Investigation of Treated Incinerated Bottom Ash (IBA) as Fine Aggregate Replacement in Structural Concrete – from Waste to Construction Material

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Abstract

With the shortage of sand and its ever-increasing needs for urbanisation due to concreting, researchers have been seeking alternative materials to replace natural sands in concrete. Among the potential fine aggregate alternatives is the cement-treated Incinerated Bottom Ash (IBA), which is a granular byproduct of incinerating municipal solid waste. However, leaching of hazardous substances from untreated IBA is a major issue that hinders its usage in engineering applications. In this study, treated IBA (GO-IBA™) was adopted, where the pollutants are encapsulated within the pellet structure, hence reducing the leaching of hazardous substances.

This work aims at experimentally investigating the effects of replacing natural fine aggregates in structural concrete with treated and untreated IBA on fresh properties, hardened properties and durability. Secondly, in order to reduce the reliance on natural sands, the performance of concrete mixes using manufactured sand with IBA replacement is also assessed. Moreover, to further bring down the CO2 emissions during concrete production, the feasibility of replacing fine aggregates with IBA in concrete using blended cement is also experimentally studied.

Accordingly, experimental investigations on four series of speimens were carried out: (1) C Sand mixes with rIBA – untreated IBA (rIBA) replacing natural sand (C Sand) with OPC as binder, (2) C Sand mixes with GO-IBA™ – treated IBA replacing C Sand with OPC as binder, (3) M Sand mixes with GO-IBA™ – treated IBA replacing manufactured sand (M Sand) with OPC as binder, and (4) PBFC mixes with GO-IBA™ – treated IBA replacing M Sand with CEM III/B cement as binder. In each test series, fine aggregate replacement levels were set at increments of 25% to study the effects better. Different test are employed to study the individual concrete properties which are categorised into three main properties: (1) Fresh properties (slump, bleeding, setting time and air pore content), (2) Hardened properties (compressive strength test and modulus of elasticity (MOE) test) and (3) Durability properties (water penetration (WPT), water absorption (WAT), rapid chloride penetration test (RCPT) and accelerated carbonation test.

The test results show that using untreated IBA to replace fine aggregates leads to inferior workability, significantly reduced mechanical properties and degraded durability, making it not suitable as a fine aggregate replacement for structural concrete.

When using treated IBA as the fine aggregate replacement (for both C Sand mixes and M Sand mixes), the workability still tends to reduce with the replacement level, possibly due to the porous nature and high water absorption properties of GO-IBA™, while the compressive strength exhibits insignificant reduction till 75% replacement level. In terms of durability, both the C Sand mixes and M Sand mixes with treated IBA replacement show improved water penetration depths till 75% replacement level and better RCPT and accelerated carbonation test results till 100% replacement level. Nevertheless, increasing the treated IBA replacement level leads to higher water absorption, which affects the workability of the mix and yields higher air pore content. In this work, it is also found that pre-wetting of the GO-IBA™ results in improved workability and compressive strength development.

In the last series of the test, with the addition of Ground Granulated Blast furnace Slag(GGBS) as the binder, most of the fresh properties were improved over the cement counterparts (M Sand mixes), except for the delayed setting time due to the longer hydration time involving GGBS. Hardened properties of the PBFC mixes with GO-IBA™ remain broadly similar in trend to the cement counterpart. In terms of durability, the WAT and WPT results exhibit degraded performance compared with the cement counterparts, due to the longer hydration time needed for GGBS. RCPT results remain similar in trend, while accelerated carbonation test results show poorer performance than the cement counterparts.

Keywords: Cold-bonded palletisation, Waste, Incinerated Bottom Ash, Concrete, Aggregates replacement.

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Author's Declaration

I hereby declare that this dissertation is my original work and that it has been written by me in its entirety and has not been submitted for any degree in any university previously. I have acknowledged all the sources of information which have been used.

Abbreviations

ASR	Alkali Silica Reaction
BCA	Building and Construction Authority
CIBA	Cold-bonded Palletized Aggregates
Ecm	Elastic Modulus
FA	Fly Ash
GGBS	Ground Granulated Blast Furnace Slag
GO-IBA™	treated IBA
IBA	Incineration Bottom Ash
IC	internal curing
IFA	Incineration Fly Ash
ITZ	Interfacial Transition Zone
LOI	Loss On Ignition
LWA	lightweight aggregate
MOE	Modulus of Elasticity
MSW	Municipal Solid Waste
NEA	National Environment Agency
OPC	Ordinary Portland Cement
PSD	particle size distribution
RCPT	Rapid Chloride Penetration Test
SCC	Self-Compacting Concrete
SSD	Saturated Surface Dry

URA	Urban Redevelopment Authority
WP	Water permeability
WC	water/cement

Chapter 1 - Introduction

Singapore is a highly urbanised and densely populated country. According to the National Environment Agency (NEA), a total of around 5.88 million tonnes of Municipal Solid Waste (MSW) was generated nationwide in 2020, which translates to MSW generation per capita of approximately 1 ton per year (NEA, 2020). Incineration is an efficient method for waste management since it significantly reduces waste volume and weight, together with the benefit of thermal energy production (Teo, V., 2002). It is estimated that approximately 1,500 tonnes of Incineration Bottom Ash (IBA) and 300 tonnes of Incineration Fly Ash (IFA) are produced every day in Singapore.

1.1 Landfilling

As both IBA and IFA contain toxic heavy metals such as lead, cadmium, chromium, and arsenic, they are classified as hazardous (Teo, V., 2002) and are mandated to be landfilled (NEA, 2020).

Costing 610 million Singapore dollars to build in 1999, Pulau Semakau was the first offshore landfill in the world. It was deliberately chosen to be offshore due to the land constraints in mainland Singapore, which is still an existing problem that the government faces. As shown in Figure 1.1, Pulau Semakau is being filled up at a significant rate. It is expected to be filled up by 2035 (Zero Waste City, 2020), 10 years earlier than the originally expected filled-up date of 2045 (Cua, G., 1993).

Figure 1.1: Time-lapse satellite images of Pulau Semakau from 2000 to 2019 (Zero Waste City, 2020)

To relieve the landfill burden on Pulau Semakau, the Singapore government has introduced a policy goal to become a Zero Waste Nation, aiming to reduce the daily waste sent to Semakau Landfill by 30% by 2030. The waste problem is not exclusive to Singapore, and it is a global problem (See Figure 1.2). The world generates 2.01 billion tonnes of MSW annually. This figure is expected to rise to 3.4 billion tonnes by 2050 (Kaza *et al.*, 2018).

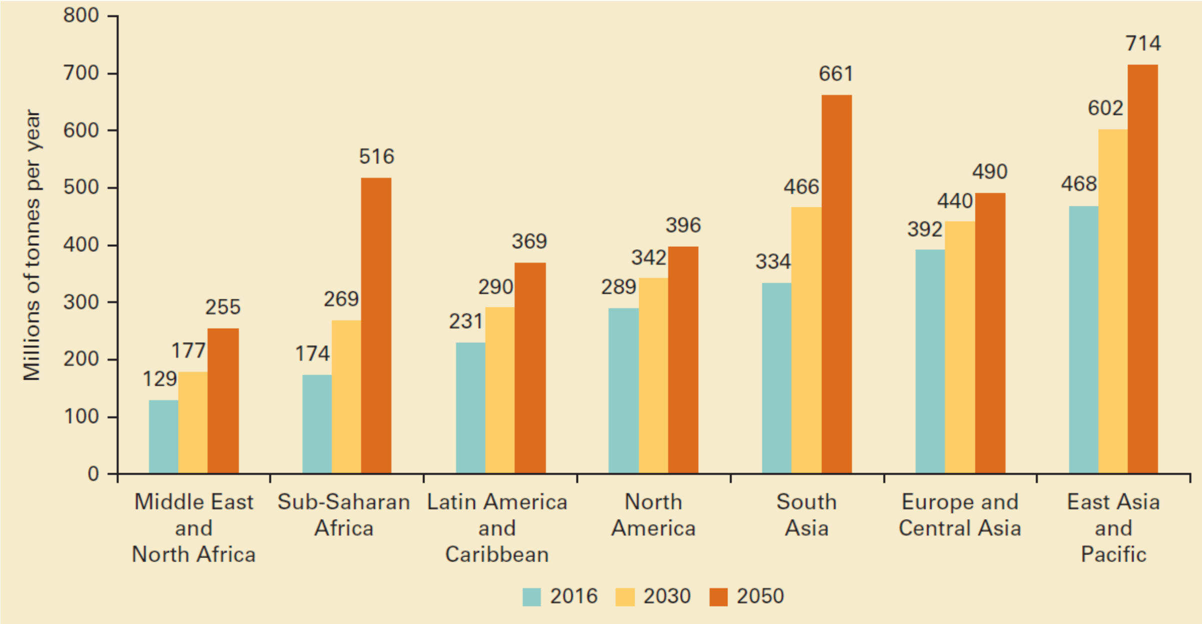


Figure 1.2: Waste generation per annum by global regions (Kaza et al., 2018)

1.2 IBA as Aggregates

According to the 2013 Population White Paper, Singapore's total population will increase from the current 6.04 million to 6.5 - 6.9 million by 2030 (National Population and Division, 2024). This projected population growth is expected to cause a substantial rise in concrete demand, as new infrastructure will be required to accommodate the expanding population. To support this growth, Singapore has used over 500 million tonnes of aggregates in the past 20 years, most of which were imported from other countries. The source of non-renewable natural aggregates from both local and distant regions are depleting rapidly, while the demand for aggregates continues to rise (Edwards, B., 2015).

In consideration of the landfill constraint and the shortage of natural resources, replacing natural aggregates in concrete with Incinerator Bottom Ash (IBA) holds considerable research significance, which may not only reduce the dependence on imports of natural aggregates but also alleviate the environmental burden caused by municipal wastes.

However, IBA in its raw form contains hazardous materials, such as lead, cadmium, zinc, and copper, which may leach out and contaminate surrounding environments. Furthermore, many previous studies have found that the usage of untreated IBA in concrete also leads to inferior concrete properties (Lynn *et al*., 2016; Pera *et al*., 1997; Dhir *et al*., 2003). Accodingly, IBA is ready to be used as an aggregate alternative only if a suitable treatment is given to help reduce the leachability of harmful substances from it.

Many treatment methods have been proposed in recent decades to reduce the leachability of hazardous materials in IBA, among which Cold-Bonded Pelletisation is an emerging and sustainable method which is particularly suitable for converting the treated IBA into artificial aggregates for construction use due to its superior grain size control. Cold-bonded palletised aggregates consume lower energy, low carbon emissions, and low cost, making it an advantageous process (Tara *et al.*, 2019). Many other authors also had varying success utilising cold-bonded palletisation for treating IBA (Tang and Brouwers, 2018; Liu *et al.*, 2022a; Liu *et al.*, 2022b; Li *et al.*, 2023).

1.3 Research Objective

This study aims at experimentally exploring the material behaviour of concrete with fine aggregates being replaced with treated IBA, where the focus is on the fresh properties, hardened properties and durability properties. Based on the test results, the feasibility of using concrete with treated IBA in structural concrete will be assessed. Among various treatment methods, cold-bonded pelletisation is a low-temperature process that is more energy- and cost-saving and has superior grain size control. Accordingly, in this work, the treated IBA using cold-bonded pelletisation is to be studied due to its cost and size control advantages.

The main objectives of the research are summarised as follows:

- To experimentally examine the physical and chemical properties of untreated and treated IBA samples, and assess the feasibility of using treated IBA in construction applications;
- To evaluate the influence of replacing fine aggregates with treated IBA on fresh properties, mechanical properties and durability properties of three different concrete type:
    - Type 1: normal concrete using Portland cement and natural river sand (C Sand);
    - Type 2: sustainable concrete using Portland cement and manufactured sand (M

Sand);

- Type 3: a more sustainable concrete using Portland cement blended with GGBS as the cementing material and manufactured sand (M Sand) as fine aggregates.

- To provide recommendations on an optimal fine aggregate replacement percentage for the concrete mixes in order to be used as a structural concrete that preserves good workability, strength and durability.

1.4 Outline of Dissertation

Each chapter is dedicated to each main theme. Details of the works as follows;

Chapter 2 is a bibliographic review of studies related to untreated and treated IBA. References are selected to provide as wide a coverage as possible. Gaps in knowledge are brought up in this chapter.

Chapter 3 outlines the research methodology with a detailed explanation of why the test method was chosen. A summary of the materials used in this study, as well as their properties and techniques, with reference made to applicable codes and specifications used to obtain the properties.

Chapter 4 is the core of the thesis, which is directed at the evaluation of the effects on concrete properties of aggregate replacement with untreated and treated IBA by employing different experimental techniques. Results of the investigation are presented and explanations are given.

Chapter 5 presents an extension to the previous chapter by incorporating Ground Granulated Blast Furnace Slag (GGBS) blended cement with the treated IBA. Here, the effects of cement replacement are investigated and presented.

The conclusion of the work is summarised in ***Chapter 6***, along with the recommendations for future work.

Chapter 2 - Literature Review

2.1 General

In this chapter, an overview of the physical and chemical properties of untreated IBA is first presented, followed by a summary of previous studies investigating concrete in which fine aggregates were replaced with untreated IBA. Subsequently, the cold-bonded pelletisation method for IBA treatment and the resulting physical and chemical properties of the treated material are discussed. The chapter also reviews the current state of research on the use of treated IBA in concrete. Finally, concluding remarks are provided to summarise the literature review and identify the research gaps to be addressed.

2.2 Physical and Chemical Properties of Untreated IBA

Incinerator Bottom Ash (IBA) is the main solid residue from waste incineration plants, which consists of inert materials such as sand, glass, ceramics and metals. The physical and chemical properties of untreated IBA have been studied in the past decades.

In the work of Lynn et al. (2016), the physical properties of untreated IBA were reported based on 14 samples. The bulk density was measured at 1400kg/m3, and an average specific gravity was found to be 2.32. Lynn et al. (2016) postulated that the irregularity in morphology results in a higher specific surface area of IBA compared to natural sand, resulting in higher water absorption. This observation supported the findings by Tay, J.H. (1988), who reported a 2.5 times higher water absorption of IBA compared to natural aggregates.

In the experimental work of Lynn et al. (2016), the chemical composition of untreated IBA was also reported, with the key results given as follows: SiO_2 37.5%, CaO 22.2%, Al_2O_3 10.3%, Fe_2O_3 8.1%, Na_2O 2.9%, SO_3 2.4%, P_2O_5 2.4%, MgO 1.9% and K_2O 1.4%. A similar range is also reported in the work conducted by Siakia et al. (2008). In addition, in the work of Lynn et al. (2016), a high SO_3 content of 2.4% was reported, indicating the potential for deleterious expansion when used in combination with cement.

The presence of anhydrite and gypsum may cause delayed ettringite formation when used in conjunction with cement (Saikia et al., 2008). The emission of hydrogen gas due to the reaction of metallic aluminium in the IBA and aqueous $Ca(OH)_2$ released by cement during the hydration phase has been reported to increase the porosity of concrete, which could lead to other durability problems (Pera et al., 1997). Additionally, due to the presence of waste glass in IBA, concerns regarding Alkali-Silica Reaction (ASR) have been expressed (Muller & Rubner, 2006).

2.3 Concrete with Untreated IBA as Fine Aggregate Replacement

In this section, previous experimental studies on concrete with untreated IBA as the fine aggregate replacement are reviewed, with the influence of using untreated IBA on the fresh, hardened and durability properties summarised in sub-sections 2.3.1-2.3.3, respectively.

2.3.1 Influence on Fresh Properties

In the experimental study conducted by Tay, J.H. (1988), compared to natural fine aggregates, untreated IBA tends to absorb more water, resulting in a reduction in slump and bleeding. Hu *et al.* (2010) also reported similar findings of higher water absorption of 6.62% and 2.75% for both coarse and fine fractions of IBA, respectively. Loss in flow was reported in the works of Cheng *et al.*(2011) detailing the high water absorption of IBA.

Regarding the setting time, considerable variation in opinions persists among researchers. In the research work of van der Wegen *et al.* (2016), it was found that concrete with untreated IBA as fine aggregates led to a prolonged setting time of 3 hours, possibly owing to the interference from zinc and lead in the IBA. Tay J.H. (1988) observed prolonged delays in setting up, which lasted up to 10 days, resulting from the high loss on ignition (LOI). Cheng *et al.* (2011) also reported higher setting time and found that the higher C_3A content may have contributed to the observed phenomenon. On the other hand, Dhir *et al.* (2002) found that no such significant delays were observed. These discrepancies may stem from differences in the source of the IBA as well as the pretreatment method employed.

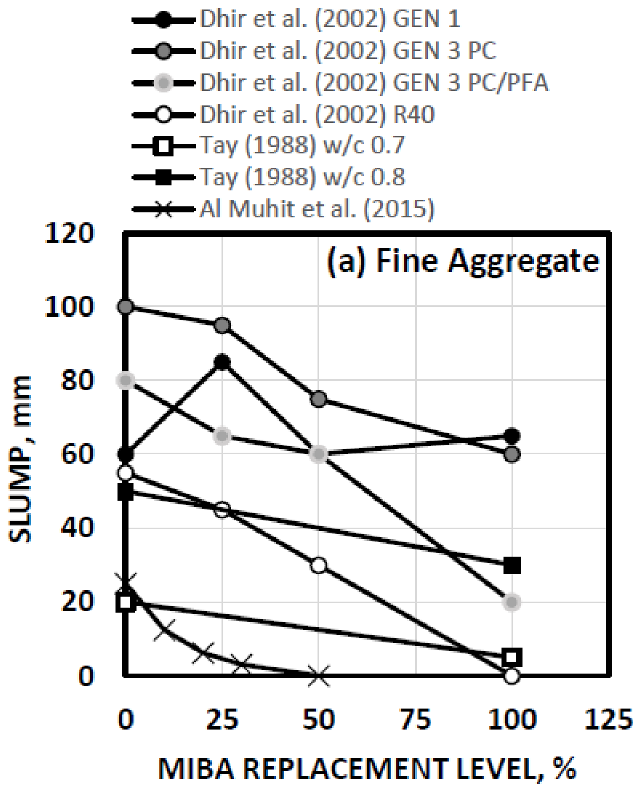


Figure 2.1: Slump value in relation to IBA replacement level (Ciarán J. Lynn, 2016)

2.3.2 Influence on Hardened Properties

IBA as a fine aggregate replacement was reported to cause a notable reduction in compressive strength as the replacement level increases. To address this issue, researchers such as Dhir *et al.* (2002) applied pre-treating method, i.e., washing the IBA, to remove organics, salts, and metals that were detrimental to strength development. However, as shown in Figure 2.2, although washing improved the compressive strength, the reduction relative to the control mix remains considerable. A similar trend of the decline in strength is also reported for flexural and tensile strength by van der Wegen (2013).

It is reported by Saikia *et al.* (2015) that the possible reason for the reduction in concrete strength could be due to the high LOI of IBA. The deleterious carbonaceous materials which may affect the cement hydration of the concrete. On the other hand, Pera *et al.* (1997) reported that the emission of hydrogen gas produced during OPC hydration causes cracks in the concrete due to the reaction of metallic aluminium present in the IBA with the aqueous calcium hydroxide (portlandite). Therefore, it is unclear whether the degradation of hardened properties of IBA-replaced natural fine aggregate concrete is due to a single factor or a combination of factors.

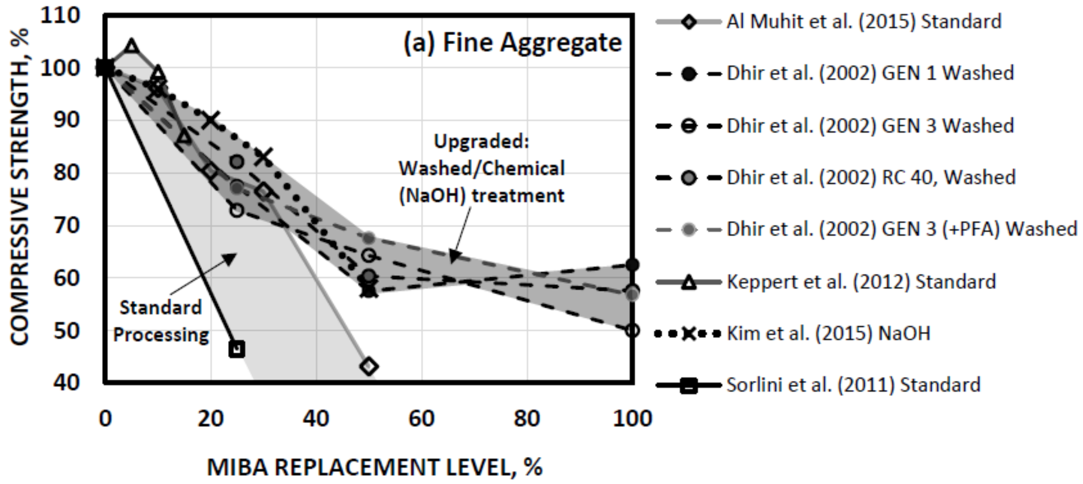


Figure 2.2: Compressive strength in relation to standard and pre-treated MSWIBA replacement level (Ciarán J. Lynn, 2016)

2.3.3 Influence on Durability Properties

As mentioned in Section 2.2, the chemical composition of untreated IBA introduces deleterious substances such as heavy metals when used in a concrete matrix. Pera *et al.* (1997) reported that the reaction of metallic aluminium with aqueous $Ca(OH)_2$ caused a significant emission of hydrogen, which introduces cracks into the matrix, thereby weakening the system. Müller and Bubner also reported that this reaction could proceed long after the concrete hardens when moisture is present, increasing the risk of spalling (2006). The elevated porosity, which leads to higher water penetration and absorption with increasing untreated IBA replacement levels, was also reported in the works of Al Muhit *et al.* (2015) and Dhir *et al.* (2002).

The elevated porosity, coupled with the high reactive silica present in the untreated IBA, also increased the potential for ASR reaction, which is potentially detrimental for structural purposes (Müller & Rubner, 2006).

It is clear that the high chloride content present in the IBA poses an obstacle for the use of concrete with steel reinforcement as the chloride diffusion coefficient increased from 13.6×10^{-12} m^2/s to 18.0×10^{-12} m^2/s with just 20% of coarse aggregate replacement with washed IBA (van Der Wegen, 2013). Zermeño *et al.* (2017) also reported that the risk of steel rebar corrosion is very high as the chloride level reaches critical levels and deterioration of the passive layer of the steel rebar is initiated.

van der Wegen *et al.* (2013) reported that the carbonation depth decreased from 3.5 mm to 2.6 mm for a 20% coarse aggregate replacement with IBA. It was also reported that the IBA resulted in high water absorption, competing with the available moisture, thereby slowing the rate of carbonation, as carbonation requires aqueous $Ca(OH)_2$ to convert to carbonic acid.

2.4 Treated IBA Using Cold-Bonded Pelletisation

2.4.1 Cold-Bonded Pelletisation

IBA, in its untreated form, poses several challenges when used as aggregates in concrete due to the leaching of deleterious substances. Several treatment methods have been developed to reduce the deleterious materials in it, including: (1) washing, (2) magnetic separation, (3) carbonation, (4) chemical extraction, (5) sintering and (6) cold-bonded pelletisation.

In recent years, cold-bonded pelletisation is gaining traction, as it generates fewer waste streams compared to other methods, such as washing (Poranek *et al.*, 2021). Additionally, cold-bonded pelletisation is effective in impeding the leaching of deleterious substances and has lower energy consumption when compared to methods such as sintering.

Cold-bonded pelletisation employs a disc palletiser, and the whole procedure is broken into two stages. As illustrated in Figure 2.1, in the first stage, all dried materials, including IBA and cement, are thoroughly mixed in Zone 1; while in the second stage, water is added to form granules, followed by the final addition of cement, resulting in the formation of pellets in Zone 2 (Tang & Brouwers, 2018).

