased. All concrete mixes containing HA exhibited faster early strength gain up to 7 days, however all but one HA concrete mix displayed slower strength gain beyond 28 days of age with respect to the control mix.
4. The results of the 28-day splitting tensile strength testing of concrete containing HA behaved in a very similar manner to the compressive strength results suggesting the two strength characteristics are very closely related.
5. The addition of HA affected the flexural strength of concrete slightly differently to the compressive and tensile strength. Concrete mixes containing up to 25% HA replacement showed no appreciable negative impact on the 28-day flexural strength and beyond 25% HA replacement the flexural strength decreased as the amount of ash increased. The flexural strength dropped considerably for the 50% HA mix suggesting the flexural strength

of concrete is more greatly impacted by the addition of HA when compared to the compressive and tensile strength.

6. The existing empirical relationship between concrete density, compressive strength and modulus of elasticity does not appear to be affected by the addition of HA in the concrete however this conclusion is based on very limited test data.
7. The density of the hardened concrete decreased almost linearly as the amount of HA in the concrete mix increased, with an ultimate reduction in density of 9.5% for the 75% HA mix.
8. Under a scanning electron microscope, the microstructure of concrete containing 25% HA replacement appeared very similar to the control sample. At 75% HA replacement, the concrete microstructure was perceptibly different to the control sample with significantly less ettringite crystal development.
9. The research suggests that the potential optimum rate for replacement of natural fine aggregate with HA is approximately 25% by volume. This replacement amount maximises the amount of HA used without significantly affecting the concrete strength performance.

6.2 Future research recommendations

This study has provided promising results suggesting that HA has the potential to replace up to 25% of the fine natural aggregate in concrete. However, the testing conducted has not investigated all of the properties of concrete that could be affected. These promising compressive, tensile and flexural strength results provide a compelling argument to suggest that further research and testing on the subject is warranted. There are aspects of this research project that deserve further investigation and the literature review reveals numerous other performance characteristics of concrete that could be affected by the HA. The following list outlines suggested areas where further research would be beneficial:

1. Any substantial uptake in the use of HA in concrete would require the capability to maintain the desired level of workability in HA concrete mixes. Further research in this area could focus on additional testing of the HA to conclusively determine its water absorption. Another potential avenue for research in this area would be the use of plasticisers to maintain workability in HA concrete mixes.
2. Due to the observed test errors and limited usable information for modulus of elasticity testing in this project, future studies should include modulus of elasticity testing to conclusively determine the effects of HA incorporation.
3. This research determined an approximate optimum amount for HA replacement. Further studies could be conducted using smaller increments of HA replacement amounts to refine this optimum HA amount.

4. Concrete durability is another very important performance characteristic of concrete that was not examined in this research project. Further research should be conducted to determine how the incorporation of HA in concrete affects durability properties including but not limited to abrasion resistance, drying shrinkage, chemical resistance, and water penetration.
5. Further study should be conducted to examine the potential environmental and safety risks caused by the use of HA in concrete. Potential environmental or safety issues could be present in the procurement, handling and transport of HA as well as the cutting, handling and disposal or repurposing of HA concrete at end of life.
6. Future research should be conducted to thoroughly examine the financial viability of incorporating HA into concrete on a large scale. Most commercial business decisions are heavily influenced by financial factors, so if a significant financial benefit from using HA could be proven, the mainstream concrete industry would be more likely to consider the use of HA in concrete.
7. As established in the literature review, pond ash characteristics vary significantly from source to source. Future studies could be conducted to test a large range of pond ash sources to develop a register of sources and the corresponding ash properties. This information should include both physical and chemical properties of HA sources and would be helpful in determining which ash sources might behave similarly when incorporated in concrete and which sources might require further testing and research.

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APPENDIX A - Project specification

ENG4111/4112 Research Project
Project Specification

For: Drew Obst

Title: Use of harvested ash as replacement for fine aggregate in concrete

Major: Civil Engineering

Supervisor: Associate Professor Weena Lokuge

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

Project Aim: To determine the viability of using ash from coal fired power production in place of a portion of the fine aggregate in concrete.