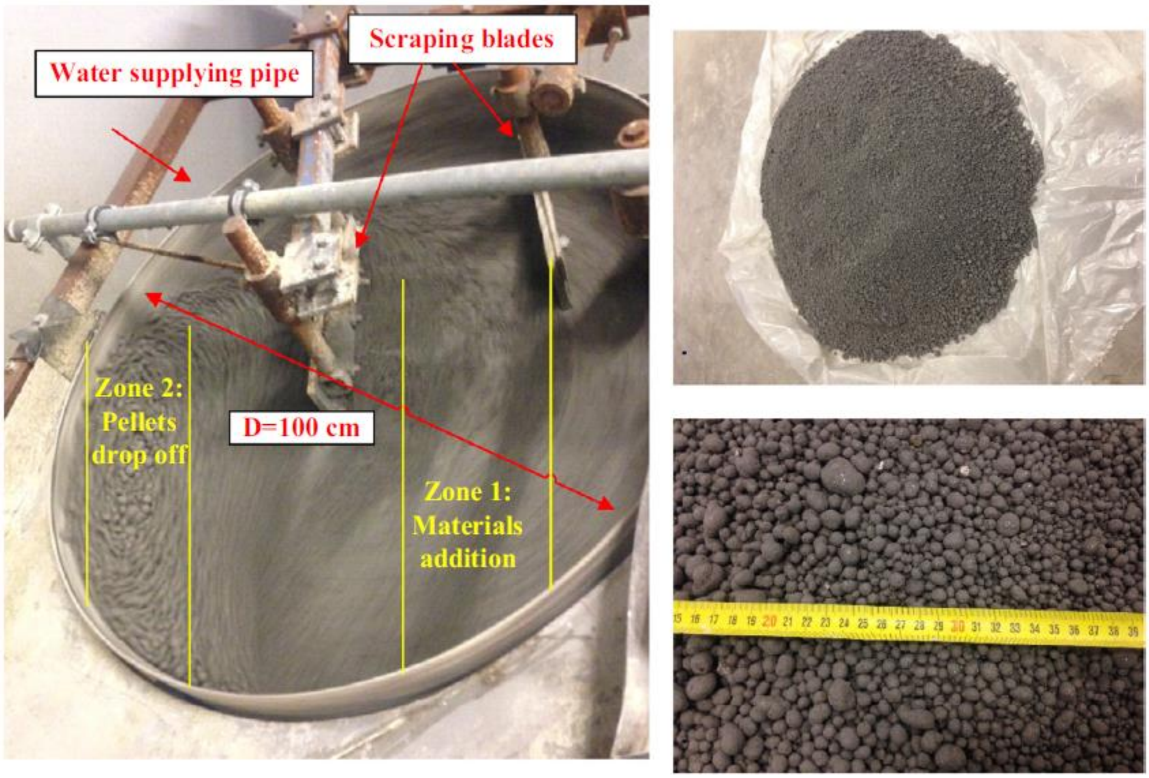


Figure 2.3: Process of artificial aggregates produced using cold-bonded pelletisation technique in concrete applications (Tang & Brouwers, 2018)

2.4.2 Physical and Chemical Properties of IBA Treated by Cold-Bonded Pelletisation

Li *et al.* (2023) experimentally investigated the physical and chemical properties of IBA treated by cold-bonded pelletisation. From the test results, treated IBA exhibited water absorption values ranging from 15.3% to 18.4%, which are comparable to those of untreated IBA. The specific gravity of treated IBA was between 1.56-1.72, with its bulk density slightly below 1 g/cm³. Li *et al.* (2023) also conducted water absorption tests on treated IBA, where in material preparation, they maintained the treated IBA in a surface-saturated, dry condition to preserve adequate workability. This decrease in specific gravity after IBA treatment is due to the lower density of cement coating in comparison with the density of IBA. Accordingly, in the coating process the overall density of the treated IBA is decreased.

In terms of the chemical composition, the addition of cementitious materials through cold-bonded pelletisation inevitably changes the chemical composition of IBA. However, there is no available detailed chemical composition of treated IBA using cold bonded palletisation. Nevertheless, the reduction in chloride ions has been studied by Li *et al.* (2023), who reported that the free state of chloride ions in untreated IBA is high, but it reduces drastically in treated IBA. The chloride ions in the treated IBA were reported to have either converted into a more stable form, such as Freidel's Salts, or leached out during the curing phase after the treatment, before the use in concrete mixing.

2.4.3 Concrete with IBA Treated by Cold-Bonded Pelletisation

A few research studies have used IBA treated by cold-bonded pelletisation to replace coarse aggregates in concrete, including Liu *et al.* (2022a), Liu *et al.* (2022b), and Tang and Brouwers (2018).

In terms of fresh properties, Tang and Brouwers (2018) investigated the treated IBA in SCC mixes and concluded that the replacement of coarse aggregates with treated IBA with particle sizes ranging from 4-12mm had no significant impact on flow ring test results. They also stated that cold-bonded palletised aggregates (CIBA) reduced the viscosity of concrete, which is associated with strength. However, Güneyisi *et al.* (2015) reported a decrease in V-funnel flow timing in relation to increasing replacement levels. This contradicts the works of Tang & Brouwers (2018), which show no significant impact on the flow ring results.

In terms of hardened properties, concrete with treated IBA as coarse aggregate replacement exhibits a trend of strength reduction similar to untreated IBA counterparts, with many authors reporting consistent strength reductions in relation to the replacement level (Liu *et al.*, 2022a; Tang *et al.*, 2018). This finding was also consistent with the results of the tensile splitting test. Liu *et al.* (2022b) also reported on the relationship between the bulk density and strength, where higher bulk density led to higher strength. Although the sources of treated IBA were different and applications were diverse in the realm of concrete, similarities were observed that the higher the replacement level, the lower the concrete strength.

In terms of durability, Tang and Brouwers (2018) conducted water penetration tests and observed that the water penetration depth increased with increasing replacement level. However, contradicting findings were found in the work of Li *et al.* (2023), where a reduction in water absorption with increasing the replacement level was reported. The contradictory findings between the two authors could be attributed to the moisture state of the treated IBA used, as Li *et al.* (2023) chose to keep the treated IBA in a saturated surface dry (SSD) state.

Liu *et al.* (2022a) conducted carbonation tests on concrete with coarse aggregates replaced with treated IBA, and they observed an elevated carbonation rate as the replacement level increased, and attributed the phenomenon to the high porosity of treated IBA, which allows the CO_2 to travel through the aggregates.

Both Liu *et al.* (2022b) and Li *et al.* (2023) report a decrease in chloride diffusivity, but with two different explanations. Li *et al.* (2023) reported that the interfacial transition zone (ITZ) between the treated IBA and the cement matrix was essentially integrated with no gaps. Liu *et al.* (2022b) supplement this by reporting that the refinement of pores in treated IBA, which replaced concrete with increasing replacement levels, led to a decrease in transitional pores, resulting in lower chloride penetration.

2.5 Concluding Remarks

2.5.1 Summary

In this chapter, an overview of the properties of untreated and treated IBA, along with their applications in concrete, has been reviewed.

When untreated IBA replaces natural sand in concrete, it typically causes reduced slump and bleeding due to high water absorption, reduced compressive, flexural, and tensile strengths largely because of high loss on ignition (LOI) and gas evolution from metallic aluminium. The durability of such concretes is also compromised: higher porosity and chloride content tend to increase water absorption and steel corrosion. Although carbonation depth may decrease slightly, the overall durability performance remains poor. Furthermore, untreated IBA contains toxic elements such as lead, cadmium, zinc, and copper, which pose a risk of leaching and environmental contamination. With many previous studies reporting numerous detrimental effects of untreated IBA usage in concrete, it is concluded that untreated IBA is unsuitable for direct usage in concrete applications, and there is a need for the treatment of IBA before any usage in concrete applications.

There are a few treatment methods developed to overcome the limitations of untreated IBA, particularly on the environmental aspect. Among different methods, cold-bonded pelletisation is energy-efficient and environmentally friendly, which adds cement to dried IBA to form and harden uniform-sized pellets. It was found from previous studies that the free state of chloride ions in this treated IBA drastically reduces in comparison with untreated IBA, hence making it a promising aggregate substitute.

2.5.2 Research Gap

The treatment of IBA using cold-bonded pelletisation is relatively new, as publications on this topic have only emerged recently. It is worth noting that the available literature on the concrete applications using treated IBA is limited to coarse aggregate replacement only.

Moreover, from the available literature on concrete with coarse aggregate replaced with treated IBA using cold-bonded pelletisation, it was found that the concrete strength still shows a general decrease pattern as the replacement level increases, which may hinder its application to structural concrete.

From the author's opinion, coarse aggregates contribute much more to the hardness, stiffness, and strength of concrete, in comparison with fine aggregates, though both play important but different roles. Accordingly, replacing fine aggregates in concrete with treated IBA represents a more theoretically sound approach. On one hand, treated IBA can replace fine aggregates and reduce the dependence on imports of natural aggregates; on the other hand, the natural coarse aggregate with superior strengths and stiffnesses can still help maintain the desirable mechanical properties of concrete. However, there has not been any research in this area so far, possibly due to the previous manufacturing limitations on the pelletisation procedure, which made it challenging to manufacture pellets with sizes smaller than 4mm. This indicates a research gap to be addressed in order to promote the use of treated IBA in structural concrete applications.

Recently, with the advances in technology, cold-bonded pelletised IBA with smaller sizes has become available in the market. Therefore, it is worthwhile to experimentally investigate the performance of concrete incorporating cold-bonded pelletised IBA as a replacement for fine aggregates, which will provide useful guidance for the development of new sustainable structural concrete.

Chapter 3 - Experimental Programme

This chapter was categorised into two sections: (1) Section 3.1 presents the apparatus and techniques used for the measurement of the concrete properties, with an explanation of the experimental methods. (2) Section 3.2 shows the material relevant to this study.

3.1 Experimental Overview

The objective of the experiment is to investigate the concrete properties when treated IBA is used as a fine aggregate replacement for structural concrete. The experimental programme is designed to assess both the short-term performance and durability of the concrete. The observations from this study will provide valuable insight into the effect of GO-IBA™ replacement in structural concrete applications. Multiple angles of the possible use cases of GO-IBA™ would be simulated, including the replacement of current incumbent fine aggregates and the use of different cement types. Results observed from the individual concrete properties tested will be examined, and a favourable replacement dosage will be recommended.

3.1.1 Testing Methods

Concrete properties will be divided into four broad categories:

(1) Aggregate properties - properties that govern the aggregates characteristics.

(2) Fresh Concrete properties – properties that govern the fresh state of concrete.

(3) Hardened Concrete properties – properties that govern the hardened state of concrete.

(4) Durability of Concrete – properties that govern the long-term properties of the concrete against weathering elements.

The detailed properties of concrete are tested based on standardised European Standard (EN) or American Standard Testing Methods (ASTM) outlined in Table 3.1 to ensure high repeatability and comparability.

Table 3.1

List of concrete properties test

	Properties	Test Methods
Aggregate Properties	Sieve Analysis	EN 12620:2008
	Particle Density and Water Absorption	EN 1097-6:2013
Fresh Concrete Properties	Slump test	EN12350-2:2019
	Setting time	ASTM C403/403M-23
	Air content	EN 12350-7:2019
	Bleeding	EN 480 -4:2005
Hardened Concrete Properties	Compressive Strength	EN 12390-2
	Modulus of Elasticity	EN 12390-13
Durability of Concrete	Water absorption test	BS 1881 – 122:2011
	Water Penetration Test	EN 12390-8
	Rapid Chloride Permeability Test	ASTM C1202
	Accelerated Carbonation test	EN 12390-13

3.1.2 Design Mix

The experimental programme consists of four discrete series, each exploring different combinations of binder type and sand replacement material as shown in Table 3.2. This setup enables a comprehensive evaluation of the influence of binder type or sand replacement material on concrete performance.

Conventionally, concrete is mixed with only OPC as a binder, and the fine aggregates used are river sand, also known as C Sand. However, the rate of use of C Sand outpaces the rate of its natural replacement rate, leading to the use of manufactured sand (M Sand), which is derived from the crushing of granite into sand fractions for use as a sustainable alternative. Therefore, the effect of partial substitution on M Sand will also be investigated due to the trend in using this material as a fine aggregate.

The use of supplementary cementitious materials (SCM) is primarily driven by environmental concerns regarding the production of OPC, which produces about 1 ton of CO_2 per ton of OPC. SCMs are mainly used as a partial replacement for OPC, which originated from industrial waste, such as fly ash from the coal combustion of an electrical power plant and ground granulated blast-furnace slag (GGBS) from the steel industry. SCMs not only provide a green alternative to OPC but also offer excellent chemical resistance due to the denser C-S-H structures they form, as well as economical savings. Therefore, the performance of concrete with GGBS as the SCM will also be investigated in this research.

Commonly in the field, structures that require resistance to environmental factors, such as the marine and underground environment, require concrete that has CEM III equivalent cement, which is Portland cement blended with >65% GGBS in accordance with EN196-1, known as Portland blended furnace cement (PBFC). Nowadays, due to the Paris Agreement on climate change, the demand for sustainable materials in the built environment is increasing, driving the popularity of concrete incorporating CEM II or CEM III equivalent cement. This allows building developers to achieve greener incentives under the Singapore Green Building Council (SGBC) certificate scheme.

A baseline study on replacing natural aggregates with untreated IBA was conducted to better understand the risk of using untreated IBA for concrete application. This study underscores the need for further research in this area, given the potential implications for the construction industry and the materials science field, as well as the need for sustainable and efficient construction materials.

Table 3.2

Mix series details

Series	Mixes known as	Binder type	Sand Type Replaced	Replacement Material	Replacement Level (%)
1	rIBA Mixes	OPC	C Sand	rIBA	0, 25, 50, 75, 100
2	C Sand Mixes	OPC	C Sand	GO-IBA™	0, 25, 50, 75, 100
3	M Sand Mixes	OPC	M Sand	GO-IBA™	0, 25, 50, 75, 100
4	PPBFC Mixes	PBFC	M Sand	GO-IBA™	0, 25, 50, 75, 100

The concrete mix is designed to be in the S4 range in accordance with EN 206:2013. The replacement level will be based on volumetric replacement levels instead of weight replacement due to the difference in rIBA and the GO-IBA™ density compared to natural aggregate. In comparison, the density of natural aggregate is approximately 2.64 g/cm³, compared to GO-IBA™ density, which is approximately 1.98 g/cm³. Hence, any direct replacement by weight will increase the final concrete volume, making the study non-comparable. The replacement level is set at 25% increments to better study the effects of replacing natural fine aggregates.

The mix design utilised is shown in the tables below;

Table 3.3

Series 1 mix using untreated IBA as replacement for natural sand in OPC mixes

Content of rIBA mix		Sample Name				
		R0	R25	R50	R75	R100
Fine aggregates replacement level (%)		0	25	50	75	100
Binder (kg/M^3)	OPC	400.00				
	GGBS	0.00				
Fine Aggregates (kg/M^3)	rIBA	0.00	77.70	155.30	233.00	310.60
	M Sand	0.00				
	C Sand	820.00	615.00	410.00	205.00	0.00
Coarse Aggregates (kg/M^3)	20mm	930.00				
Admixture (kg/M^3)	N200	4.00				
Mixing Water (kg/M^3)	Water	170.00				

Table 3.4

Series 2 mix using GO-IBA™ *as a replacement for natural sand in OPC mixes*

Content of C sand Mix		Sample Name				
		C0	C25	C50	C75	C100
Fine aggregates replacement level (%)		0	25	50	75	100
Binder (kg/M^3)	OPC	400.00				
	GGBS	0.00				
Fine Aggregates (kg/M^3)	GO-IBA™	0.00	147.54	295.08	442.61	590.15
	M Sand	0.00				
	C Sand	820.00	615.00	410.00	205.00	0.00
Coarse Aggregates (kg/M3)	20mm	930.00				
Admixture (kg/M3)	N200	4.00				
Mixing Water (kg/M3)	Water	170.00				

Table 3.5

Series 3 mix using GO-IBA™ *as a replacement for Manufactured Sand in OPC mixes*

Content of M Sand Mix		Sample Name				
		M0	M25	M50	M75	M100
Fine aggregates replacement level (%)		0	25	50	75	100
Binder (kg/M^3)	OPC			400.00		
	GGBS			0.00		
Fine Aggregates (kg/M^3)	GO-IBA™	0.00	147.54	295.08	442.61	590.15
	M Sand	820.00	615.00	410.00	205.00	0.00
	C Sand			0.00		
Coarse Aggregates (kg/M^3)	20mm			930.00		
Admixture (kg/M^3)	N200			4.00		
Mixing Water (kg/M^3)	Water			170.00		

Table 3.6

Series 4 mix using GO-IBA™ as a replacement for Manufactured Sand in PBFC mixes

Content of PBFC Mix		Sample Name				
		P0	P25	P50	P75	P100
Fine aggregates replacement level (%)		0	25	50	75	100
Binder (kg/M^3)	OPC			120.00		
	GGBS			280.00		
Fine Aggregates (kg/M^3)	GO-IBA™	0	147.54	295.08	442.61	590.15
	M Sand	820.00	615.00	410.00	205.00	0.00
	C Sand			0.00		
Coarse Aggregates (kg/M^3)	20mm			930.00		
Admixture (kg/M^3)	N200			4.00		
Mixing Water (kg/M^3)	Water			170.00		

3.1.3 Curing Conditions

As stipulated in SS: EN 206, all concrete samples are cured under water at 27 $^oC \pm 2\ ^oC$.

Tests were conducted at earlier ages, such as 3 days, which was relevant to the prevailing use of precast members in the built environment of Singapore. This precast member usually will require faster strength development, as the turnaround time for production is short.

Longer test ages at 91 days were used to compare the mixes that utilise GGBS, as the latent hydraulicity of GGBS will result in a much slower hydration rate than OPC.

The majority of the curing ages for the test follow the specified test ages in accordance with the respective standards to ensure reproducibility and comparable results.

Table 3.7

Curing Ages for test done

Type of test	The Mix series involved	No. of days cured before testing
Compressive Strength Test	1, 2, 3, 4	3, 7, 28, 91
Modulus of Elasticity	2, 3, 4	28
Water absorption test	2, 3, 4	28
Water Penetration Test	1, 2, 3, 4	28
Rapid Chloride Penetration Test	1, 2, 3, 4	56
Accelerated Carbonation Test	3, 4	28

3.1.4 Test Methods

3.1.4.1 Sieve Analysis

Aggregates are defined in two categories: fines (size <4mm) and coarse (size >4mm). Grading of aggregates will be done in accordance with EN 12620:2008.

Grading of the aggregates will be determined with the use of a sieve shaker with a series of standard sieves with different size openings, ranging from the largest opening at the top to the smallest opening at the bottom. The sieving sizes are as follows in Table 3.8.

Table 3.8

List of sieve openings for aggregate particle size analysis

Aggregate Types	Coarse	Fines
	28	4
	20	2
Sieve openings (mm)	10	1
	5	0.25
	2.5	0.063

3.1.4.2 Particle Density and Water Absorption

As GO-IBA™ is less dense than the natural aggregates that it will be replacing with, direct placement by weight of natural aggregates will have a profound effect on the volume of the aggregates, which in turn affects the binding ability of the cement paste. Therefore, it is important that the density is determined before usage.

As stipulated in EN 1097-6:2013, aggregate specimens are left in a wire basket and immersed in a water tank for 24h (± 0.5h). After 24h, the samples were patted dry and weighed, subsequently dried in an oven at 105 °c for another 24h and weighed. The weight is recorded and calculated based on the formula below;

Apparent Particle Density;

$$\rho_a = \rho_w \frac{M_4}{M_4 - (M_2 - M_3)} \quad Eqn.(1)$$

Oven Dried Particle Density;

$$\rho_{rd} = \rho_w \frac{M_4}{M_1 - (M_2 - M_3)} \quad Eqn.(2)$$

Saturated and surface-dried particle Density;

$$\rho_{ssd} = \rho_w \frac{M_1}{M_1 - (M_2 - M_3)} \quad Eqn.(3)$$

and Water Absorption after immersion for 24h, WA_{24}, following formula 4;

$$WA_{24} = \frac{M_1 - M_4}{M_4} \times 100 \quad Eqn.(4)$$

Where;

ρ_w	is the density of water at room temperature
M_1	is the mass surface saturated and surface dried aggregate in the air
M_2	is the apparent mass in the water of the basket containing the saturated aggregates
M_3	is the apparent mass in the water of the empty basket
M_4	is the mass of the oven-dried sample in air.

3.1.4.3 Slump Test

The workability of concrete is paramount for its applications as it needs to be moulded into complex shapes with ease. The slump test was carried out in accordance with EN 12350-2:2019.

Table 3.9

Slump class (EN 206-2013)

Class	Slump tested in Accordance with EN 12350-2 (mm)
S1	10 - 40
S2	50 - 90
S3	100 - 150
S4	160 - 210
S5	≥ 220

3.1.4.4 Air Pore Content

Concrete strength is greatly influenced by the porosity of the concrete. The contribution to concrete porosity can be classified into two sources: workmanship and effects of constituent materials. The specimen is then placed in an air content tester as specified in EN 12350-7:2019 to measure the air content in the freshly mixed concrete. Measurement is made using TESTING Bluhm & Feuerherdt GmbH Air Entrainment Meter 8 litres shown in Figure 3.2.

Figure 3.1: Air Entrainment Meter for the measurement of Air Pore Content

3.1.4.5 Bleeding

Determination of bleeding in the concrete (EN 480-4) is a test that measures the stability of the homogeneity of the concrete mixture. As the GO-IBA™ replacement increases, the possibility of this homogeneity might be disturbed. Hence, this test will be able to track the stability of the mixture, which is correlated to the homogeneity among the aggregates and cement paste to achieve stable hardened and durability properties of the concrete.

3.1.4.6 Setting Time

In the field, concrete needs to be transported from concrete mixing plants to the construction site for concrete placement, such as pumping of concrete into moulds, which will require concrete to maintain workability for a minimum of 2 hours before hardening. The potential change in setting time can be detrimental to the concrete's ability to be transported and jeopardise the process of concrete placement. Measurement was done using the NL Scientific model 4004 X 001 shown in Figure 3.3 at R.A.K. Materials Consultant Labs.

Therefore, the freshly mixed concrete will be subjected to ASTM C403/403M-23 for measurement of setting time.

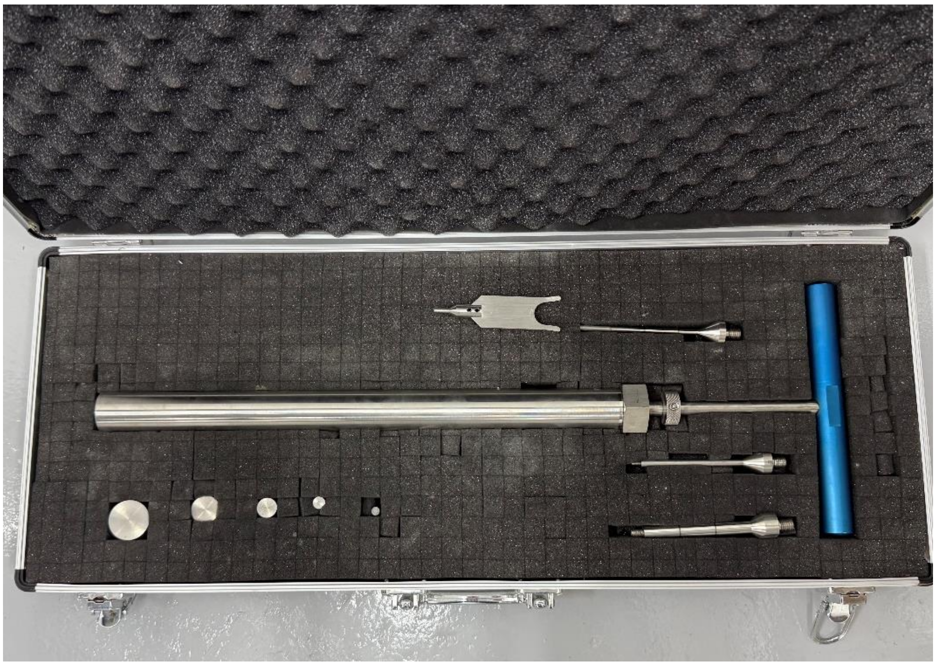


Figure 3.2: Setting time apparatus

3.1.4.7 Compressive Strength

Compressive strength is the most fundamental property of concrete and has a direct relationship with most of the other properties. Therefore, it is imperative that the compressive strength is tested to correlate with other data to have a holistic approach to review the concrete performance. The hardened concrete will be tested in accordance with EN 12390-2. Measurement was done using the Matest Concrete compressive machine 2000kN shown in Figure 3.4 at TÜV SÜD Pte Ltd.

Figure 3.3: Matest concrete compressive test machine 2000 kN

3.1.4.8 Modulus of Elasticity

Modulus of elasticity (MOE) is a measure of how the concrete deforms under stress. It is an important factor which designers often use during the design of the structures to ensure the serviceability requirement will be met. Accordingly, the MOE is tested pursuant to EN 12390-13. Eurocode 2 also specifies the minimum Elastic Modulus (*Ecm*) to be met according to the designed concrete cube strength.

Measurement was done using the ultimate tensile machine (UTM) by Shenzhen Wance Testing Machine DTC 500 and Epsilon Technology Corp Averaging Axial Extensometer 3542RA2-100M-250M-ST shown in Figures 3.5 to 3.8 at R.A.K. Materials Consultant Labs.

Table 3.10

Eurocode 2 specification for Concrete Elastic Modulus (EN 1992 -1-1:2004)

Symbol	Description	C25/30	C30/37	C35/45	C40/50	C45/55	C50/60
fck (MPa)	Characteristic cylinder compressive strength	25	30	35	40	45	50
fck,cube (MPa)	Characteristic cube compressive strength	30	37	45	50	55	60
fcm (MPa)	Mean cylinder compressive strength	33	38	43	48	53	58
fctm (MPa)	Mean tensile strength	2.56	2.90	3.21	3.51	3.80	4.07
Ecm (MPa)	Secant modulus of elasticity	31476	32837	34077	35220	36283	37278

Figure 3.4: Shenzhen Wance Testing Machine DTC 500 UTM

Figure 3.5: Data logger for UTM

Figure 3.6: Extensometer for MOE

Figure 3.7: Testing setup for MOE

3.1.4.9 Water Absorption Test and Water Penetration Test

Concrete durability is a complex topic, as its long-term performance is measured under various conditions, ranging from basic material properties, such as creep, to complex chemical attacks while exposed to weathering elements. Due to its complications, it is easier to compartmentalise each form of attack and study its effect in isolation. Many durability concerns are directed to chemical attacks, as this form of attack is often regarded as deadly due to its involvement with weathering elements.

Most concrete attacks utilise water as a medium to initiate their reaction with the hardened concrete constituents, making water both an enemy and a friend to concrete, as it is also necessary for cement hydration purposes. The idea of testing water absorption and water penetration under pressure is to assess the permeability of the concrete, as permeation of fluids or gases requires that the pores of the concrete be interconnected.

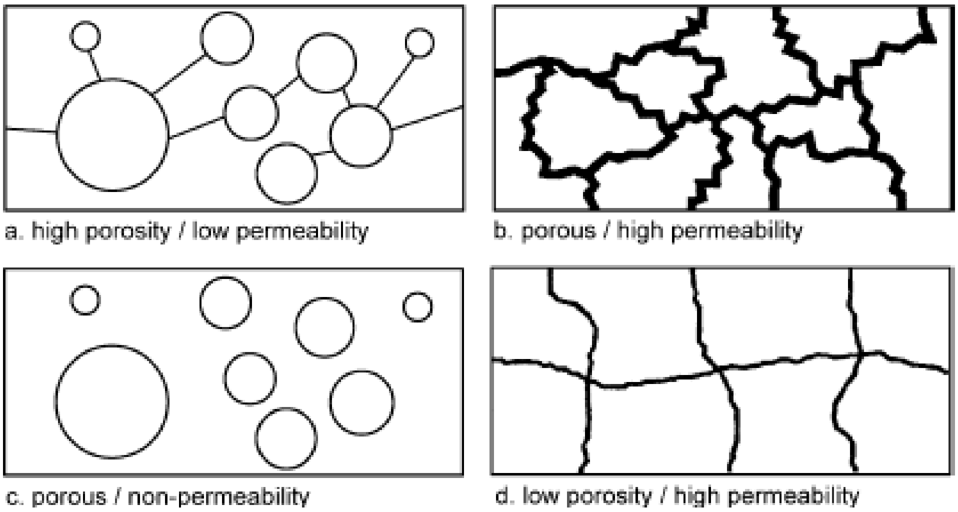


Figure 3.8: Schematic drawing of between porosity and permeability (EuroLightCon, 1998)

As Al-Jabri, M. (2022) explained, water interaction mechanisms include flow, capillary absorption, diffusion, solvation, reaction, evaporation, crystallisation, erosion, solidification, *etc*. The difference between water absorption and water penetration is that water absorption utilises the capillary pores as a transport mechanism, while water penetration is subjected to hydrostatic pressure (Zaccardi *et al.*, 2018).

As most of the concrete attacks require water to be present as a medium, making the concrete less permeable will reduce the chance of concrete attacks such as a chloride attack, sulfate attack, or Alkali-Silica reaction (ASR). As such, the water penetration and water absorption tests are of interest.

An average of three samples for each test will be tested for the water absorption test in accordance with BS 1881-122:2011+A1:2020 and the water penetration test in accordance with EN 12390-8. Water Penetration test measurement was done on the NL Scientific model 4022X/002, shown in Figure 3.9, at the R.A.K. Materials Consultant Labs. Water absorption test measurement was also done at the R.A.K. Materials Consultant Labs, as shown in Figure 3.10 to 3.12.

Figure 3.9: Water Penetration Test rig

Figure 3.10: Oven used for water absorption specimen prior to testing

Figure 3.11: Desiccator used for storage before water absorption test

Figure 3.12: Water absorption specimen weighs in before submerging in water

3.1.4.10 Rapid Chloride Penetration Test (RCPT)

Chloride attack is a common concrete failure, accounting for 40% of concrete failures in the world (ESCSI, 2024). The source of chlorides can be traced to internal (raw material of concrete, such as aggregate or admixtures) or from external (Seawater or deicing salts) factors.

The attack of the chloride is not on the concrete itself but on the reinforcement bar within the concrete structure. Coupled with the presence of oxygen and water, corrosion of the reinforcement bar creates rust, and rust itself can occupy six times its original volume, depending on the oxidation state. The process of rusting exerts pressure against the hydrated cement paste, which will eventually give way once the tensile strength is exceeded, resulting in concrete spalling.

As per ASTM C1202, a correlation of the RCPT results and the long-term chloride penetration of the concrete is given in Table 3.11 below

Table 3.11

Chloride ion penetrability based on charge passed (ASTM C1202)

Chloride Penetration	56-Day Rapid Chloride Permeability Charge Passed (Coulombs)
High	>4,000
Moderate	2,000 – 4,000
Low	1,000 – 2,000
Very Low	100 – 1,000
Negligible	<100

The specimens will be tested by the accelerated test method known as RCPT in accordance with ASTM C1202, and the measurement is done using Giatec Scientific Inc. Perma 2 shown in Figures 3.13 and 3.14.

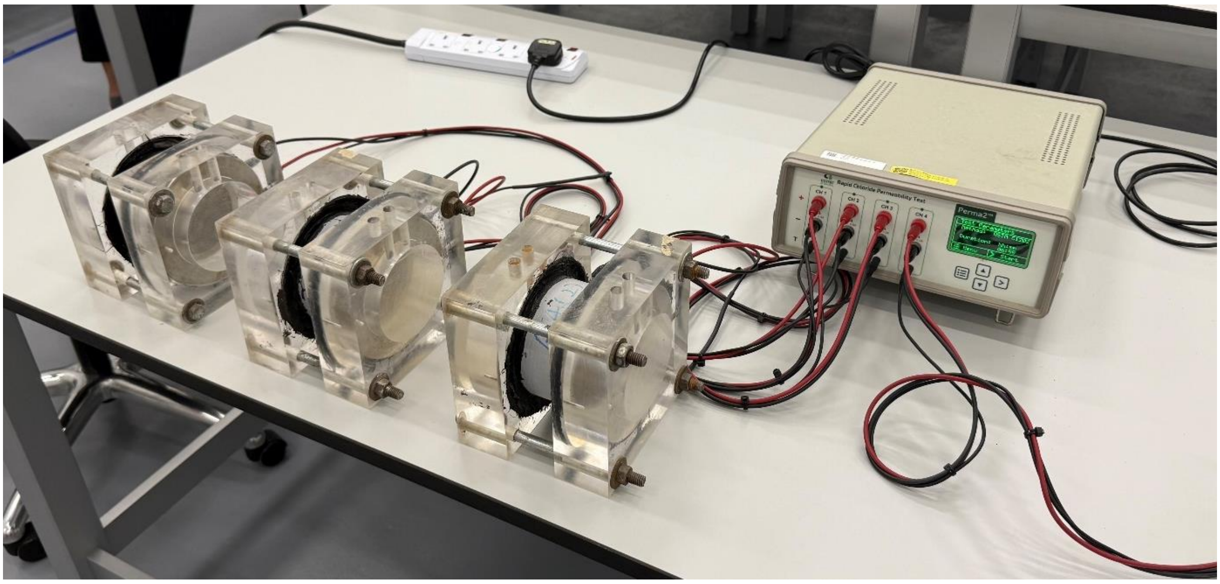


Figure 3.13: RCPT test rigs

Figure 3.14: Giatec Scientific Inc. Perma2

3.1.4.11 Carbonation Test

It is well established that the high alkalinity of concrete creates a passivation layer of protection around the steel rebar and protects it from the effects of chloride attack. As concrete is commonly reinforced with steel reinforcement, the concrete also has to be investigated for the ability to prevent this passive layer from deteriorating. This process of the depasivation is linked to a process known as carbonation.

Carbonation operates by the reaction of carbon dioxide within the atmosphere with calcium hydroxide ($Ca(OH)_2$) in the concrete, to form calcium carbonate ($CaCO_3$), resulting in a drop in alkalinity, which reduces the passive layer that was supposed to protect the steel reinforcement from corrosion.

An average of two samples will be tested in accordance with EN 12390-12 at a maximum duration of 70 days in the accelerated carbonation chamber. The cube at the end of the test will be split in half when sprayed with phenolphthalein, and the areas that did not change colour shall be observed as carbonated areas of the concrete. Measurement was done on the NL Scientific Concrete Carbonation Test Chamber, shown in Figure 3.15, at the R.A.K. Materials Consultant Labs

Figure 3.15: Carbonation Chamber

3.2 Materials

In this section, the raw materials used are shown in Table 4.1, and their properties will be discussed.

Table 3.12

List of raw materials used

Material
Ordinary Portland Cement (OPC)
Ground Granulated Blast-Furnace Slag (GGBS)
Untreated IBA (rIBA)
Manufactured Sand (M Sand)
Natural Sand (C Sand)
20mm Granites
Plastisier (N200)
Water

3.2.1 Aggregates

All aggregates used are collected from the same batch of delivery, stored and sealed in large jumbo bags before use. Fine natural aggregates are measured for moisture content before the concrete mixing. Moisture correction is done to ensure a consistent water/cement (w/c) ratio.

3.2.1.1 Coarse Natural Aggregates

Crushed granite with a maximum size of 20 mm and specific gravity of 2.6, conforming to SS EN 12620:2008, was sourced from a Building and Construction Authority (BCA) approved supplier.

Sieve Size(mm)	40.0	31.5	20.0	16.0	14.0	10.0	8.0	6.3	4.0	2.0	1.0	0.063
Cumulative Passing %	100	100	92	78	63	36	25	16	8	3	1	0.9

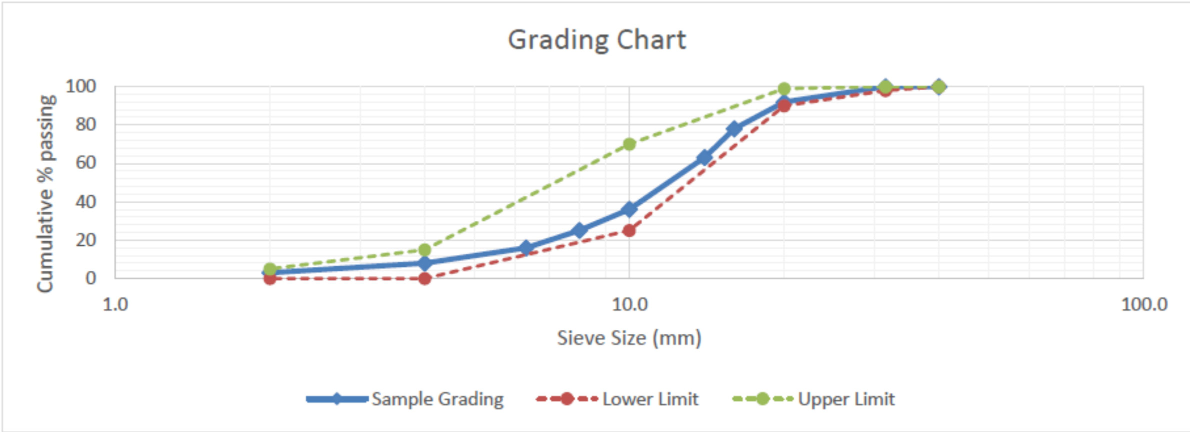


Figure 3.16: Particle size distribution of coarse natural aggregates

Table 3.13

Physical properties of coarse aggregates

Physical Properties	Results
Fines Content (%)	0.9
Flakiness Index	11
Shape Index	10
Particle Density on oven-dried basis (mg/m3)	2.56
Particle Density on saturated surface dry (mg/m3)	2.58
Apparent Particle Density (mg/m3)	2.62
Water Absorption (% of dry weight)	0.84

3.2.1.2 Fine Natural Aggregates (C Sand)

River sand was used in this study with a specific gravity of 2.6, conforming to SS EN 12620:2008, and was stored in the same manner as coarse aggregates.

Sieve Size(mm)	8.0	6.3	4.0	2.8	2.0	1.0	0.5	0.25	0.125	0.063
Cumulative Passing %	100	99	91	85	74	46	19	6	3	2.5

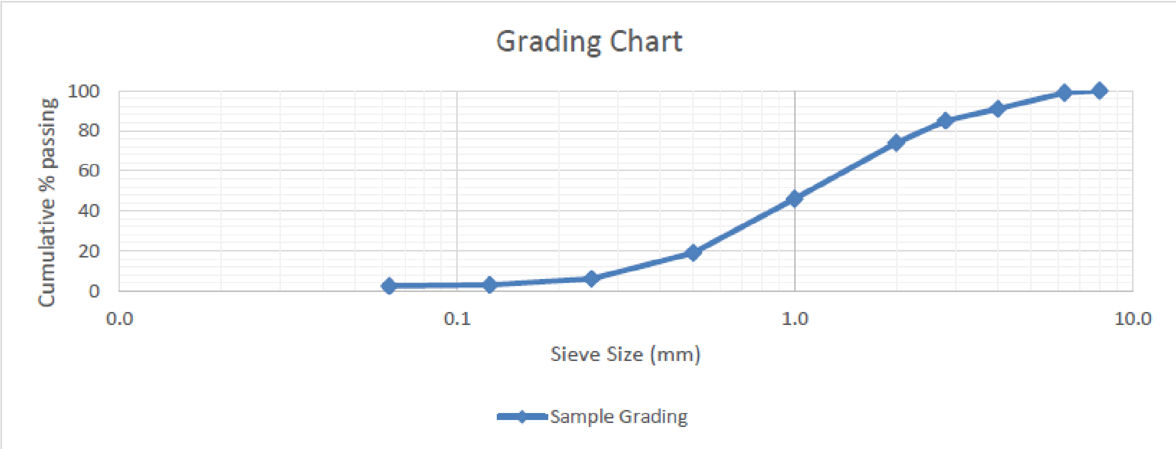


Figure 3.17: Particle size distribution of natural sand (C Sand)

Table 3.14

Physical properties of fine natural aggregates (C Sand)

Physical Properties	Results
Fines Content (%)	2.5
Silt Content (%)	8.8
Water Soluble Chloride Content CI-, (%)	<0.01
Particle Density on oven-dried basis (mg/m3)	2.51
Particle Density on saturated surface dry (mg/m3)	2.52
Apparent Particle Density (mg/m3)	2.53
Water Absorption (% of dry weight)	0.24
Potential presence of humus	Negative

3.2.1.3 Manufactured Sand (M Sand)

Manufactured Sand, commonly known as M Sand, may be used in place of natural sand in concrete to address the problem of river sand depletion. It is produced by crushing rocks, into fine, angular particles. In this study, M Sand is sourced from a BCA-approved supplier. The properties of M Sand are shown below.

Sieve Size(mm)	8.0	6.3	4.0	2.8	2.0	1.0	0.5	0.25	0.125	0.063
Cumulative Passing %	100	99	87	80	70	48	29	15	10	8.8

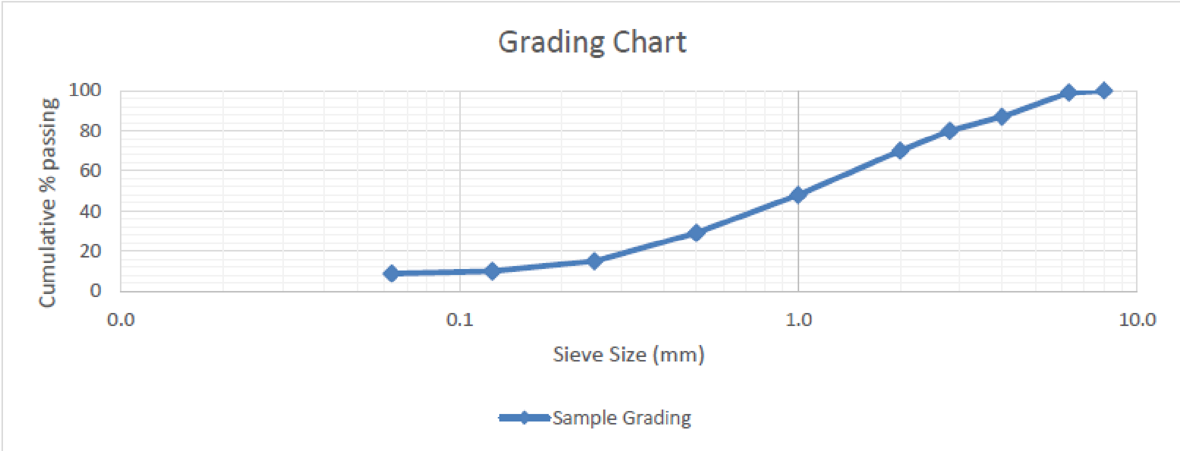


Figure 3.18: Particle size distribution of M Sand

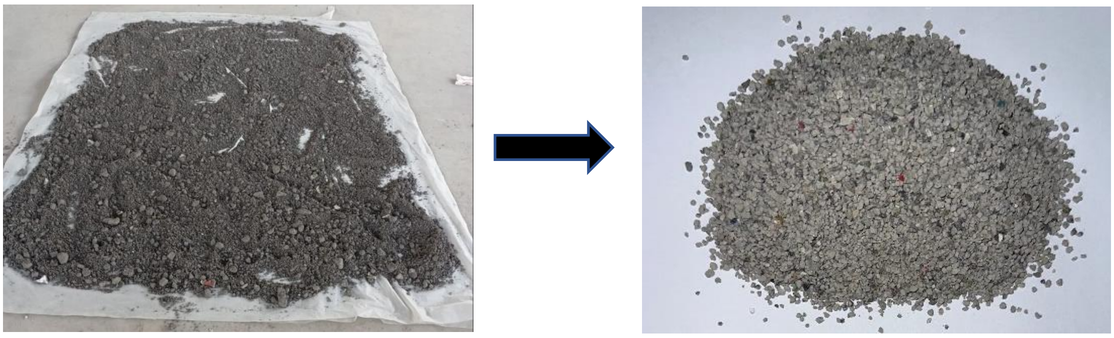
Table 3.15

Physical properties of M Sand

Physical Properties	Results
Fines Content (%)	8.8
Slit Content (%)	17.4
Water Soluble Chloride Content CI-, (%)	<0.01
Particle Density on oven-dried basis (mg/m3)	2.59
Particle Density on saturated surface dry (mg/m3)	2.60
Apparent Particle Density (mg/m3)	2.61
Water Absorption (% of dry weight)	0.25
Potential presence of humus	Negative

3.2.1.4 Untreated IBA

The untreated IBA is first obtained from NEA, where a pre-treatment was done beforehand to recover metals from the IBA. The IBA was dried to achieve the SSD condition before being sieved to remove particles larger than 4mm.



(a) IBA before drying and sieving (b) IBA after drying and sieving

Figure 3.19: IBA collected, dried and sieved into sizes < 4mm

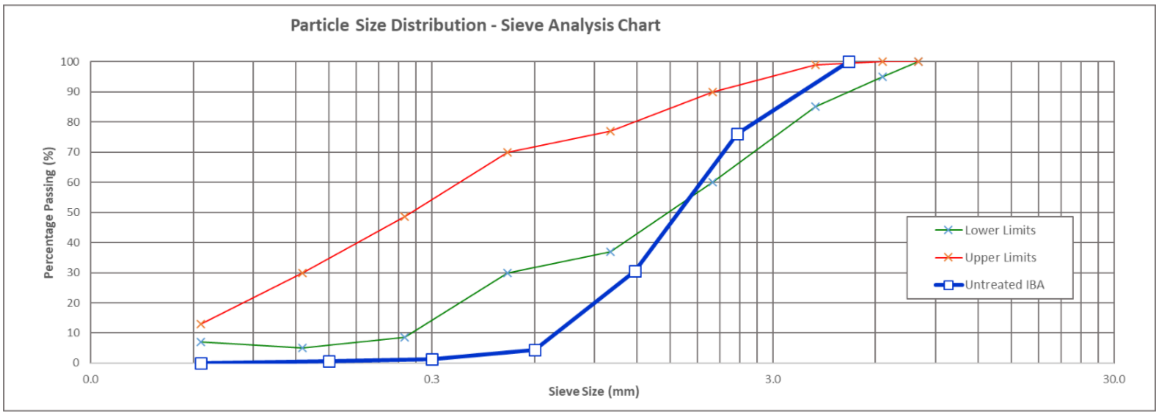


Figure 3.20: Particle size distribution of untreated IBA

As mentioned in Section 3.3.9, untreated IBA contains a significant amount of chlorides. Shimadzu EDX-7200 was used to obtain the chemical composition via X-ray Fluorescence (XRF). The chloride results show a high percentage of 2.961% as shown in Figure 4.5.

Table 3.16

Chemical composition of untreated IBA via XRF

Chemical Compositions	Test Results (%)
CaO	41.138
SiO_2	16.269
SO_3	15.132
Al_2O_3	8.297
Fe_2O_3	7.777
Cl-	2.961
P_2O_5	2.231
MgO	1.994
TiO_2	1.657
K_2O	1.054
ZnO	0.656
CuO	0.219
SrO	0.204
MnO	0.168
Cr_2O_3	0.079
PbO	0.059
NiO	0.037
SnO_2	0.032
SbO_3	0.021
Br	0.008
Rb_2O	0.005
Tr_2O_3	0.002

Table 3.17

Sieve analysis of untreated IBA

Sieve Size (mm)	Weight Retained (g)	Weight Passing (g)	Sample Passing (%)	Accumulative Passing (%)
5	0	999	100	0
2.36	239	760	76	24
1.18	455	305	31	69
0.6	261	44	4	96
0.3	32	12	1	99
0.15	6	6	1	99
0.063	6	0	0	100

Note: Fineness Modulus = 3.872

Due to environmental concerns of the harmful substance present in the IBA, a leaching test in accordance with BS EN 12457-1:2002 was done to assess the leachates. As shown in Table 4.7, the chloride leachate amounts to 5,373 mg/kg, which would raise concerns with regard to the possibilities of chloride attack.

Table 3.18

Leaching Results of untreated IBA

Test Parameter	IBA (mg/kg)
Aluminium (Al)	20.9
Antimony (Sb)	0.03
Arsenic (As)	ND
Barium (Ba)	4.56
Cadmium (Cd)	ND
Chromium (Cr) (Total)	0.067
Chromium (Cr) (VI)	0.054
Cobalt (Co)	ND
Copper (Cu)	4.28
Manganese (Mn)	ND
Mercury (Hg)	ND
Molybdenum (Mo)	0.32
Nickel (Ni)	0.042
Lead (Pb)	ND
Sodium (Na)	2,177
Silver (Ag)	ND
Selenium (Se)	ND
Tin (Sn)	ND
Vanadium (V)	ND
Zinc (Zn)	ND
Bromide (Br-)	21.0
Chloride (Cl-)	5,373
Fluoride (F-)	ND
Sulphate (SO4)	ND
Ammonia (NH3)	0.7
Total Nitrogen (as N)	20.2
Total Phosphorus (as P)	0.079
Total Organic Carbon (TOC)	409
Chemical Oxygen Demand (COD)	1,270

3.2.1.5 Treated IBA

In this work, the treated IBA is sourced from EnGro Corporation Limited Singapore (GO-IBA™), which is treated using the cold-bonded palletisation technique to encapsulate the pollutants, hence reducing the leaching of hazardous substances. The salient properties of EnGro Corporation Limited Singapore ’s GO-IBA™ aggregates are given in Figure 4.5, Table 4.8 and 4.9.

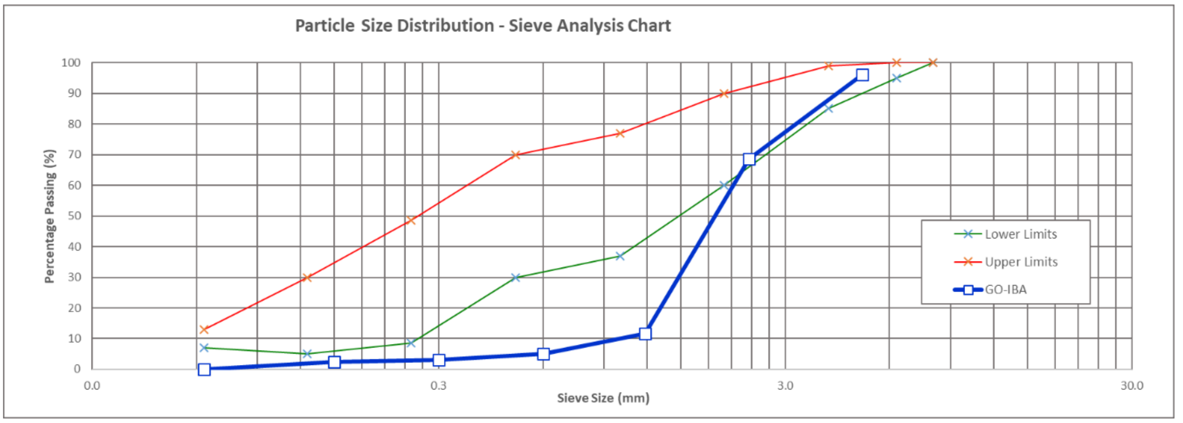


Figure 3.21: Particle size distribution of treated IBA (GO-IBA™)

Table 3.19

Sieve analysis of GO-IBA™

Sieve Size (mm)	Weight Retained (g)	Weight Passing (g)	Sample Passing (%)	Accumulative Passing (%)
5	39	961	96	4
2.36	276	685	69	32
1.18	568	117	12	88
0.6	67	50	5	95
0.3	20	30	3	97
0.15	6	24	2	98
0.063	24	0	0	100

Note: Fineness Modulus = 4.133

Table 3.20

Particle density and water absorption property of GO-IBA™

Test Reference	Test		Average
	1	2	
Particle Density on oven-dried basis (mg/m^3)	2.01	1.91	1.96
Particle Density on saturated surface dry (mg/m^3)	2.02	1.92	1.97
Apparent Particle Density (mg/m^3)	2.03	1.92	1.98
Water Absorption (% of dry weight)	0.46	0.53	0.5

**The above test is conducted in two replicates.*

The density of GO-IBA™ reported above is 1.98g/cm2. The water absorption is almost double that of natural aggregates. Li *et al.* also reported similar findings that the water absorption is about two times higher than natural aggregates (Li *et al.*, 2023). The particle size analysis of GO-IBA™ is relatively similar to that of the untreated IBA, being largely single-graded sizing of the 1-5mm range..