Programme: Version 1, 14th March 2023

1. Research existing literature that examines to the utilisation of harvested ash in concrete.
2. Determine the standard concrete component ratio for the control mix and identify a suitable range of substitution rates for the harvested ash.
3. Obtain harvested ash and perform laboratory analysis to characterise the ash to being used.
4. Batch the range of concrete mixes, cast and cure test specimens as per the procedures detailed in AS1012.
5. Perform compressive and flexural strength tests on the cured concrete specimens at a range of specimen ages.
6. Perform Scanning Electron Microscope (SEM) analysis on test specimens.
7. Analyse the test results to determine the impact of the harvested ash on the performance of the concrete specimens and identify potential optimum ash ratio.
8. Complete and submit an acceptable thesis.

APPENDIX B - Risk management plan

2393	RISK DESCRIPTION	TREND	CURRENT	RESIDUAL
	Testing mechanical properties of concrete incorporating harvested ash as replacement for fine aggregate		Low	Low

RISK OWNER	RISK IDENTIFIED ON	LAST REVIEWED ON	NEXT SCHEDULED REVIEW
Drew Obst	11/05/2023	17/05/2023	17/05/2024

RISK FACTOR(S)	EXISTING CONTROL(S)	CURRENT	PROPOSED CONTROL(S)	TREATMENT OWNER	DUE DATE	RESIDUAL
Manual handling of concrete materials, test equipment and test specimens: Possible risks are personal injury such as strains or sprains (back, legs, arms) and cuts or abrasions.	Control: Wear gloves and steel cap boots. ____________ Control: Use wheelbarrow/trolleys for transport of large/heavy items/concrete. ____________ Control: Training in correct lifting techniques. Limit aggregate sample size to 20 kg maximum. Keep work area clear. Do not lift multiple heavy items at one time. Enlist help for lifting large/awkward objects. Take time to familiarise oneself with equipment being used and correct operating procedures. Work on a controlled manner, don't rush. Work will be undertaken under supervision of competent person.	Low				Low
Working with cement/concrete: Skin/eye damage, chemical burns, lung damage	Control: Have abundant clean water nearby to wash immediately if concrete splashes on skin (shower and eye wash station). Obey all handling procedures in SDS Work will be undertaken under supervision of competent person. ____________	Low				

	Control: Wear appropriate PPE (mask for dry cement, gloves, safety glasses)					
Cement mixer: Injury from interaction with moving machine parts. Electrocution	Control: Keep work area clear so that clear zone can be established around machine when in operation. Keep other people out of work area while mixing concrete. ____________ Control: Safety cutoff switch on machine ____________ Control: Thoroughly check over machine before use. Keep power cord off the ground away from any water sources. Do not reach into machine while it is in operation. Ensure machine is off and has stopped rotating before removing concrete from mixer. Work will be undertaken under supervision of competent person. ____________ Control: Wear gloves	Low				
Testing concrete specimens in compression machines: Crushing/pinching injury, equipment damage, injury from flying debris.	Control: Ensure all safety guards/cages are in place when operating machines. ____________ Control: Check machines over thoroughly before use to ensure they are in good working order. Follow standard operating procedures for equipment. Only use equipment for its intended purpose. Work will be undertaken under supervision of competent	Very Low				

	person. ______________ Control: Wear gloves and safety glasses.			
Personnel movement around work area: Injury due to tripping over equipment, power cables, slipping on spills.	Control: Keep work area tidy. Place equipment away when not in use. Arrange power cables to be up out of the way. Clean up any spills immediately. Keep people not involved in work out of the work area. Work will be undertaken under supervision of competent person. ______________ Control: Wear appropriate closed in footwear (safety boots) with good grip soles.	Low		

ATTACHMENTS
Bastion-General-Purpose-Cement.pdf Fly Ash06122022SA Premium Cement ConcreteAustraliaEnglish.pdf

APPENDIX C - Consequential Ethics

Consequential effects

The consequences of the research project would ideally be only positive. If the research shows that pond ash can be incorporated in concrete without significantly affecting its performance, it will present a highly beneficial use for pond ash. Research by Rafieizonooz et al. (2022) suggests that once pond ash is incorporated into concrete, the cement paste encapsulates the ash particles meaning that trace elements and heavy metals will not leach out of the concrete. This means it would be possible to reduce the amount of natural fine aggregate that needs to be mined and also reduce the amount of pond ash that is stored in ponds posing significant environmental risks.