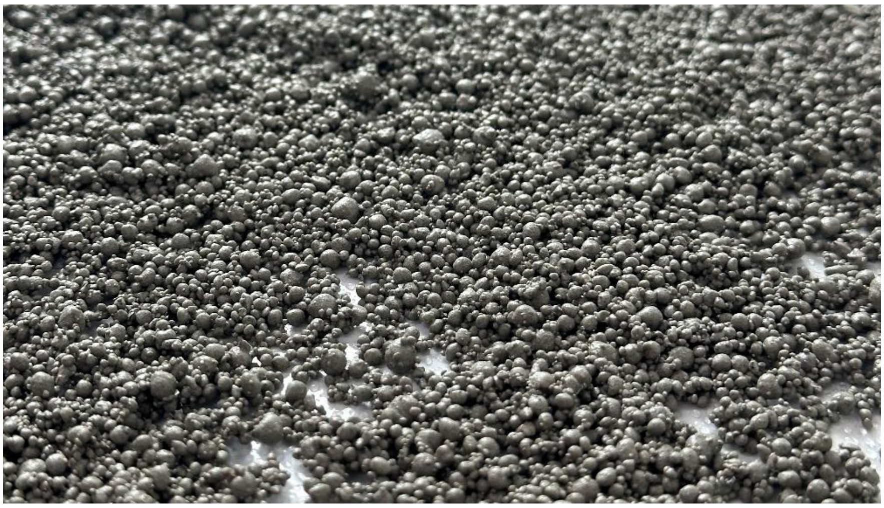


Figure 3.22: GO-IBA™ Physical appearance

As mentioned in Section 3.2.1.4, a leaching test in accordance with BS EN 12457-1:2002 was also done to assess the leachates for GO-IBA™. The reduction in chloride leachate of GO_IBA™ compared to untreated IBA is about 20 times, which is shown in Table 3.21.

Table 3.21

Leaching results of GO-IBA™

Test Parameter	GO-IBA™ (mg/kg)
Aluminium (Al)	1.77
Antimony (Sb)	ND
Arsenic (As)	ND
Barium (Ba)	1.94
Cadmium (Cd)	ND
Chromium (Cr) (Total)	ND
Chromium (Cr) (VI)	ND
Cobalt (Co)	ND
Copper (Cu)	0.051
Manganese (Mn)	ND
Mercury (Hg)	ND
Molybdenum (Mo)	ND
Nickel (Ni)	ND
Lead (Pb)	0.011
Sodium (Na)	ND
Silver (Ag)	ND
Selenium (Se)	ND
Tin (Sn)	ND
Vanadium (V)	ND
Zinc (Zn)	ND
Bromide (Br-)	1.53
Chloride (Cl-)	270
Fluoride (F-)	ND
Sulphate (SO4)	ND
Ammonia (NH3)	0.53
Total Nitrogen (as N)	1.79
Total Phosphorus (as P)	0.029
Total Organic Carbon (TOC)	42.3
Chemical Oxygen Demand (COD)	124

3.2.2 Cement

3.2.2.1 Ordinary Portland Cement (OPC)

Ordinary Portland Cement CEM I 52.5N, conforming to SS:EN 197-1 was sourced from EnGro Corporation Limited Singapore and was used in this research. The cement was set aside and stored according to the manufacturer's recommended storage. Additional measures were taken, such as PE lining of the jumbo bags, and minimal opening of the bags to ensure minimal contact with moisture.

The details of the chemical and physical properties of the OPC were otained from EnGro Corporation Limited Singapore are shown below;

Table 3.22

Chemical composition of OPC

Chemical Properties	Test Results
Loss on Ignition (%, m/m)	3.02
Sulfate as SO3 (%, m/m)	2.26
Insoluble Residue (%, m/m)	0.29
Manganese as MnO (%, m/m)	0.08
Total Silica as SiO2 (%, m/m)	20.35
Iron (III) Oxide as Fe2O3 (%, m/m)	2.97
Aluminium Oxide as Al2O3 (%, m/m)	4.85
Calcium Oxide as CaO (%, m/m)	61.88
Magnesium Oxide as MgO (%, m/m)	2.20
Chloride as Cl- (%, m/m)	<0.01
Sodium Oxide as Na2O (%, m/m)	0.110
Potassium Oxide as K2O (%, m/m)	0.65
Total Alkalinity(c) as Na2O + 0.658 K2O (%, m/m)	0.51

Table 3.23

Physical properties of OPC

Physical Properties		Test Results
Consistency of cement paste (%)		28.5
Penetration (mm)		8
Initial setting time (minutes)		125
Final setting time (minutes)		170
Soundness (mm)		0.5
45µm retained (%)		3.1
90µm retained (%)		0.1
Fineness (m^2/kg)		417
	2 days	29.7
Average Compressive Strength (MPa)	7 days	45.5
	28 days	59.0

3.2.2.2 Ground Granulated Blast Furnace Slag (GGBS)

Ground Granulated Blast Furnace Slag conforming to SS:EN 15167-1 was sourced from EnGro Corporation Limited Singapore and was used in the test. Similar storage conditions to OPC were used to ensure minimal variance in concrete results caused by OPC and GGBS.

The details of the chemical and physical properties of the GGBS is obtained from EnGro Corporation Limited Singapore are shown below.

Table 3.24

Chemical properties of GGBS

Chemical Properties	Test Results
Corrected loss on Ignition (%, m/m)	0.75
Sulfate as SO3 (%, m/m)	0.23
Insoluble Residue (%, m/m)	0.87
Manganese as MnO (%, m/m)	0.43
Total Silica as SiO_2 (%, m/m)	32.04
Iron (III) Oxide as Fe_2O_3 (%, m/m)	0.60
Aluminium Oxide as Al_2O_3 (%, m/m)	14.54
Calcium Oxide as CaO (%, m/m)	39.43
Magnesium Oxide as MgO (%, m/m)	8.92
Chloride as Cl- (%, m/m)	0.02
Sodium Oxide as Na_2O (%, m/m)	0.37
Potassium Oxide as K_2O (%, m/m)	0.35
Total Alkalinity (%, m/m)	0.60
Sulfide as S_2- (%, m/m)	0.78

Table 3.25

Physical properties of GGBS

Chemical Properties	Test Results
Fineness (m2/kg)	446
Residue (%)	
45 µm sieve	3.0
90 µm sieve	0.2
Consistency of Cement paste (%)	29.0
Initial Setting Time (minutes)	140
Activity Index (%) at	
3-day	67.7
7-day	95.5
28-day	114.2

3.2.3 Mixing Water

Tap water was used for the concrete mixing and pre-wetting of the GO-IBA™.

3.2.4 Plasticiser

Water-reducing admixtures are an important part of modern-day concrete as they allow the use of a lower cement-to-water ratio to achieve higher strength while maintaining high workability. MapeFluid N200 water-reducing admixture was sourced from Mapei Far East Private Limited. The technical data is presented in the table below.

Table 3.26

Technical data for Mapefluid N200

Consistency	Liquid
Colour	Brown
Density according to ISO 758 (g/cm^3)	1.20±
Classification according to EN934-2	High range, water reducing, superplasticiser
Chlorides soluble in water according to EN 480-10 (%)	<0.1
Alkali Content (NaO equivalent) according to EN 480-12 (%)	<6.0

Chapter 4 – Effects of Aggregate Replacement

4.1 Overview

This section first presents the discussion of aggregate properties and the effects of aggregate replacement on: (1) Fresh concrete properties, (2) Hardened concrete properties, (3) Durability properties.

4.2 Aggregate Properties

4.2.1 Particle Size Analysis (PSA)

When comparing natural aggregates, both C Sand and M Sand are comparable as shown in Figure 5.1. The only exception is the higher fine contents of M Sand at 8.8% compared to C Sand at 2.5%. Both naturally derived sand has a similar water absorption of 0.24-0.25%.

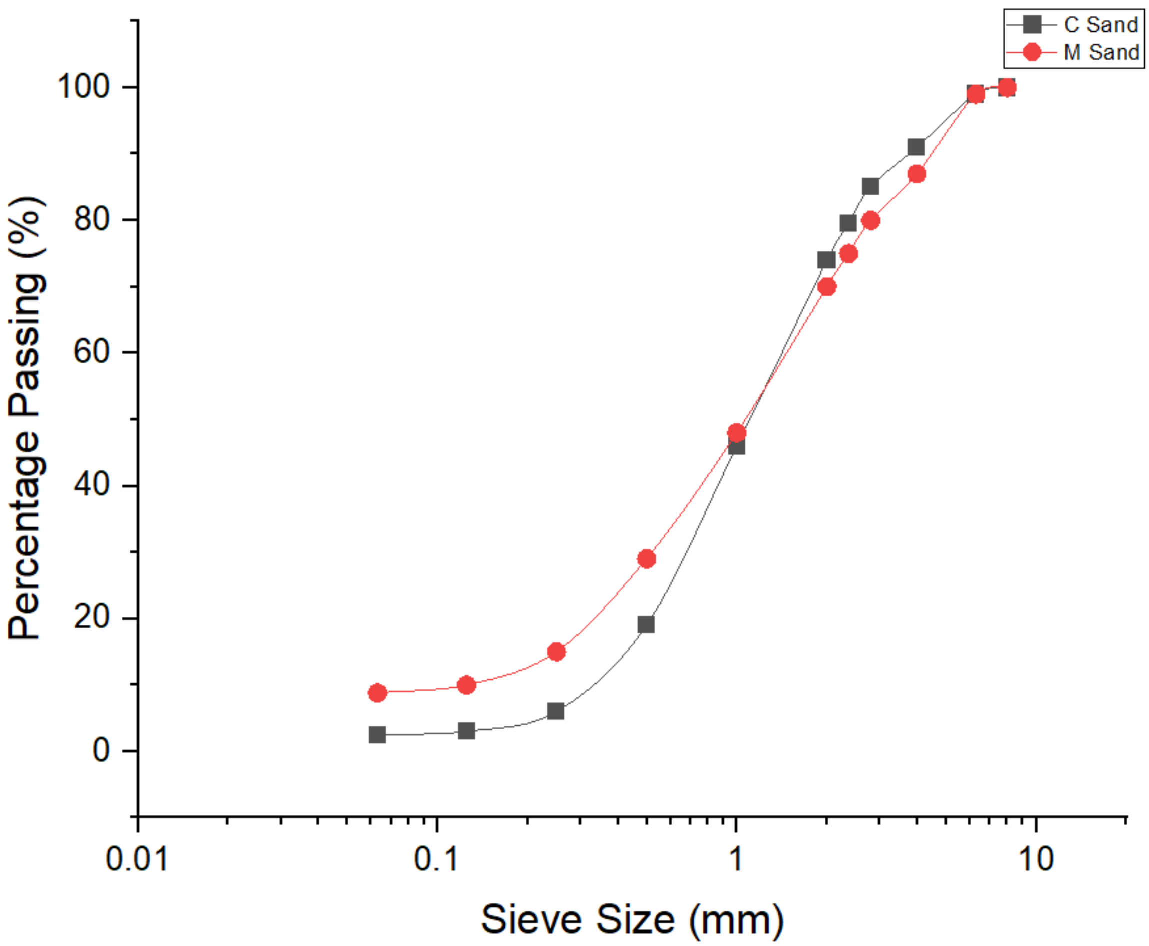


Figure 5.1: PSA results of C Sand and M Sand

Untreated IBA PSA results, when compared to C Sand as shown in Figure 5.2, show a much finer gradation. This finer gradation curve can be explained by the pre-sieving that was done to exclude particle sizes larger than 4mm to be used in this test, as GO-IBA™'s largest particle size used is less than 5mm.

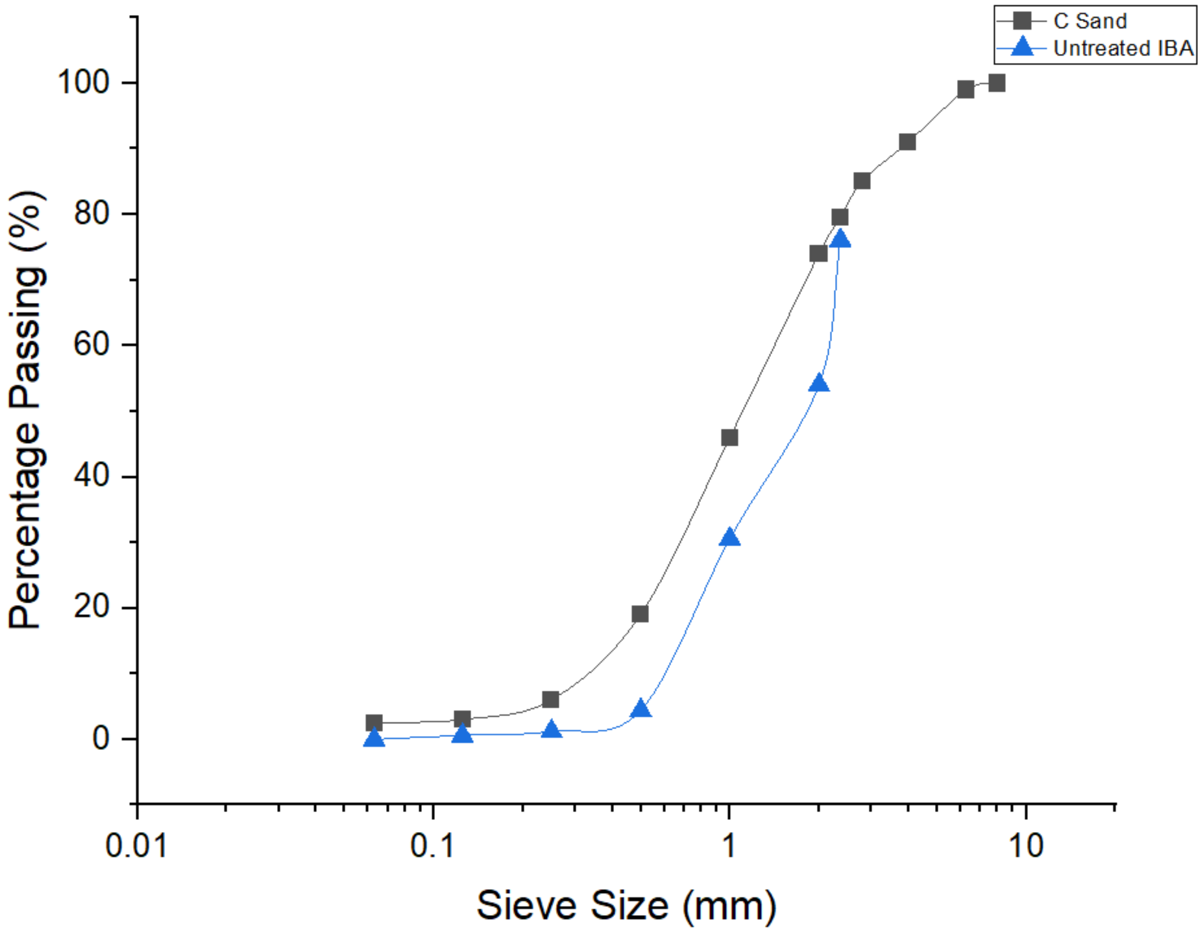


Figure 5.2: PSA results of C Sand and Untreated IBA

GO-IBA™ PSA results are noticeably finer than those of untreated IBA, as shown in Figure 5.3. However, the fineness modulus of GO-IBA™ at 4.133 is larger than that of the untreated IBA at 3.872. Both untreated and GO-IBA™ exhibit a single gradation particle sizing. The reason for the single gradation of GO-IBA™ can be linked to the manufacturing process, as larger particle sizes of more than 5mm are being limited.

The density of GO-IBA™ is lower than that of naturally derived aggregates at 1.98g/cm^3, compared to that of C Sand and M Sand at 2.52 and 2.62g/cm^3, respectively. Therefore, as explained in Section 3.1.2, the replacement levels are on the basis of volume rather than weight to prevent experimental error.

As aggregates make up a large portion of volume in concrete, it is expected that upon replacement with either untreated IBA or GO-IBA™, certain changes in concrete properties will be observed.

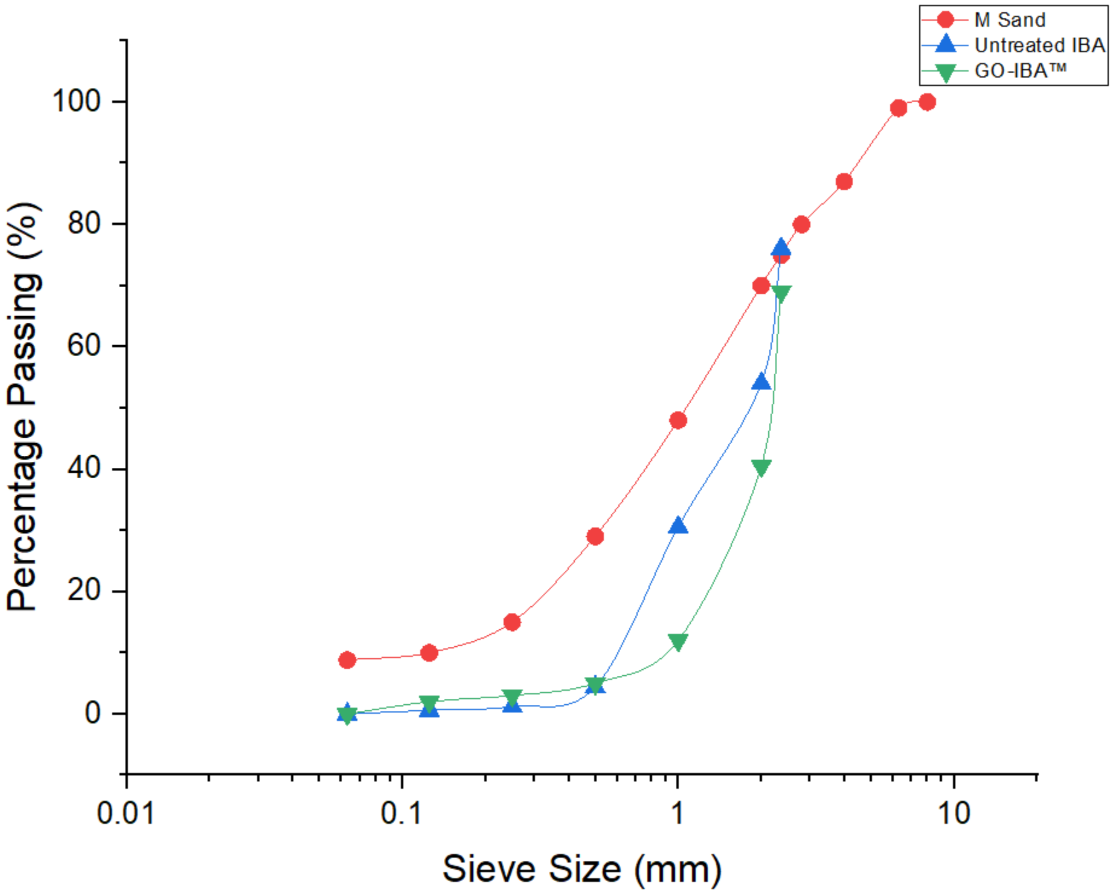


Figure 5.3: PSA results of GO-IBA™, Untreated IBA and M Sand

4.2.2 Leaching Results of Untreated IBA and GO-IBA™

The environmental performance of both untreated IBA and GO-IBA™ was compared in Table 4.1. Considering that cement hydration happens through ionic movement through water, known as pore solutions, the leaching of other substances will ultimately affect the hydration process. Upon treatment, the majority of the parameters were reduced. As soluble chlorides were of significant concern in rIBA, as reviewed earlier, the chlorides were also reduced by about 20 times after treatment.

Table 4.1

Leaching results of Untreated IBA and GO-IBA™

Test Parameter	IBA (mg/kg)	GO-IBA™ (mg/kg)
Aluminium (Al)	20.9	1.77
Antimony (Sb)	0.03	ND
Arsenic (As)	ND	ND
Barium (Ba)	4.56	1.94
Cadmium (Cd)	ND	ND
Chromium (Cr) (Total)	0.067	ND
Chromium (Cr) (VI)	0.054	ND
Cobalt (Co)	ND	ND
Copper (Cu)	4.28	0.051
Manganese (Mn)	ND	ND
Mercury (Hg)	ND	ND
Molybdenum (Mo)	0.32	ND
Nickel (Ni)	0.042	ND
Lead (Pb)	ND	0.011
Sodium (Na)	2,177	ND
Silver (Ag)	ND	ND
Selenium (Se)	ND	ND
Tin (Sn)	ND	ND
Vanadium (V)	ND	ND
Zinc (Zn)	ND	ND
Bromide (Br-)	21.0	1.53
Chloride (Cl-)	5,373	270
Fluoride (F-)	ND	ND
Sulphate (SO4)	ND	ND
Ammonia (NH3)	0.7	0.53
Total Nitrogen (as N)	20.2	1.79
Total Phosphorus (as P)	0.079	0.029
Total Organic Carbon (TOC)	409	42.3
Chemical Oxygen Demand (COD)	1,270	124

4.2.3 Summary

The single gradation of untreated IBA and GO-IBA™ is expected due to the pre-sieving selection process for untreated IBA and the manufacturing process of GO-IBA™. However, the leaching results are an important point to note, as the majority of the leachates are significantly reduced. From the foregoing analysis, it is expected that certain concrete properties will be altered upon replacement with both untreated IBA and GO-IBA™.

4.3 Baseline Study with rIBA Mixes

4.3.1 Slump

Concrete must not only be strong enough to withstand the load it is designed to carry, but it is also paramount that it can be moulded into the intended shapes, making concrete the ideal candidate to build structures with. Therefore, it is crucial to quantify the workability of concrete by measuring the slump retention. Concrete slump classes, as shown in Table 3.9, are a common way to classify the workability of fresh concrete. Between R0 and R25, the slump decreases markedly with increasing rIBA replacement levels. Beyond R25, in the range from R50 to R100, the slump remains broadly similar. Due to the weak and porous nature of rIBA, a crushing effect observed during concrete mixing may have contributed to the reduction in slump by increasing the fines content. The high-water absorption of IBA is reported by Tay, J.H. (1988), which is also another possibility that could have caused the reduction in the slump. This reduction in slump retention may lead to difficulties in concrete placement and, in turn, the quality of the hardened concrete.

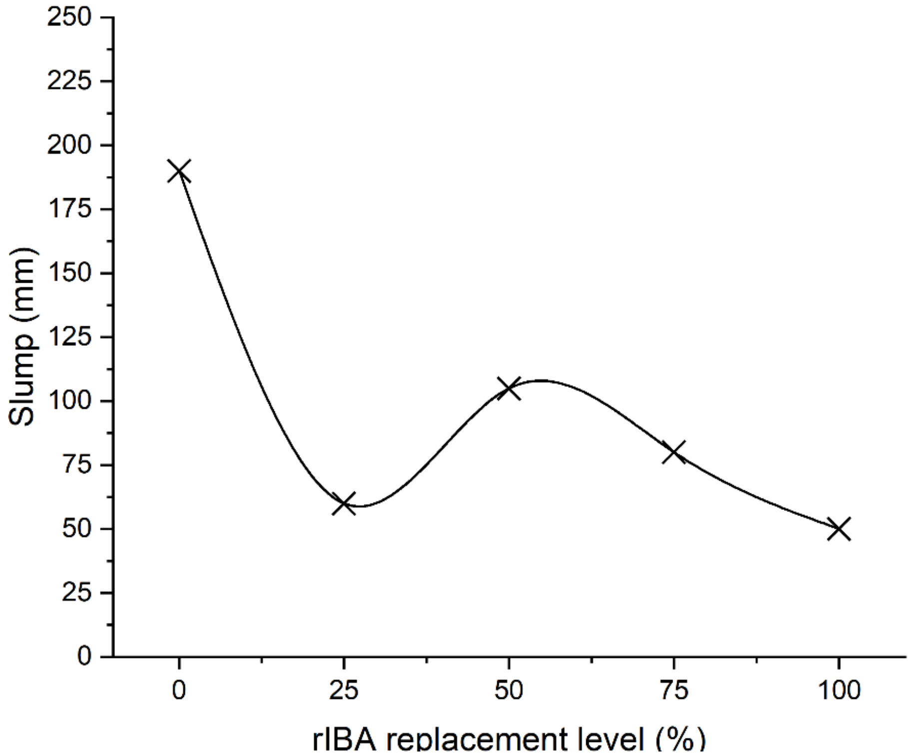


Figure 4.1: Slump results of rIBA mixes

4.3.2 Compressive Strength

The average strength data for rIBA mixes across all curing ages are plotted in Figure 4.2. Both early age tests (3 and 7 days) for R25 show a significant drop in strength compared to the control, with reductions of 17.38% and 25.97%, respectively. A linear decline in strength was observed till the 75% replacement for both 3 and 7 day results.

The 28-day result continued to show a clear trend of decrease in strength of 22.68%, 31.38%, 37.02%, and 42.30% from R0 to R100, respectively. This reduction in strength may have been attributed to the weak and porous nature of rIBA, which makes it less resistant to crushing as an aggregate. Additionally, as suggested by Pera *et al.* (1997), the reaction of metallic aluminium in rIBA with the portlandite in OPC causes a release of hydrogen gas, which creates large pores within the concrete, further reducing its strength.

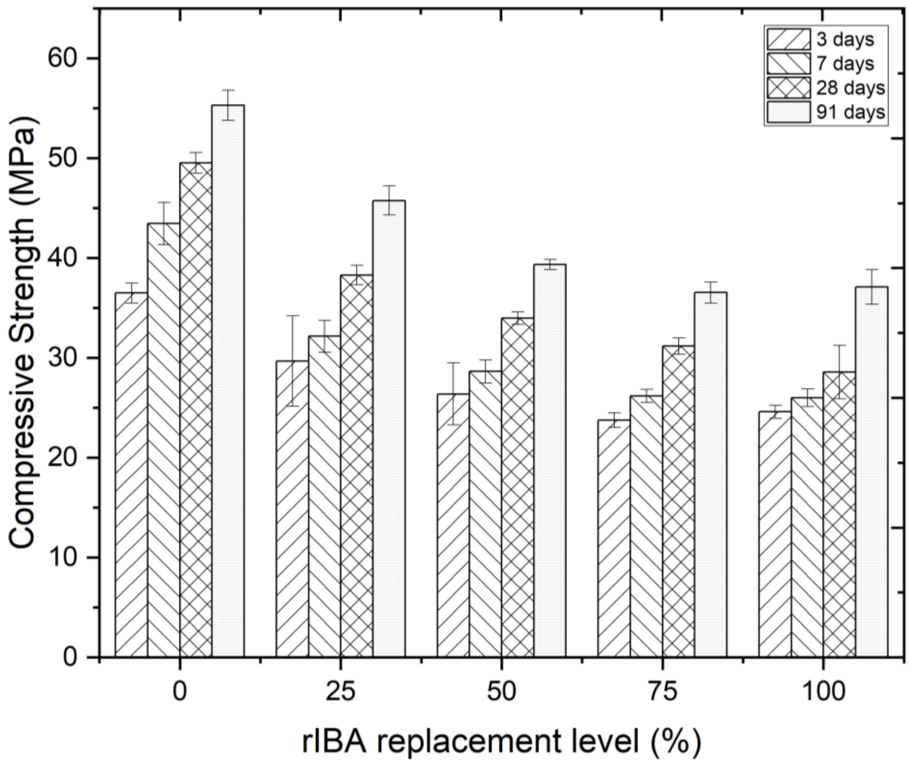


Figure 4.2: Compressive Strengths of rIBA mixes

The introduction of porosity will reduce compressive strength, as observed in the results above. The significant reduction in strength further solidifies the notion that IBA cannot be used in the untreated form.

4.3.3 Durability

4.3.3.1 Water Penetration Test (WPT)

As explained in Section 3.1.4.9, water serves as a medium for various concrete attacks, including chloride attacks.

Increasing the replacement amount of rIBA mixes results in greater water penetration compared to the control. Plotted in Figure 4.3, R25 experienced approximately 3 times increase in water penetration, which corresponds to approximately 76 mm penetration depth. R50 showed a modest improvement over R25, with a penetration depth of 56 mm. Both R75 and R100 recorded penetration depths exceeding 100 mm, which proved to be detrimental.

These findings further support the compressive strength results, and the observed trend is consistent with those reported by Pera *et al.* (1997). This increased porosity contributes to a greater water penetration depth in the concrete cubes, directly correlating with the observed reduction in compressive strength.

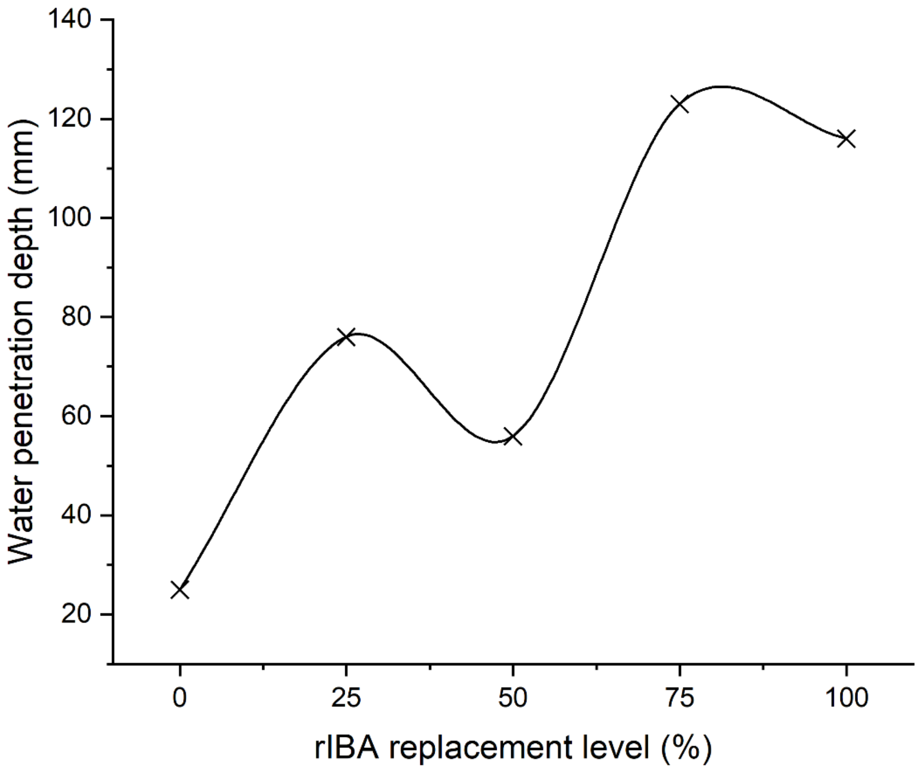


Figure 4.3: Water penetration depth of rIBA mixes

4.3.3.2 Water Absorption Test (WAT)

As mentioned in Section 3.1.4.9, the WAT is an indirect measure of the capillary porosity of the concrete.

The water absorption test results for rIBA mixtures are shown in Figure 4.4. As the rIBA replacement level increases, water absorption decreases for both the R25 and R50 mixes. However, for the R75 mix and R100, absorption increases but still remains slightly better than for the R0 mix. This finding contrasts with the results from Section 4.3.3.2, which focused on water penetration. It is a well-known phenomenon that larger pore sizes and a higher quantity of pores affect these outcomes. Pera *et al.* (1997) reported that hydrogen emission causes cracks to occur. The WAT results reported may suggest that the presence of a significant number of large pores, such as air voids or cracks within the concrete, may have contributed to the decreased compressive strength and adversely affected the water absorption properties (Pera, J., 1997; Al-Jabri, M., 2022). Consequently, it remains inconclusive whether the concrete pores are the primary issue, and further testing, as it is beyond the scope of this study, will be necessary to clarify these results.

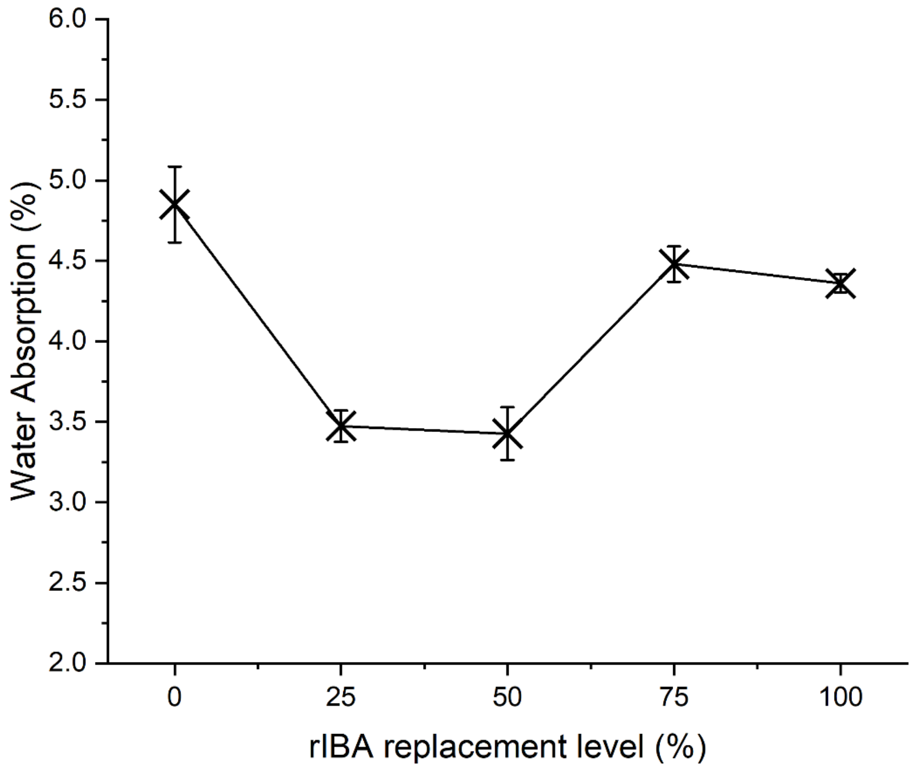


Figure 4.4: Water Absorption results of rIBA mixes

4.3.3.3 Rapid Chloride Penetration Test (RCPT)

As mentioned in Section 3.1.4.10, chloride attack is the most common form of concrete failure. Therefore, it was imperative to test the ability of the concrete to resist chloride.

Surprisingly, the RCPT results, as plotted in Figure 4.5, showed an improvement in chloride resistivity as the replacement level increased. Possible reasons for these findings can be explained by the following: (1) Chlorides might be leached out, given the underwater curing and the porous nature of rIBA mixes. (2) Chloride ions in the untreated IBA could be converted into more stable forms, such as Friedel's salts. (3) The rIBA mixes that have chlorides leached out could have absorbed the chloride ions during the testing phase. Given the paucity of studies surrounding untreated IBA in fine aggregate replacement in concrete applications, the definitive reason is unclear.

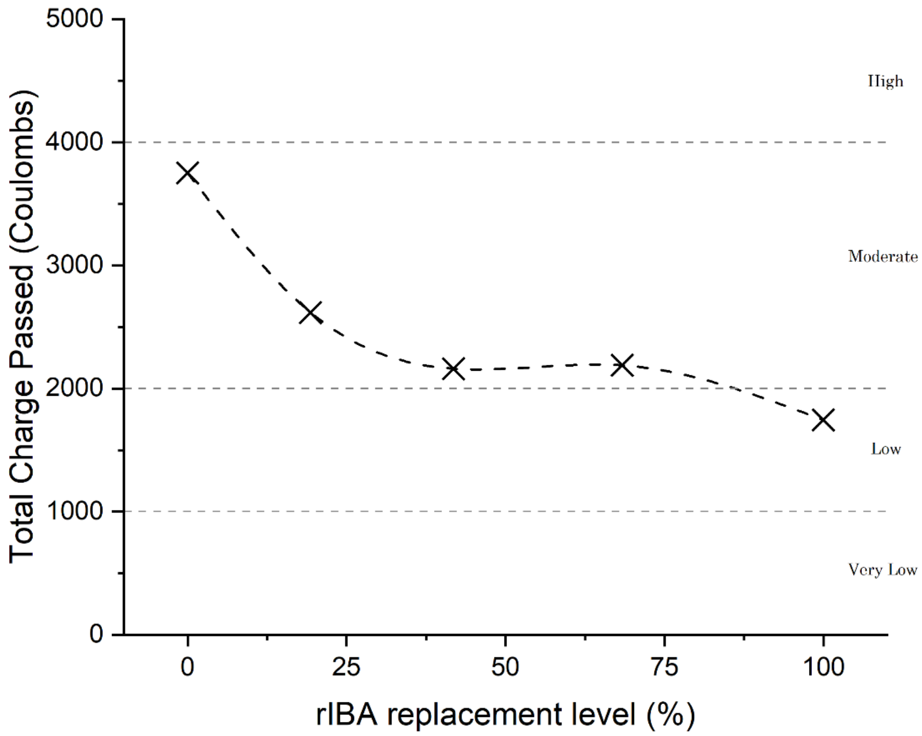


Figure 4.5: RCPT results of rIBA mixes

4.2.4 rIBA Results Summary

A slump loss of up to 2 grades of slump classes upon replacement with untreated IBA is unacceptable. A possible use case entails the increase of admixtures or water to maintain the same level of slump, which will ultimately result in increased cost and loss of strength.

The above observation of the significant reduction in compressive strength is detrimental as the loss in strength was significant. Compressive strength is a fundamental property of concrete and is closely linked to other important properties, such as the Modulus of Elasticity.

High water penetration is deemed to result in a higher likelihood of concrete attacks, such as chloride attack and carbonation, due to the increased possibility of the presence of water medium to facilitate these attacks. The primary reason for the significant reduction in strength and increase in water penetration is attributed mainly due to the in-situ reaction of rIBA with portlandite in OPC, resulting in substantial emissions of hydrogen. This was similar to the works of Pera *et al*. (1997).

At any given rIBA replacement level, the mixes exhibited improved water absorption results. RCPT data also exhibited a similar tendency of improvements in the total charge passed with increasing rIBA replacement levels.

Saikia *et al.* (2015) also reported the high loss on ignition (LOI) of rIBA, indicating the presence of deleterious materials. Coupled with the emission of hydrogen causing cracks in the concrete as reported in the works of Pera *et al.* (1997) and the results shown in the previous sections, there is beyond a doubt that any usage of untreated IBA is detrimental for concrete to be used as a structural component in construction.

The outcomes of this baseline study provide new insights into the influence of untreated IBA on several aspects of concrete. Whilst the idea of using rIBA directly into concrete without treatment seems to be the ideal scenario, the results reported previously showed the devastating effects of it. However, much work remains to be done, particularly with GO-IBA™. This is the central trust for the following sections.

4.3 GO-IBA™ Replacement in Natural Aggregates

4.3.1 Fresh Properties

4.3.1.1 Slump

C Sand is generally rounder and smoother due to the repeated erosion of the river flow. However, M Sand does not share the same surface profile as C Sand, as it is formed from the crushing of larger granites, resulting in a more flaky and angular physical appearance. As a result, M sand has a notoriety for poor concrete workability properties, making it an ideal candidate for the study of workability effects when replacing it with GO-IBA™. The C Sand and M Sand mix slump results are plotted in Figure 4.6.

For the C sand mix, C0 and C25 have similar slump results at 190mm. C50 and C75 reduce in slump to 170 mm and 155 mm, respectively. The slump loss is most pronounced at C100 (40 mm) *vis-à-vis* other replacement levels.

M sand mixes show similar results at 190 mm for M0. However, once replaced with GO-IBA™, the values drop significantly to 110 mm for both M25 and M50, and 120 mm for M75. The general expectation that GO-IBA™ will improve the slump due to its spherical shape is not apparent.

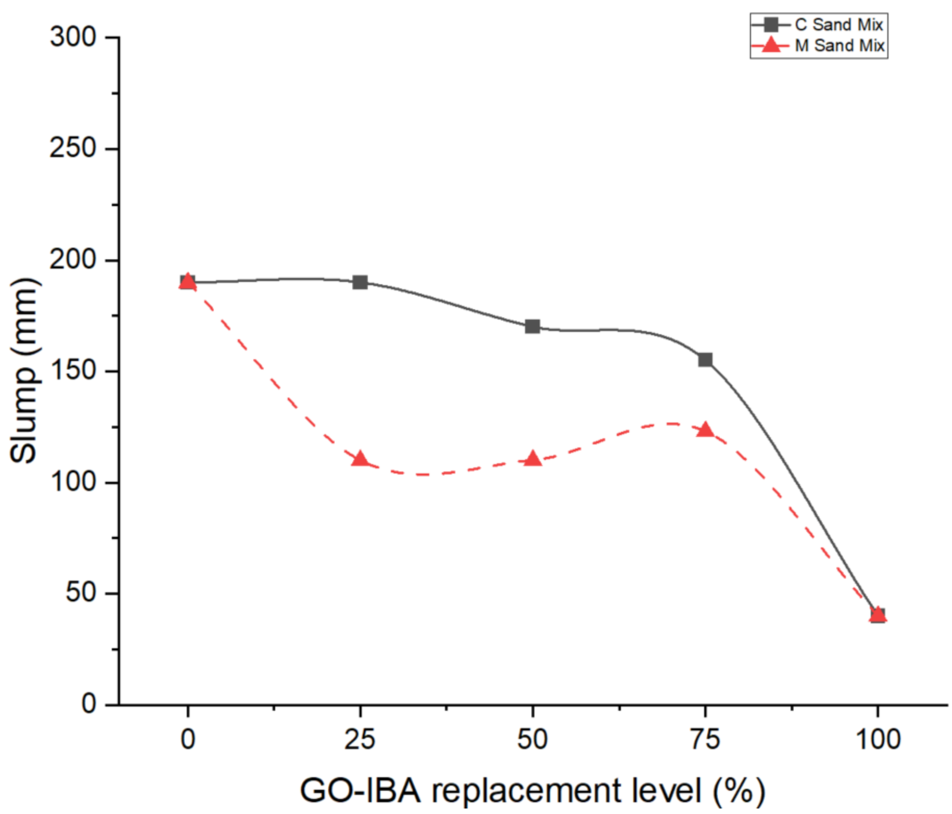


Figure 4.6: Slump results of C Sand Mix and M Sand mix with GO-IBA™ replacement

This result contradicts the scholarly works of Tang & Brouwer (2018) and Güneyisi *et al.* (2015), who both reported improvements in workability. This apparent anomaly can be reconciled if it is remembered that GO-IBA™ has a higher water absorption ratio, almost double that of natural aggregates. The higher water absorption properties of GO-IBA™ could have competed with the free water for workability. Further investigation will be done in Section 4.3.1.2.

4.3.1.2 Pre-wetted GO-IBA™

As explained in Section 4.3.1.1, the slump results observed earlier were not expected, as the round profile of GO-IBA™ shown in Figure 3.22 should have improved the slump, akin to the well-known ball-bearing effects of sphere-shaped particles as illustrated in Figure 5.9. However, the slump was retrograding, and the high-water absorption of the GO-IBA™ itself was suspected as the main culprit. This prompted further investigation by attempting to isolate the high-water absorption of GO-IBA™ through pre-wetting, which simulates the conditions under which GO-IBA™ is typically supplied in the field.

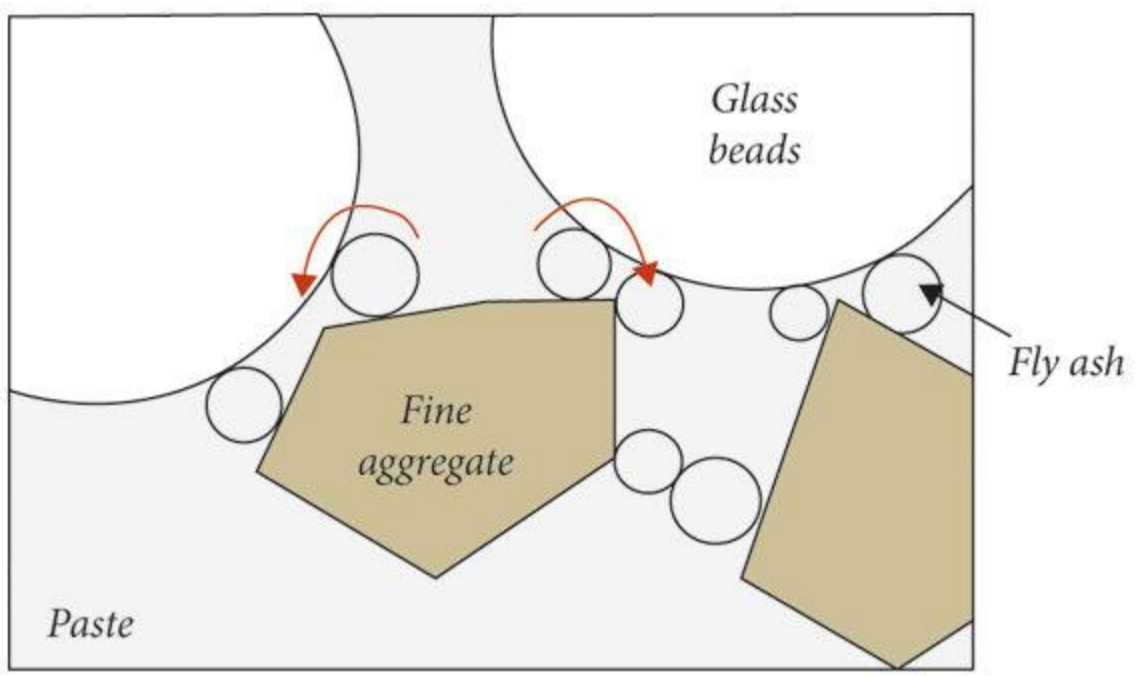


Figure 4.7: Ball-bearing effect of fly ash on the interaction between fine aggregates (Puthipad et al., 2016)

GO-IBA™ was pre-wetted in water for 24 hours and was drained of excess water to an SSD state before usage. This was to ensure the GO-IBA™ is saturated with water, thus eliminating the effects of water absorption from GO-IBA™ competing for free water needed for workability. M sand mix was used for this comparison to evaluate this phenomenon.

As seen in Figure 4.8, the slump results improve as the GO-IBA™ replacement level increases. Comparing the individual slump results of M Sand mixes, the replacement levels for W25 and W50 improved by a similar amount, at around 18.18%, compared to M25 and M50. W75 and W100 showed the most significant improvement, with increases of 46.34% and 475%, respectively. This further supports the observation of high-water absorption in GO-IBA™.

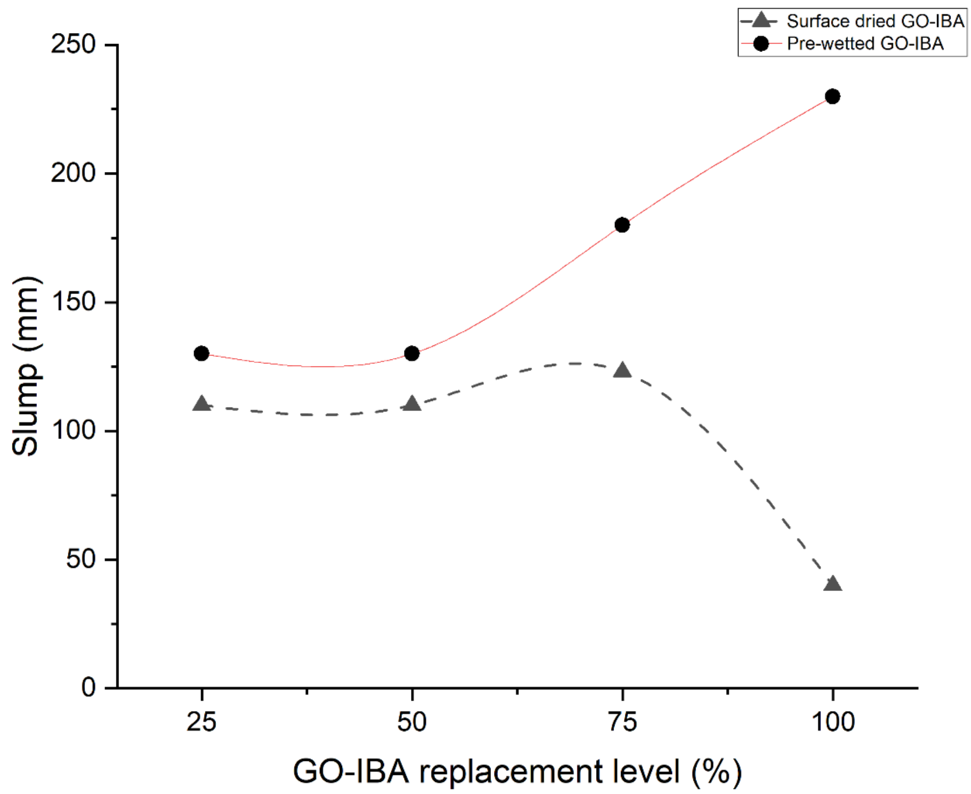


Figure 4.8: M sand mixes with oven-dried GO-IBA™ versus pre-wetted GO-IBA™™™™™™™™

4.3.1.3 Bleeding

Concrete is a homogeneous mixture of fine and coarse aggregates, cementitious binders and water. The lack of a homogeneous mixture, such as in the case of segregation of fines and coarse aggregates, will cause structural defects, including homogeneity and surface cracks. These defects not only affect the strength development of the concrete but also affect the concrete durability properties, resulting in a decline in the serviceability of the concrete.