A potential risk of this research is exposure to the heavy metals and sometimes arsenic that are contained in HA. These elements are usually present in pond ash in small amounts and would only pose a risk with long term exposure. Studies show that long term exposure to these substances can cause cancer, skin lesions and organ damage, but effects from short term exposure are very rare (Järup 2003). However, while working with the HA it will be important to wear appropriate protective equipment to minimise skin contact with the HA. Personal cleaning after working with HA will also be a priority to reduce the chance of contamination by HA. This risk could also be minimised by avoiding working with the HA in a dry state where possible. In its dry state the ash would produce dust that could be inhaled and is hard to contain. Working with the ash in a damp state would greatly reduce this risk.

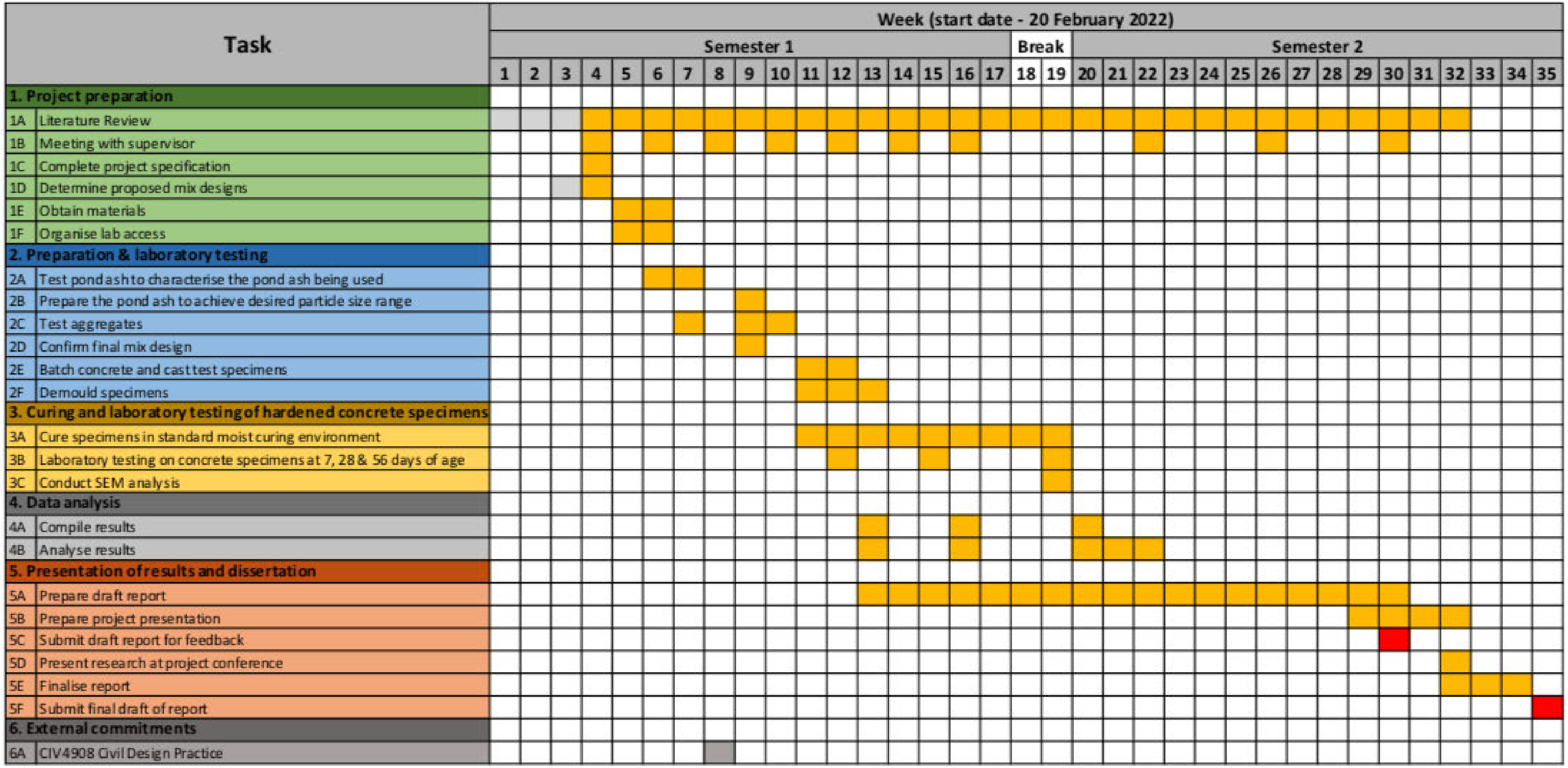
One of the main concerns with pond ash is the risk of heavy metals leaching into local water supplies. To conduct this research, it will be necessary to obtain HA and remove it from its storage pond to the experiment location. This presents a risk of contaminating the water supply of the experiment location. To combat this risk, the HA will be stored in sealed buckets or bags that prevent water ingress or egress. After testing is complete the work area will also be cleaned thoroughly to ensure no ash is left on site and any leftover material is stored appropriately or returned to the original source location.