Due to the high absorption of the GO-IBA™, no bleeding was observed for both C sand and M sand mixes throughout the replacement levels. The results are also congruent with the findings of the slump results observed in Section 4.3.1.1.

4.3.1.4 Setting Time

Similar to the slump test, an analogous dependence is observed in setting time; the setting time decreases with the replacement level for both mixes. The setting time results for C Sand mixes are illustrated in Table 4.2. The difference in initial and final setting time between C25, C50 and C75 is within 30 minutes and 1 hour, respectively. However, for C100, the difference was larger for both setting times (> 100 mins) when compared to C75.

Table 4.2

Setting time of C sand mixes with GO-IBA™ replacement

Sample Name	Setting Time (Mins)	
	Initial	Final
C0	310	440
C25	230	380
C50	205	310
C75	200	375
C100	80	215

The variations in M Sand mixes indicate that M0, M25, M50, and M75 exhibited minimal differences in both initial and setting times, with discrepancies of less than 30 minutes as shown in Table 4.3. These findings align with the results obtained from the slump tests discussed in Section 5.3.1.1 for M25, M50, and M75.

Table 4.3

Setting time of M sand mixes with GO-IBA™ replacement

Sample Name	Setting Time (Mins)	
	Initial	Final
M0	101	225
M25	110	220
M50	115	205
M75	100	200
M100	80	215

The above findings and trends further confirm that the contributing factor is the high-water absorptivity of GO-IBA™, which causes a change in the W/C ratio in the mix, thereby reducing the setting time.

4.3.1.5 Air Pore Content

Air pores within concrete are generally viewed as detrimental, as increased porosity can weaken durability and strength. It is widely accepted that porosity becomes problematic when it exceeds 3%.

After replacing with GO-IBA™ on both M Sand and C Sand mixes demonstrated higher air pore content, with C Sand mixes exhibiting a more linear trend compared to M Sand mixes, as shown in Figure 4.9. Notably, C Sand mixes surpass the 3% threshold at C50, C75, and C100/M100. As shown earlier in the case of slump results, a similar decreasing trend is observed for C50, C75, and C100/M100. The poorer workability might result in improper compaction of concrete, resulting in higher air pore content.

In M Sand mixes, replacing up to 25% of the M Sand with GO-IBA™ (M25) enhances air pore content. However, exceeding 50% replacement level leads to an increase in air pore content. This suggests that the optimal particle packing occurs within the 25% replacement range. At the 100% replacement level, the air content exceeds the 3% threshold.

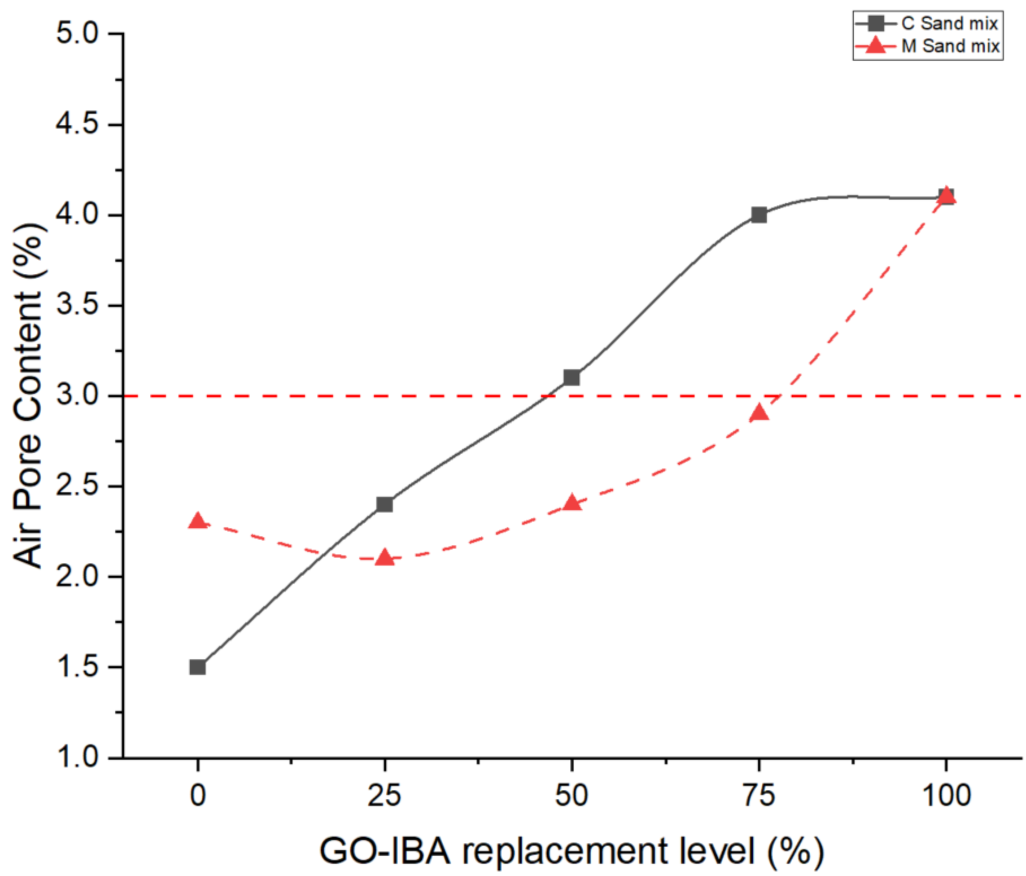


Figure 4.9: Air Pore Content results of C Sand Mix and M Sand mix with GO-IBA™ replacement

4.3.2 Hardened properties

4.3.2.1 Compressive Strength

As mentioned in Section 3.1.3, compressive strength is tested at 3, 7, 28, and 91 days. Similarly, the compressive strength results for both C sand and M sand mixes are plotted in Figure 4.10. and 4.11, respectively.

It is desirable to assess the earlier ages (3 and 7 days) due to the increased use of precast applications in the Singapore construction industry. A variation of 10% strength loss compared to the control mixes (C0 and M0) will be considered unsatisfactory. The reference for this arbitrary value is drawn from EN 206.

For C sand mixes, the results at early ages (3 and 7 days) displayed no clear trend and were statistically similar, as indicated by overlapping error bars. Similar patterns were observed at 28 and 91 days. Mixes with GO-IBA™ replacements (C25, C50, and C75) showed only a 1-3 MPa difference compared to C0. However, the results for C100 at 28 days were approximately 6 MPa lower than those for C0, reflecting a difference of 10.6%, which is considered unsatisfactory.

A similar trend was seen with M sand at 28 and 91 days. Except for M100, all replacement levels differed by only 1-5 MPa from M0 at 28 days, with statistically comparable results. In contrast, M100 were significantly lower in compressive strength, showing reductions of about 7 MPa at 28 days and 11 MPa at 91 days, equating to 13.6% and 18.2% less than M0, respectively, which were deemed unsatisfactory. The angular profile of M sand enhanced shearing resistance, leading to greater strength in M sand mixes (M0, M25, M50, and M75) compared to C sand mixes at the same levels.

In both mixes, it is demonstrated that up to 75% of the GO-IBA™ replacement level is satisfactory, while 100% of the replacement level is unsatisfactory because the reduction in compressive strength exceeds 10% compared to the control mixes.

It is conceivable that the rounder aggregate profile of GO-IBA™ does not fit into the common trend reported in the literature for both C sand and M sand mixes. Additionally, the decline of M sand content in the M-sand mixes should theoretically lower the compressive strength as the GO-IBA™ replacement level increases. However, this was not observed.

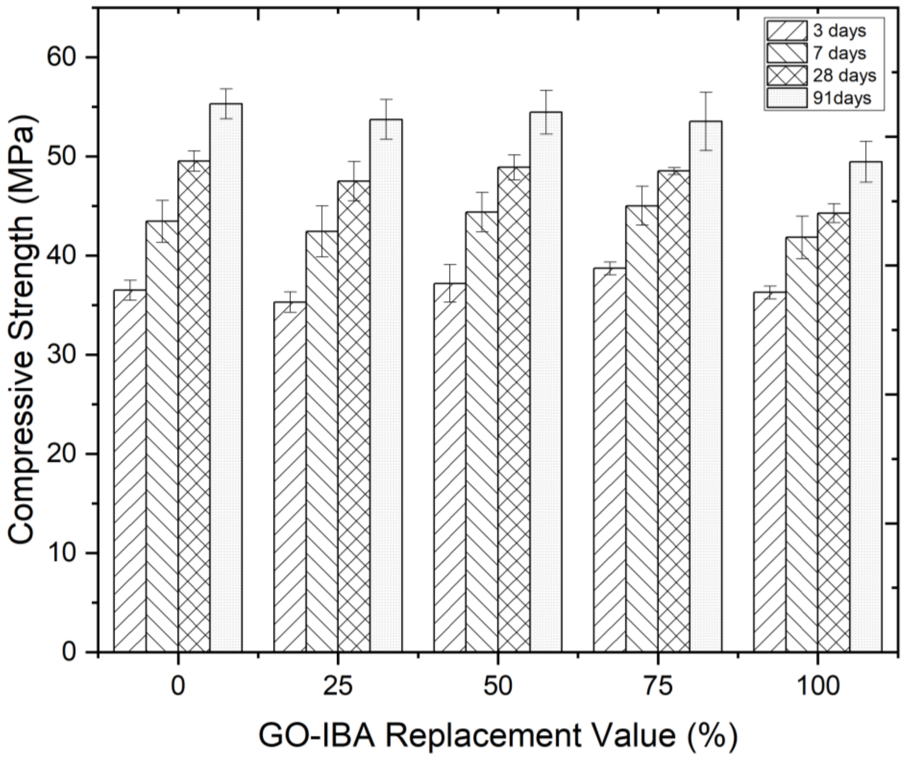


Figure 4.10: Compressive Strengths of C Sand mixes with GO-IBA™ replacement

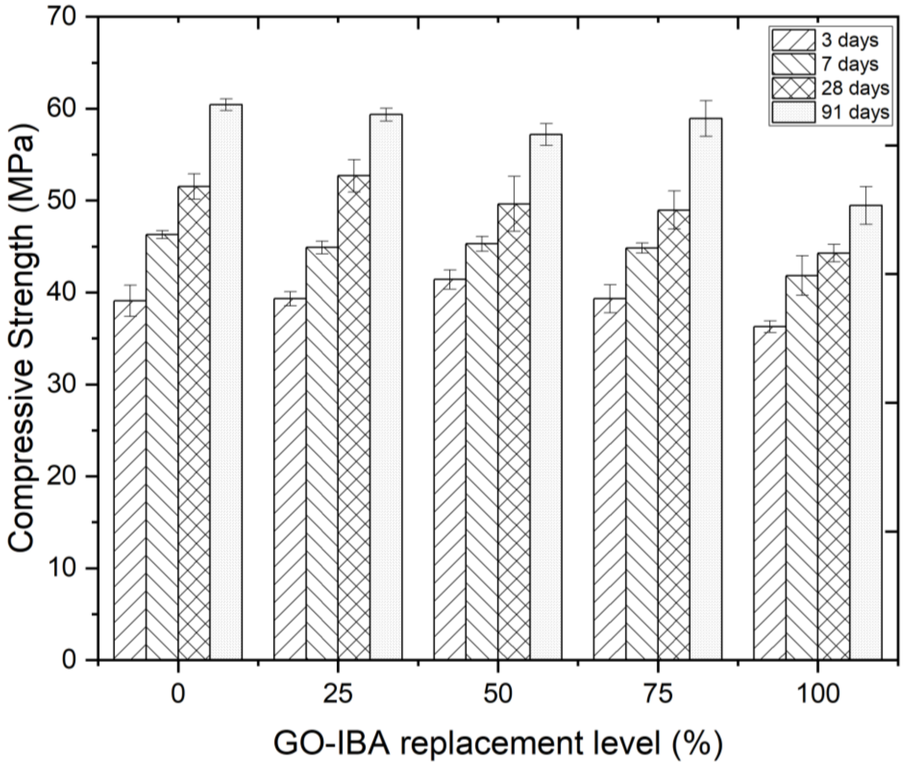


Figure 4.11: Compressive strengths of M Sand mixes with GO-IBA™ replacement

In Section 4.3.1.2, pre-wetted GO-IBA™ were proven to mitigate the high-water absorption and establish the ball bearing effect of GO-IBA™. In the next section, pre-wetted GO-IBA™ will be used further to investigate the ball bearing effect on compressive strength.

4.3.2.2 Pre-wetted GO-IBA™ Compressive Strength

Previously, in Section 4.3.1.2, the effects of pre-wetting GO-IBA™ on the concrete slump were studied. However, as the pre-wetted GO-IBA™ is saturated, a concomitant increase in water is introduced into the mix, resulting in a change in the water-to-cement (w/c) ratio of the concrete mix. It is a well-known phenomenon that the change in w/c ratio has a direct relationship with concrete strength.

Figures 4.12 and 4.13 show the pre-wetted GO-IBA™ replaced concrete at 7 and 28 day compressive strength performance compared to M Sand mixes, which use GO-IBA™ in SSD state in the same replacement ratio stipulated in Section 3.2.3.

In the M Sand mix, as detailed in Section 4.3.1.2, the 7-day compressive strength results from M0 to M75 were statistically comparable, with an average difference of approximately 1-5 MPa. After prewetting the GO-IBA™ prior to mixing, the difference between the mixes increased to around 6.5 MPa compared to the control. W25 exhibited similarities to M0, while W50 showed an improvement of nearly 2 MPa over the control. W75 and W100 experienced a slight decline from the control. The comparison between the pre-wetted GO-IBA™ and M Sand at 7 days showed an increase in compressive strength for W25 and W50, surpassing the control with values of 2.12 MPa and 3.75 MPa, respectively, reflecting improvements of 4.73% and 8.30%. In contrast, W75 and W100 recorded reductions of just 1.12 MPa and 1.97 MPa, respectively, compared to M75 and M100, representing percentage drops of 2.5% and 4.72%.

At 28 days, when comparing pre-wetted mixes to the control, a difference of 3.1-4.3 MPa was observed. W25 exhibits the highest compressive strength, increasing by approximately 5 MPa, after which the strength declines. Comparison of each replacement level of GO-IBA™ between mixes shows that all mixes exhibit higher compressive strength, with W25 to W100, an improvement of 7.12%, 12.45%, 6.79%, and 9.31% with respect to the increasing replacement ratios in M-sand mixes.

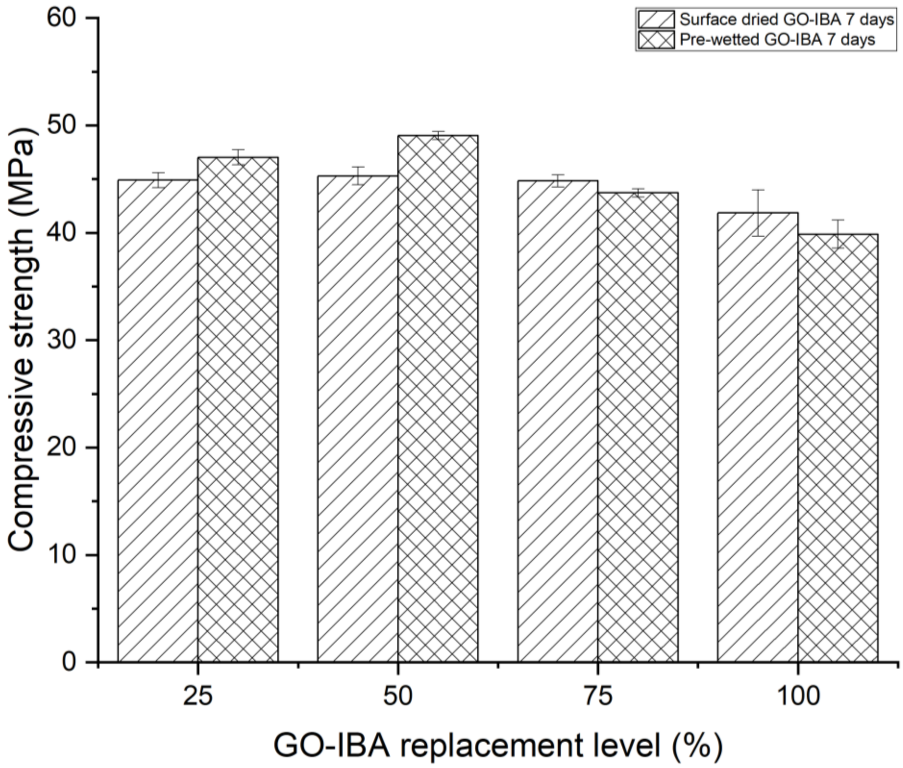


Figure 4.12: 7-day compressive strengths of M Sand mixes with oven-dried GO-IBA™ versus pre-wetted GO-IBA™ counterparts

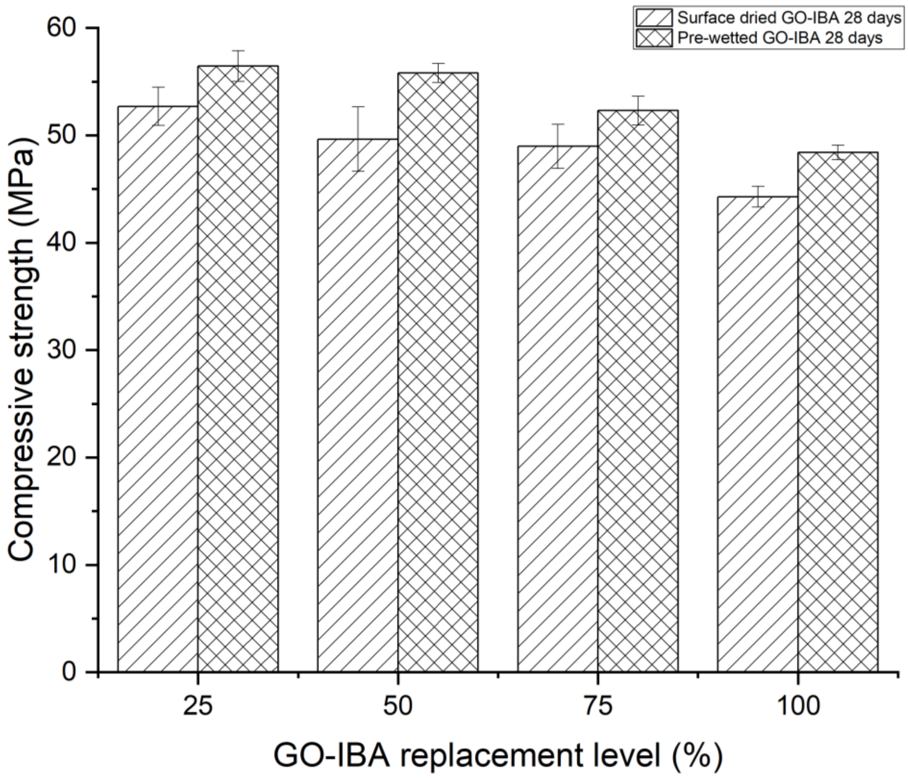


Figure 4.13: 28-day compressive strengths of M Sand mixes with oven-dried GO-IBA™ versus pre-wetted GO-IBA™ counterparts

In Figure 4.13, the study on the ball bearing effects on compressive strength did not reduce performance with increasing replacement levels, but rather complemented it at 25%, 50%, and 75% replacement levels. This further supports the hypothesis of increased internal friction resulting from the slightly larger particle size of GO-IBA™. Pul *et al*. (2017) reported that the higher the internal friction angles, the greater the increase in concrete strength, which is largely attributed to the size of the aggregates.

The compressive strength results suggest that the high absorption of the individual GO-IBA™ itself may be hindering the hydration of the cement paste. Pre-wetting the GO-IBA™ before mixing the concrete has promoted the internal curing (IC) and consequent desification of the ITZ. As Zhutovsky reported, by using water-saturated pumice as an IC agent, pre-wetted GO-IBA™ also displayed similar effects by displaying a higher compressive strength at 28 days compared to unwetted M sand mixes (Zhutovsky S., 2012).

4.3.2.2 Modulus of Elasticity (MOE)

In this section, it was decided to use an arbitrary threshold of 5% difference against control to denote unsatisfactory performance, drawing reference from a 95% Confidence Interval from a statistical point of view to avoid significant differences in concrete behaviour resulting in design errors.

As shown in Table 3.10, Eurocode 2 defines concrete strength designed to be at 40 or 50 MPa (Cylinder or Cube strength, respectively), which requires a minimum Elastic Modulus (*Ecm*) of 35,220 MPa.

As shown in Figure 4.14, C sand mixes passed the requirements. However, when compared to C0, the *Ecm* results of C75 and C100 failed the 5% threshold set.

All M sand mixes also met the requirement of the designed strength class, as shown in Figure 4.11. The decrease compared to M0 is more pronounced with increasing GO-IBA™ replacement levels. This is due to the higher strength of M sand mixes, resulting in a higher elastic modulus. Only M25 passes the 5% threshold set earlier. M50, M75 and M100 are not satisfactory.

Although all GO-IBA™ replacement levels can meet the stipulated *Ecm* in Eurocode 2, the significant drop after C50 for C Sand mix and M25 for M Sand mix is greater than 5%. The observed unsatisfactory *Ecm* results from both mixes may be undesirable from a structural design point of view.

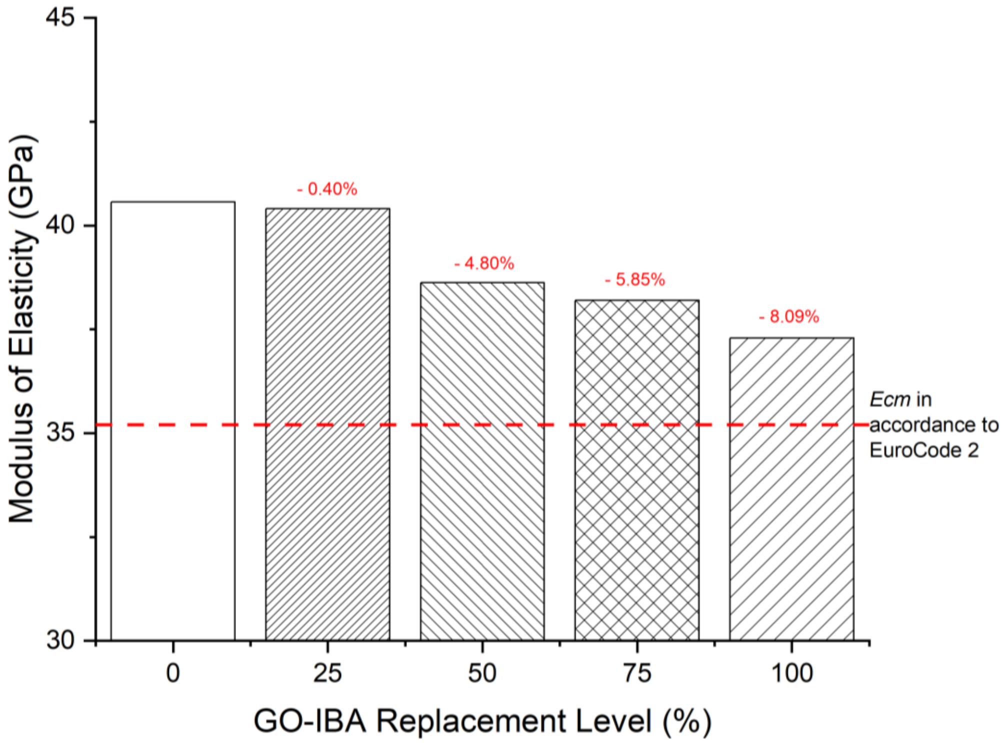


Figure 4.14: Elastic Modulus results of C Sand mixes with GO-IBA™ replacement

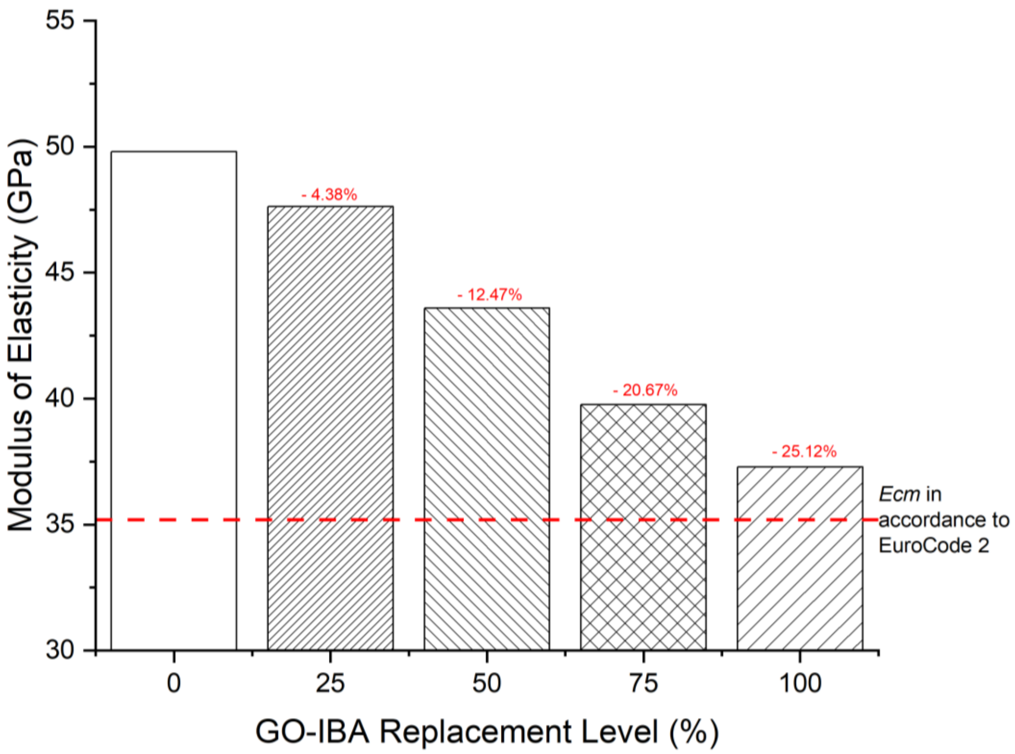


Figure 4.15: Elastic Modulus results of M Sand mixes with GO-IBA™ replacement

4.3.3 Durability properties

4.3.3.1 Water Penetration Test (WPT)

In this section, the effect of GO-IBA™ replacement on WPT for C-sand mixes and M-sand mixes will be discussed.

Figure 4.16 illustrates that the C Sand mixes have an initial penetration depth of 25 mm for C0, then exhibit a gradual decrease of approximately 2 mm at each replacement level of GO-IBA™ from C25 to C50. At C75, the penetration depth appears to plateau at 21 mm. C100 shows an increase back to 42 mm, nearly double that of C0, indicating a higher porosity in the concrete and enhanced connectivity among its pores.

The M Sand mixes, as illustrated in Figure 4.16, demonstrated a similar trend to C Sand concerning water penetration depth, though they experienced a less pronounced decline at each replacement level. The penetration depths ranged from 1 mm to 22 mm for M0 to M50, after which they plateaued at M75.

Both mixes show that WPT improves till the 75% replacement level mark. C100/M100 results are expected due to the particle size distribution being poorly graded compared to that of natural aggregates, causing voids and being interconnected, resulting in the high-water penetration depths.

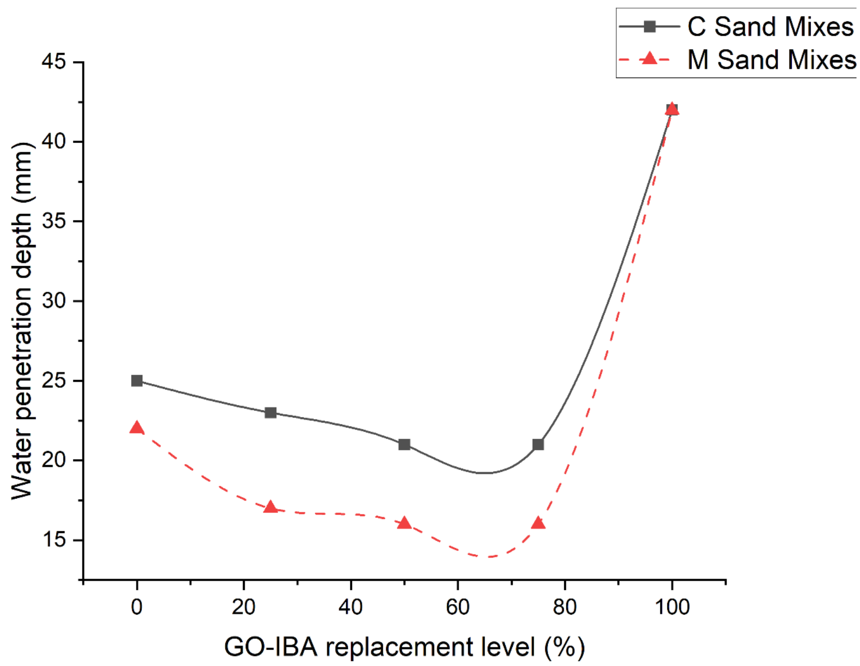


Figure 4.16: Water penetration results of C Sand Mix and M Sand mix with GO-IBA™ replacement

4.3.3.2 Water Absorption Test (WAT)

As mentioned in Section 3.1.4.9, the water absorption test is used to test the water transport mechanism through the capillary pores of the concrete.

The results in Figure 4.17 indicate no apparent effect on the C sand replacement levels. C0, C50, C75, and C100 were within the individual standard error range, with the exception of C25. Presumably, the poor workability could have resulted in the voids being formed as compaction is affected. M sand mixes, shown in Figure 4.17, showed clear signs of increments in water absorption as replacement levels of GO-IBA™ increased. M0 and M25 are at 2.56% and 2.69%, respectively. M50 and M75 are at 3.54% and 3.36%, respectively, and M100 is at 5.14%.

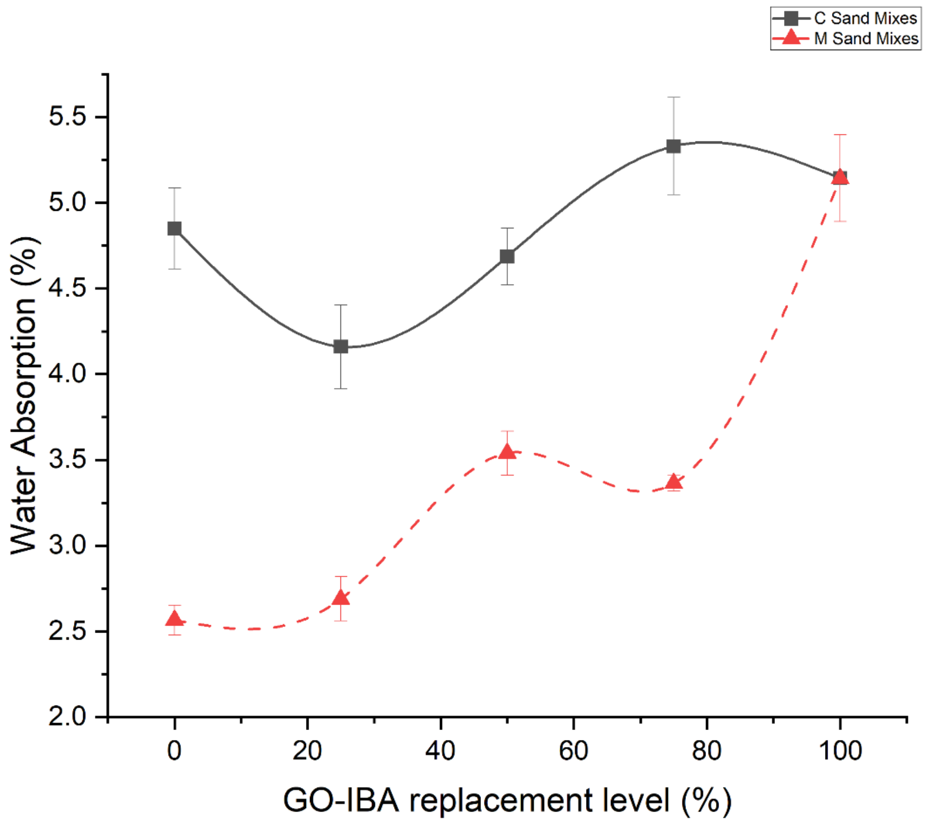


Figure 4.17: Water absorption results of C Sand Mix and M Sand mix with GO-IBA™ replacement

4.3.3.3 Rapid Chloride Penetration Test (RCPT)

Generally, RCPT test results of C sand mixes shown in Figure 4.18 showed improvements as the replacement level of GO-IBA™ increased, with C0 and C25 RCPT results in the high range in the long-term chloride penetration classification, C50 and C75 in the moderate range and C100/M100 in the low range.

It follows from the data as shown in Figure 4.18, that the major influence on the RCPT results is exerted by GO-IBA™ in the C Sand mixes, whereas a modest influence is ascribable to the M Sand mixes.

The observation here is that with increasing GO-IBA™ replacement levels, the RCPT results would be lower, which suggests that GO-IBA™ replaced concrete is more resistant to chloride ion penetration with increasing GO-IBA™ replacement levels. The reasons will be described in Section 4.4.2.

As Li *et al.* (2023) reported, the treated IBA has a significantly lower chloride content compared to rIBA, by approximately 20 times (Li *et al.*, 2023). A more plausible observed effect, as concluded by Liu *et al.* (2022b), is that the porous nature of GO-IBA™ could have resulted in a more refined ITZ.

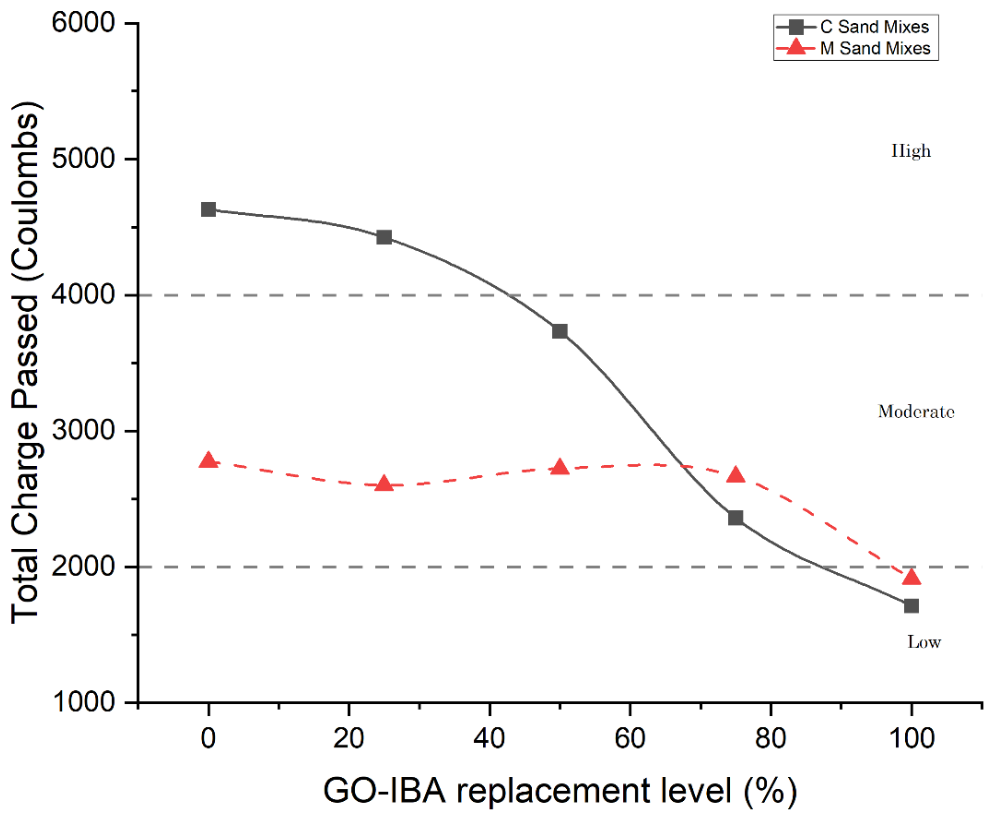


Figure 4.18: RCPT results of C Sand mix and M Sand mix with GO-IBA™ replacement

4.3.3.4 Carbonation

As explained in Section 3.1.4.11, carbonation is the eventual killer of concrete due to its atmospheric abundance. As shown in Figure 4.19, M0 and M25 exhibit carbonation penetration of 1.85 mm and 2.68 mm, respectively. In contrast, M50 and M100 show no carbonation penetration at 70 days of carbonation testing. Photos of the specimens after being sprayed with phenolphthalein are shown in Figures B.1 – B.8 in Appendix B.

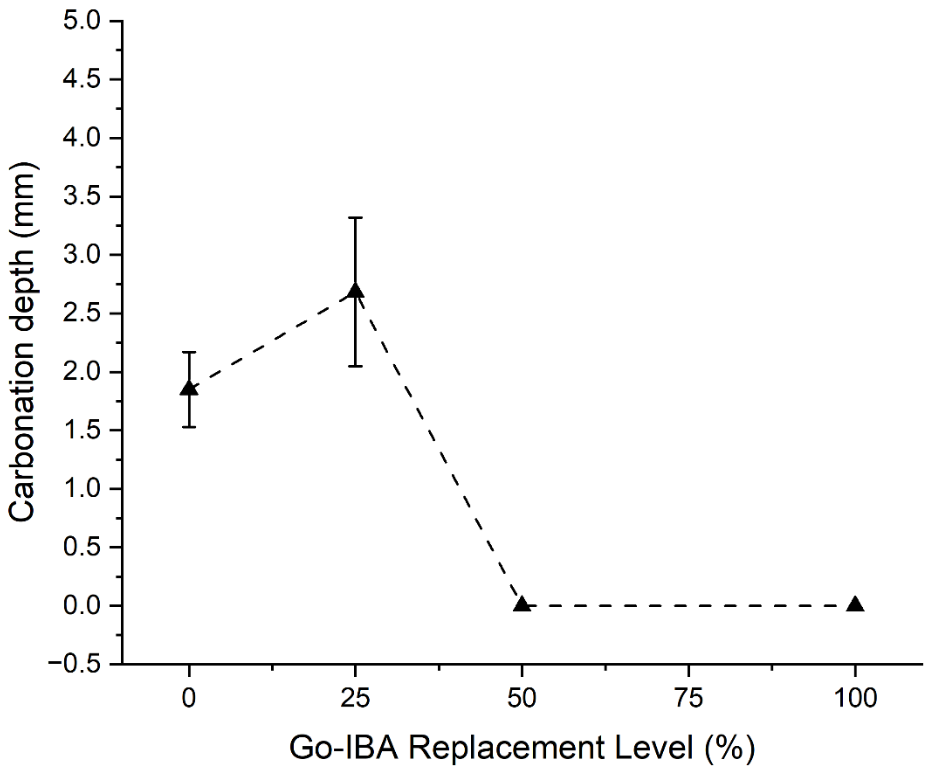


Figure 4.19: Carbonation test results of M Sand mixes with GO-IBA™ replacement

4.4 Discussion of the Relationship between Different Concrete Properties

4.4.1 Relationship of Fresh Properties to Compressive Strength

Fresh concrete properties are often observed in the field as an indicator of strength development for known concrete mixes and materials. For example, a drier concrete mix with a lower slump for concrete mixes designed for 40 MPa will tend to have higher strength at 28 days due to sand being too dry during concrete production. Consequently, the relationship between fresh properties and compressive strength of GO-IBA™ replaced concrete should be explored.

As observed in Section 4.3.1.1, the high-water absorption of GO-IBA™ has led to lower workability and faster setting times, which is detrimental for most concrete applications but may be beneficial for specific applications. Possible mitigation solutions concerning workability were also explored in Section 4.3.1.2. It also showed that the ball-bearing effect is impeded due to the high water absorption of GO-IBA™.

When comparing the decreasing slump results to compressive strength, both C Sand and M Sand mixes with replacement levels of up to 75% showed resilience in compressive strength, with differences of 1-3 MPa and 1-5 MPa, respectively. At 100% replacement, there is a drastic reduction in compressive strength for C Sand and M Sand mixes, at 10.6% and 18.2%, respectively. A similar observation is also observed with setting time properties with increasing replacement levels of compressive strength.

The apparent contradiction between GO-IBA™ replaced concrete and conventional concrete can be reconciled by the higher water absorption of GO-IBA™, which is consistent, resulting in poor workability and hence leading to a lower compressive strength. Another reason is that the single-size gradation of GO-IBA™ results in higher porosity, as shown in Figure 4.20, which is also supported by the air pore content results shown in Figure 4.9.

100% replacement levels exhibit this phenomenon significantly, as both C Sand and M Sand mixes at 100% replacement showed a drastic drop in slump results, and the reduction in compressive strength was more pronounced than at the other replacement levels. The segregation of C100/M100 shown in Figure A.5 also greatly suggests the reasons mentioned earlier.

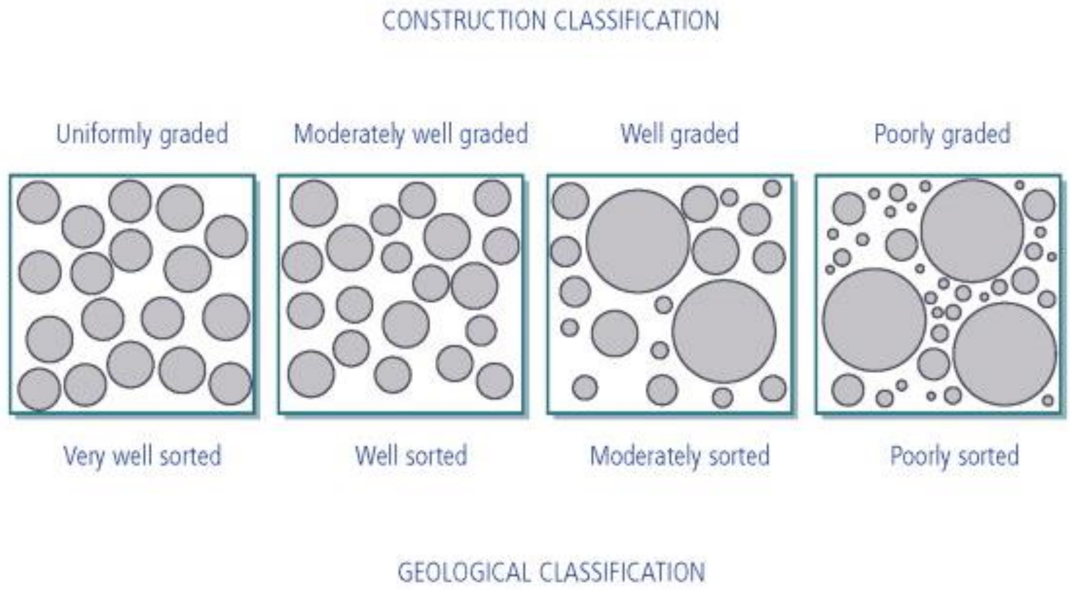


Figure 4.20: Effect of different particle size gradation on concrete packing (Ingham, J., 2010)

4.4.2 Relationship of Durability Properties vs Compressive Strength

Most chronic concrete attacks, such as chloride attack, carbonation, sulphate attack and Alkali-Silica reaction (ASR), commonly involve water as a medium within the hardened concrete, which is heavily influenced by the pore structure of the concrete.

The topic of pore structure is still a very controversial area, both in terms of experimental setup and the interpretation of results. In light of this, direct tests are developed from the cause of failure as they offer more straightforward data interpretation and readily available testing methods.

Water penetration and water absorption tests are examples of tests that directly measure the movement of water through concrete. Their relationship with compressive strength is commonly studied by many scholars, making it a reliable finding, as the denser the pore structure, the higher the compressive strength. When comparing the WPT to compressive strength results of M sand mixes, the compressive strength decline from M0 to M75 mirrors the gradual decline in WPT with increasing replacement levels. This result is supported by the observations of scholarly works by Dhir et al. (2002), Liu et al. (2022a), and Tang & Brouwers (2018), which also reported declining strength characteristics along with the round shape profile of GO-IBA™. This is also reflected in the M100 results of M Sand mixes, with both compressive strength and water penetration results reduced drastically compared to other replacement levels.

C Sand mixes also mirrored the same trend for WPT and Compressive Strength, but not the water absorption test. It is conceivable that the lack of fines and the rounder profile of C Sand create higher capillary pores, resulting in higher water absorption. Consequently, the M100 WPT results in higher values because the higher angular fines are not present at the surface of the porous GO-IBA™, blocking the path of water. M0-M75 water absorption and WPT results support this observation.

On the other hand, RCPT did not follow the trend but instead showed an opposite trend, with lower RCPT results as the replacement level increased. A possible explanation is that the pore structures of GO-IBA™ replaced concrete increases in porosity, with increased macro pores and capillary pores, but a decrease in transitional pores, resulting in a lower RCPT value as the replacement level increases. The work done by Liu *et al.* also showed that the pore refinement occurs with increasing replacement level, stating that the decrease in transitional pores would increase the resistance to chloride penetration, although the overall pores are increased(Liu *et al.*, 2022b).

Carbonation also followed the RCPT trend, as shown in Figure 4.19 and showed an inverse trend to compressive strength. Van der Wegen *et al.* (2013) postulated that the high-water absorption of the treated IBA could have contributed to the low moisture in the concrete, which impeded the carbonation, as CO_2 needs to be dissolved in water to create carbonic acid. This reported phenomenon also supports the observation, but further investigation is needed, which is beyond the scope of this research.

4.5 Summary

As previously mentioned in Section 4.4.1, the single-sized gradation of GO-IBA™ could have resulted in the worst performance in the fresh properties compared to compressive strength. To investigate further, the results of pre-wetted GO-IBA™ were examined in conjunction with other M sand mix results. The round profile of the GO-IBA™ makes it easy to form voids within the concrete matrix, let alone the single-sized gradation of the GO-IBA™. As mentioned in Section 5.4.1, most of the fresh properties actually support it. Since most of test uses GO-IBA™ in dry conditions, the effects of high-water absorption were present, which did not give conclusive evidence on the effect of the particle sizing of GO-IBA™ on the concrete properties.

The segregation of C100/M100 is shown in Figure A.18 in Appendix A, which is highly suggestive that the cause might not be due to only the high-water absorption of GO-IBA™. A similar reduction in compressive strength in W100 compared to the control was observed, mirroring the performance of M100, suggesting the macro properties are similar between these two mixes.

Consequently, when comparing the air pore content results of the M100 and W100, it is clear that the round-shaped profile of GO-IBA™ creates voids and allows water to bleed, caused by segregation as the lighter GO-IBA™ allows the denser granite coarse aggregate to settle to the bottom.

The MOE trend for the M sand mix also highly suggested that the ball bearing effect covered in Section 4.3.1.2 reduces the concrete internal friction, causing the reduction in MOE as the replacement level increases.

In view of the durability properties with the aforementioned observations, GO-IBA™-replaced concrete is summarised as below;

1. C Sand WPT results are the inverse of the WAT results due to the saturation of pores, resulting in lower WPT results.
2. As such, a 25% GO-IBA™ replacement level for both mixes is conservatively recommended for usage, with 50% GO-IBA™ still achieving broadly similar properties to control.
3. From the foregoing analysis, it is clear that favourable results and encourage the perusal of GO-IBA™ as an alternative to natural fine aggregates.

Chapter 5 - Effect of Cement Replacement

5.1 Overview

The performance of GO-IBA™, discussed in Chapter 5, centres on substituting various aggregate types with 100% Ordinary Portland Cement (OPC) as the cement binder in the concrete design mix. Consequently, it is essential to examine the viability of using GO-IBA™ as an acceptable aggregate replacement in PBFC concrete, as this could further promote the incorporation of more sustainable cementing materials.

5.2 Fresh Properties

5.2.1. Slump

As the replacement of GO-IBA™ increases, the observed slump results show a gradual decline, going from 230 mm at P0 to 180 mm at P75. This reduction becomes more pronounced at P100, where the slump results observed declines to just 60 mm, as illustrated in Figure 5.1. The results for P100 reflect a degradation of two classes in slump classification. This trend aligns closely with the slump results discussed in Chapter 5.

GGBS use in concrete has been reported by Oner and Akyuz (2007), wherein it was demonstrated that the workability of the concrete improves. However, the slump results observed for GO-IBA™ replacement in PBFC concrete mixes are contrary to the works of Oner and Akyuz (2007). These findings further reinforce the observation made in Section 4.4.2 of the higher probability of high water absorption of GO-IBA™, which affects the workability of the concrete.