APPENDIX D - Project plan

ENG4111 and 4112

Project Plan

Use of harvested ash as replacement for fine aggregate in concrete



APPENDIX E - Project resource plan

ENG4111/4112 Research Project

Project Resources

Item	Quantity required	Source	Cost ($)
Pond ash	*100 kg	Project supervisor to provide details of where this can be obtained	0.00
GP Cement powder	*100 kg	Bunnings	40.00
Coarse aggregate	*250 kg	Local quarry (preferred) or landscape supplier	25.00
Fine aggregate	*150 kg	Local quarry (preferred) or landscape supplier	15.00
Sample bags/buckets	25	Student	0.00
Shovel	1	Student	0.00
Workspace	40 m^2	USQ or private laboratory^	0.00
Access to potable water	200 L	USQ or private laboratory^	0.00
Worksheets for recording test data	2	Student to create based on test requirements	0.00
Drying oven	1	USQ or private laboratory^	0.00
Sieves	1 set	USQ or private laboratory^	0.00
Electronic balance	1	USQ or private laboratory^	0.00
Cement mixer (Optional, approximately 120 L capacity)	1	USQ or private laboratory^	0.00
Wheelbarrow (approximately 120 L capacity)	1	Student	0.00
Slump test kit (includes cone, plate, tamping rod, scoop and ruler/measuring tape)	1	USQ or private laboratory^	0.00
Concrete cylinder moulds (100 mm diameter)	24	USQ or private laboratory^	0.00
Flexure specimen moulds	6	USQ or private laboratory^	0.00
Mould oil	0.5 L	USQ or private laboratory^	0.00
Timber float	1	USQ or private laboratory^	0.00
Cleaning equipment (buckets, sponge and rags)	1	Student	10.00
Waterproof paint marker for specimen labelling	2	Office works	10.00
Old towels	2	Student supply	0.00
Curing tank meeting requirements of AS1012.8.1	1	USQ or private laboratory^	0.00
Concrete compression machine and load measuring device	1	USQ or private laboratory^	0.00
Three-point compression machine and load measuring device	1	USQ or private laboratory^	0.00
Vernier callipers for measuring specimen dimensions (accuracy 0.1 mm)	1	USQ or private laboratory^	0.00
Scanning Electron Microscope	1	USQ	0.00

Notes: *Estimated value as final quantity will depend on PSD and batch design.
^I worked for a number of years at a soil and concrete testing laboratory and can get access to lab and equipment if required.