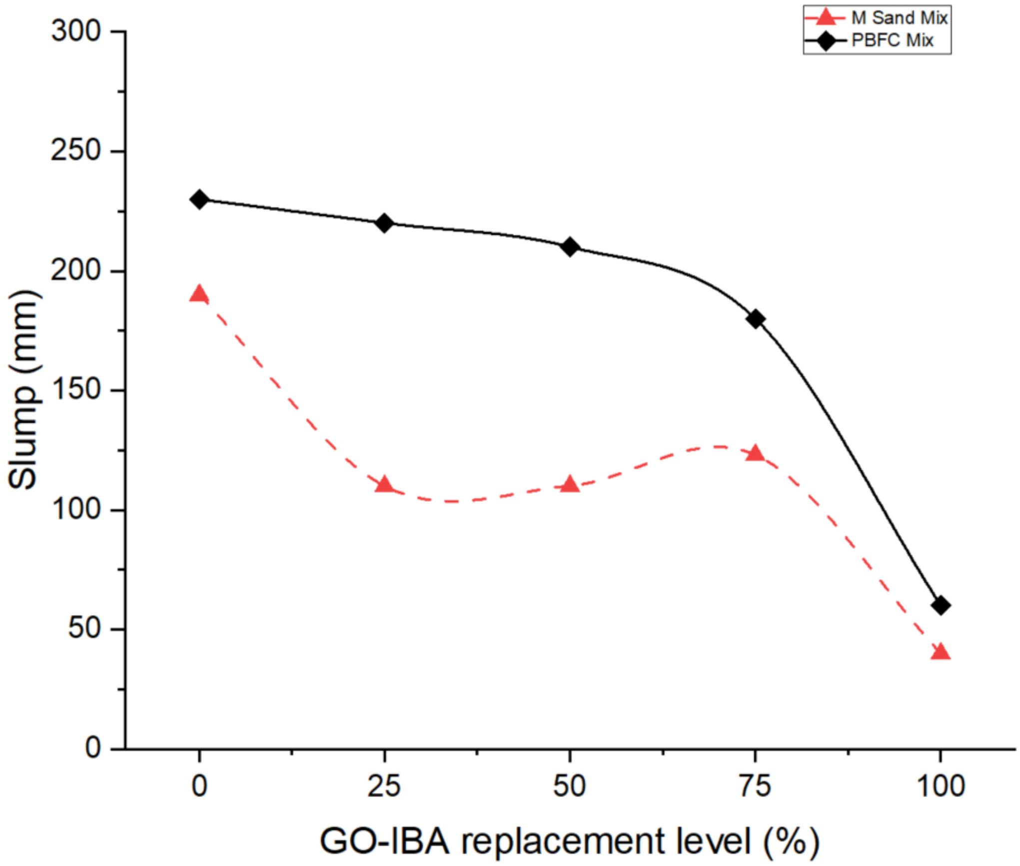


Figure 5.1: Slump results of PBFC mixes with GO-IBA™ replacement

5.2.2 Bleeding

No bleeding was observed for PBFC mixes throughout the replacement levels. The results are also consistent with the findings of the slump results observed in Section 5.2.1.

5.2.3 Setting Time

Similar to Section 5.2.1, the setting time decreases with the increasing levels of GO-IBA™ replacement as seen in Table 5.1. For comparison, M0 has an initial setting time of 101 mins and a final setting time of 225 mins, while P0 was at 165 mins and 310 mins. This observation corroborates the widely known delayed setting characteristic of the high level of GGBS-replaced concrete.

The trend remained broadly similar to a decreased setting time as Section 5.3.1.3 throughout the replacement levels, with only the final setting deviating at P50, P75, and P100. Again, the phenomenon can be explained by the high-water absorption effects of GO-IBA™. As described in Section 4.3.1.4 and 5.4.2, the higher the replacement level, the shorter the setting time generally becomes due to the change in W/C ratio caused by the high-water absorptivity of GO-IBA™.

The setting time may be improved by prewetting GO-IBA™ before mixing, as experimentally observed in Section 5.4.2. However, its effects, such as slump and bleeding, will need to be investigated to ensure proper concrete workability and homogeneity, which is beyond the scope of this research.

Table 5.1

Setting time of PBFC mixes with GO-IBA™ *replacement*

Sample Name	Setting Time (Mins)	
	Initial	Final
P0	165	310
P25	158	287
P50	153	247
P75	129	265
P100	102	250

5.2.4 Air Pore Content

The Air Pore Content of fresh concrete is closely related to its workability, as less workable concrete requires more compaction to achieve denser properties, which in turn are filled with voids that affect other properties. As elucidated in Section 4.3.1.5, more than 3% of air pore content is considered detrimental due to the potential impact on durability properties.

As illustrated in Figure 5.2, P0 exhibited a value of 1.8%, while both P25 and P50 reported similar air pore content at 2.1%. This was followed by a steady increase, with P75 measuring 2.7% and P100 reaching 3.4%. This trend mirrored that of the slump results, with a noticeable increase at P100. It appears likely that the inclusion of GGBS enhanced the workability, as evidenced by a reduction in air pore content from 2.3% in M0 to 1.8% in P0. Additionally, the previously noted high water absorptivity of GO-IBA™ may also play a role in affecting workability, contributing to the formation of more significant voids within the concrete. A more thorough investigation is provided in Section 5.5.1.

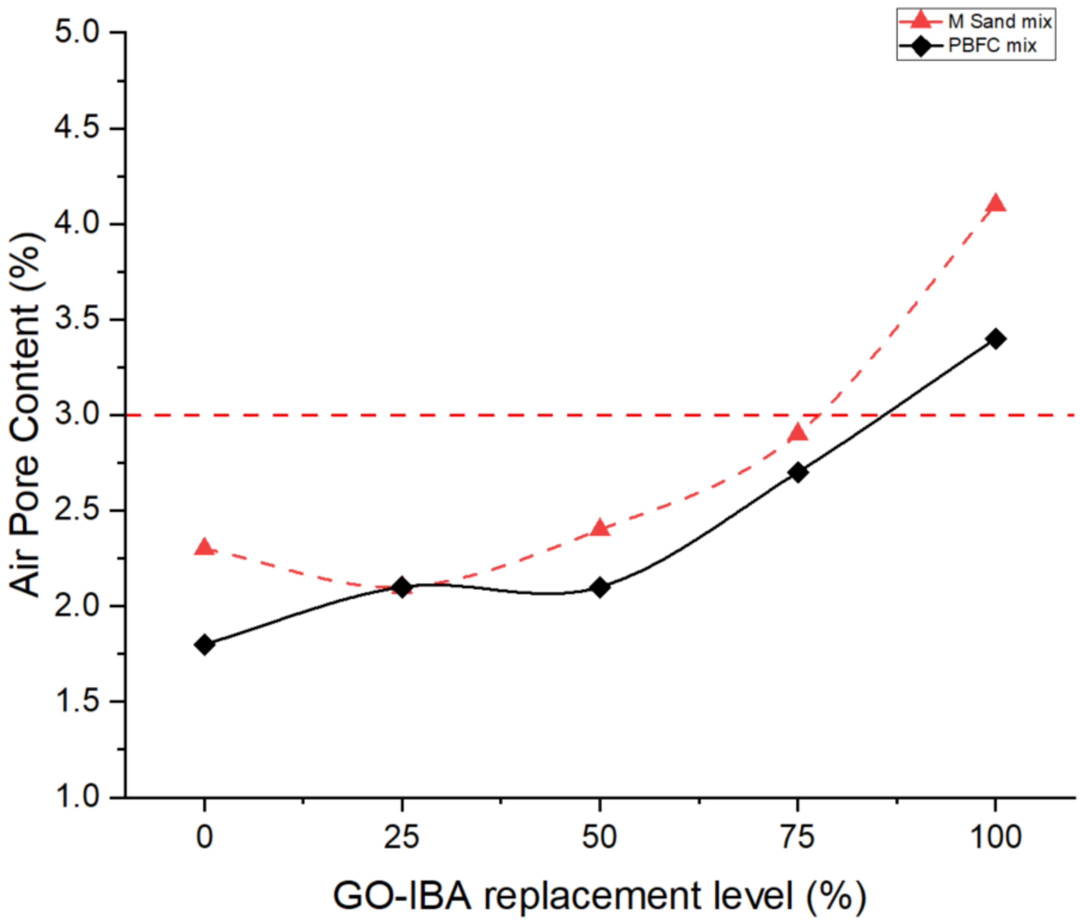


Figure 5.2: Air Pore results of PBFC mixes with GO-IBA™ replacement

5.3 Hardened Properties

5.3.1 Compressive Strength

For the PBFC mixes, the compressive strength data are illustrated in Figure 5.3. The 3 day compressive strength results indicate that the P50 mix exhibits the highest strength among the replacement levels. However, this finding is considered inconclusive due to the slower strength development associated with a high GGBS cement binder. The 7 day compressive strength improved slightly.

At both the 28 day and 91 day marks, the trend remained broadly consistent, with the compressive strength values for P25, P50, and P75 showing no significant statistical differences from one another. The 28 day results recorded were 40.48 MPa for P0, followed by 38.50 MPa for P25, 35.83 MPa for P50, 36.53 MPa for P75, and 34.88 MPa for P100.

Due to the slow rate of strength development of GGBS, 91-day compressive strength will be more comparable. At 91 days, except for P100, the other GO-IBA™ replacement levels compared to the control show a difference of only 1-3 MPa. The compressive strength from P0 to P100 is 44.86, 43.00, 41.69, 42.47, and 39.36 MPa, respectively. As outlined in Section 4.3.2.1, a loss of more than 10% in compressive strength is unsatisfactory. At 28 days, P50 and P100 showed losses of 11.48% and 18.83%, respectively. At 91 days, only P100 failed the criterion with a 12.25% loss compared to P0.

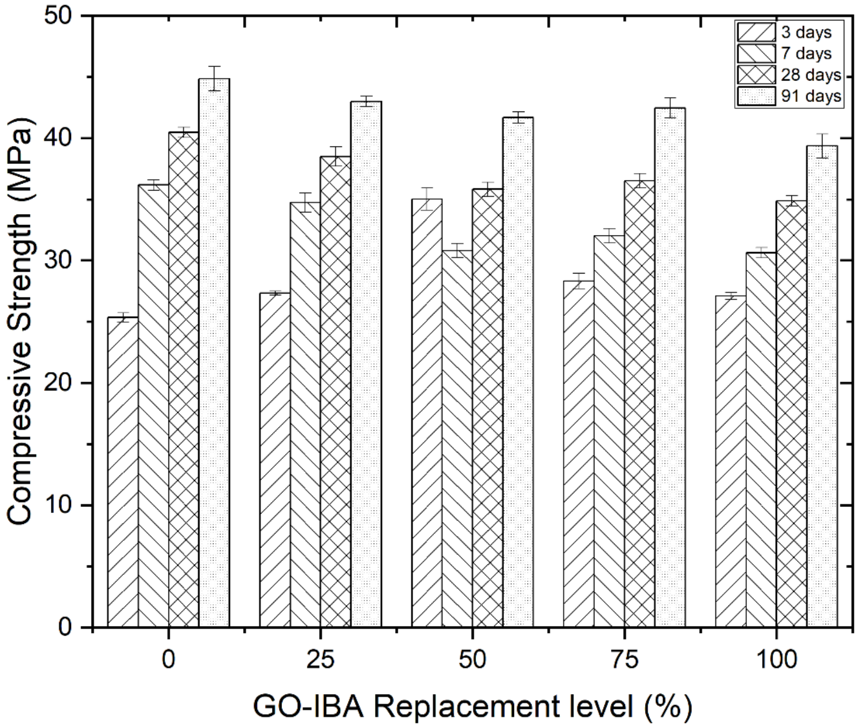


Figure 5.3: Compressive strengths of PBFC mixes with GO-IBA™ replacement

5.3.2 Modulus of Elasticity

As elucidated in Section 3.1.4.8 and Table 3.10, concrete compressive strength designed at C40/50 will have to meet a minimum *Ecm*. Additionally, a failure criterion of more than a 5% difference compared to the control is deemed unsatisfactory.

The *Ecm* for PBFC mixes is plotted in Figure 5.4. Except for P100, all other GO-IBA™ replacement levels meet the EuroCode 2 minimum requirement. When compared to P0 *Ecm* results at 45.81 GPa, P25 to P100 exhibited a declining trend of 44.74, 39.32, 37.19, and 34.17 GPa. When compared and viewed in percentage, P25 to P100 was at 2.35%, 14.17%, 18.82% and 25.41% lower than the control. It is significant that only the P25 mix meets the 5% threshold limit.

The gradual decline of *Ecm* is expected, as discussed in Section 4.3.2.2, aggregates make up more than 70% of the concrete volume, coupled with the roundness of GO-IBA™. Additionally, the trend of Ecm results for PBFC mixes is similar to that of C sand and M sand mixes, indicating that an increase in GO-IBA™ replacement level would result in a decrease in *Ecm*.

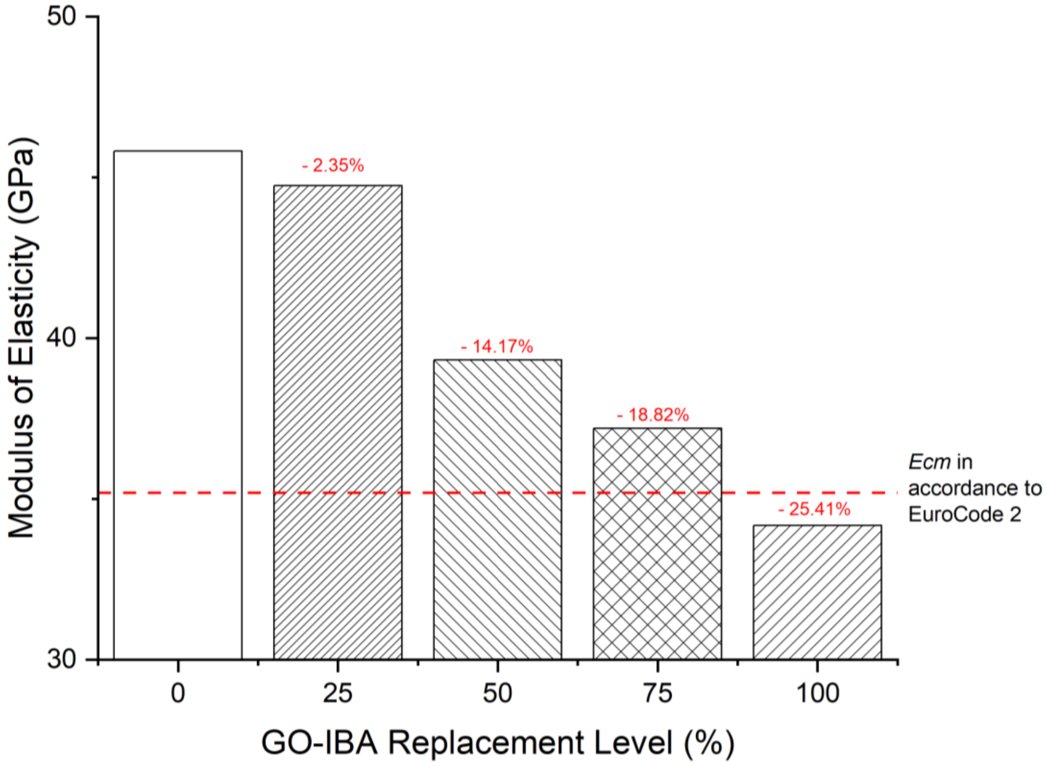


Figure 5.4: Elastic Modulus results of PBFC mixes with GO-IBA™ replacement

5.4 Durability properties

5.4.1 Water Penetration Test (WPT)

The results from the GO-IBA™ replacement in PFBC mixes demonstrated broadly comparable outcomes. As illustrated in Figure 5.5, P0 recorded a measurement of 26mm, while both P25 and P50 yielded similar results at 29mm. This improved to 18mm for P75, which then returned to 26mm for P100. However, when the standard error bars are considered, most of the mixes did not reveal significant differences from one another, indicating that, apart from P75, there is no statistical distinction among the mixes.

The results are consistent with the widely recognised GGBS benefit of densifying concrete, as the increase in GO-IBA™ replacement did not affect the water penetration results, unlike the results for C sand and M sand discussed in Chapter 4, which showed a rise in water penetration depth at 100% replacement levels. Its water penetration resistance, as observed in P75 at 18mm, and P100 is comparable to P0.

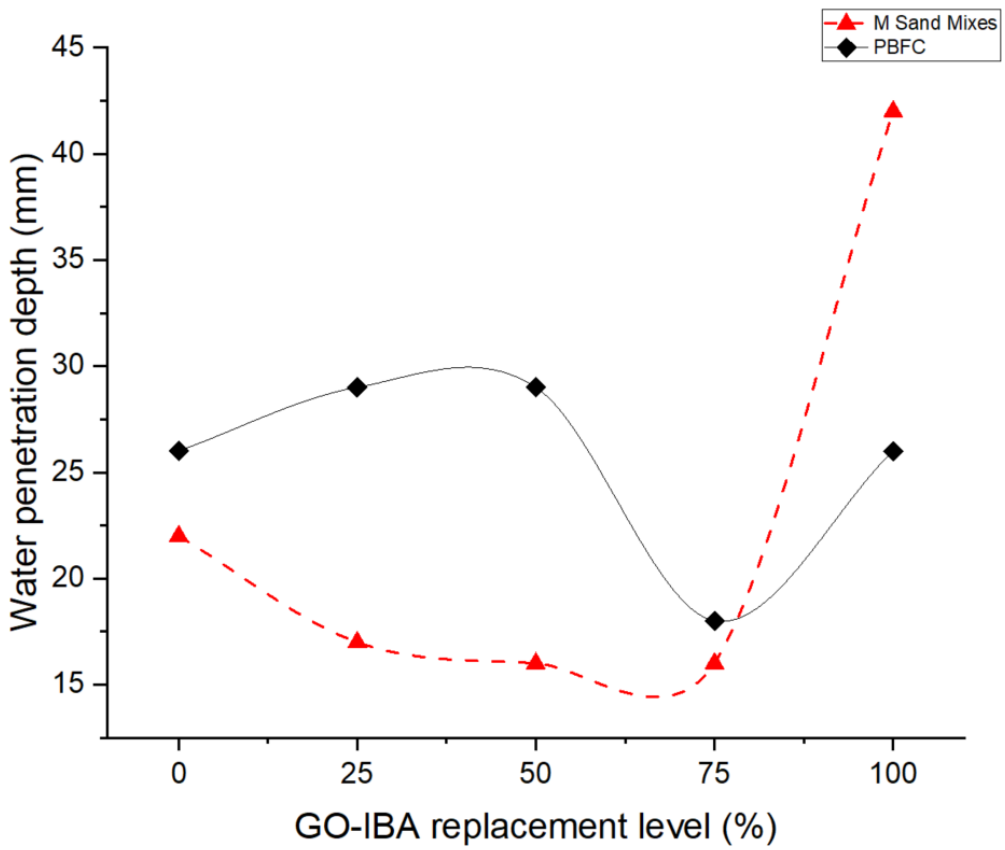


Figure 5.5: Water Penetration Test results of PBFC mixes with GO-IBA™ replacement

5.4.2 Water Absorption Test

The water absorption rates for PBFC mixes, as illustrated in Figure 5.6, indicate no clear trend in the WAT results, similar to C sand mixes as discussed in Section 4.3.3.2. However, a notable distinction is that the results are statistically different for all GO-IBA™ replacement levels in the PBFC mixes. The absorption rate for P0 was recorded at 3.27%, while P25 showed an improvement to 2.94%. This was followed by a deterioration in P50 and P75, with rates of 4.01% and 4.317%, respectively, before a slight improvement to 3.90% for P100.

The water absorption results for PBFC mixes differ significantly from those of M sand mixes, primarily due to the substitution of GGBS in the cement binder proportion. This contrasts with the widely recognised notion that GGBS enhances water permeability characteristics. Given the latent hydraulicity associated with GGBS hydration, the pore structure is postulated to remain less dense at the 28 day mark of the water absorption test. It is axiomatic that this results in greater porosity within the concrete, which accounts for the observed increase in water absorption for P0 at 3.27%, compared to M0 at 2.57%. Moreover, the subsequent results for PBFC mixes are inconclusive, mainly due to the reduced degree of hydration of GGBS at this testing age.

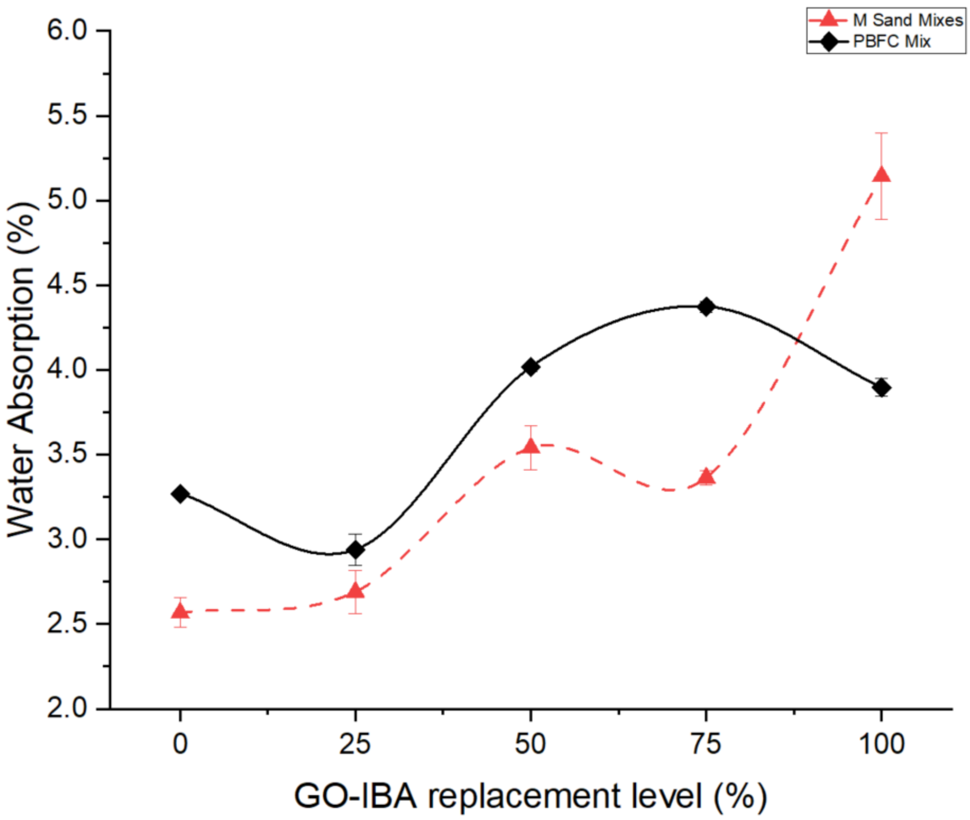


Figure 5.6: Water Absorption Test results of PBFC mixes with GO-IBA™ replacement

5.4.3 Rapid Chloride Penetration Test (RCPT)

Referring to Figure 3.11, RCPT results of PBFC mixes as illustrated in Figure 5.7 in general, have results in the very low regions, in accordance with the ASTM C1202 guidelines. P0 to P100 shows a constant reduction in results of 560, 533, 365, 277 and 243 Coulombs, respectively.

The low results of this test series are consistent with the well-known characteristic of GGBS in improving RCPT results. Similarly, as the GO-IBA™ replacement level increases, the results are lower, signifying an improvement in the chloride resistance of the concrete.

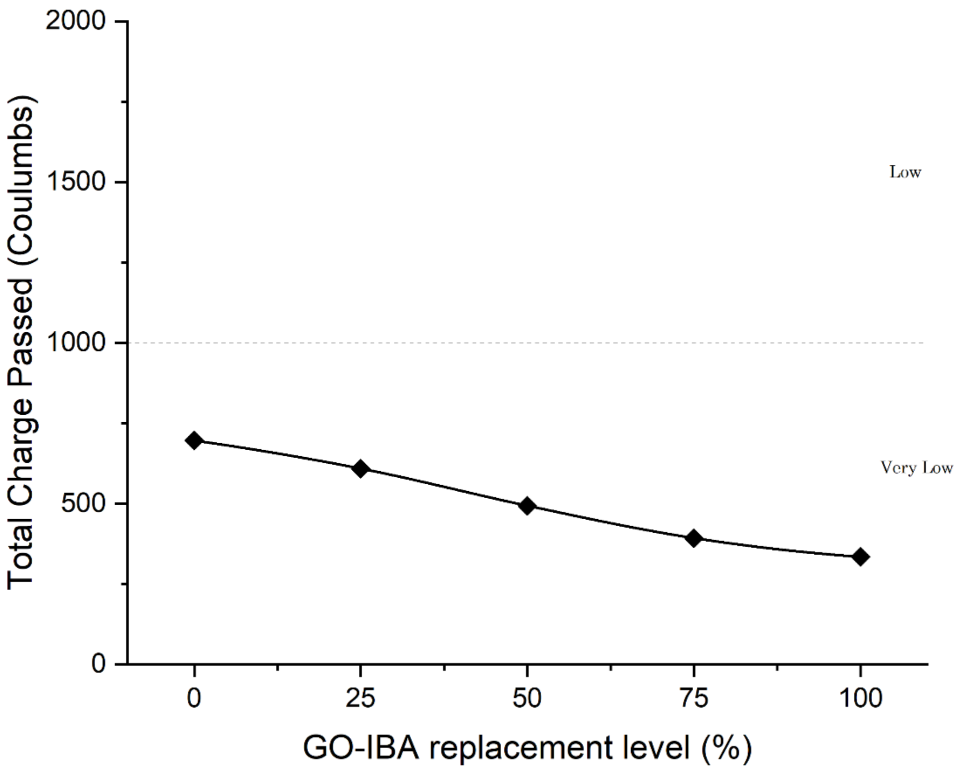


Figure 5.7: RCPT results of PBFC mixes with GO-IBA™ replacement

5.4.4 Carbonation Test

Carbonation test results in Figure 5.8 show P0 to P100 at 13.93, 11.89, 15.83 and 12.07mm, respectively. Compared to M Sand mixes, PBFC has experienced higher levels of carbonation. Lye *et al.* (2016) reported that the reason for this observation is twofold: (1) Hydration of GGBS consumes the calcium hydroxide to form CSH, causing a drop in pH. (2) The low degree of hydration due to the insufficient curing and slow reaction of GGBS increases the porosity of the pore structure, causing the carbonation of CSH (Lye *et al.*, 2016). Photos of the specimens after being sprayed with phenolphthalein are shown in the appendices from Figures B.9 – B.16.

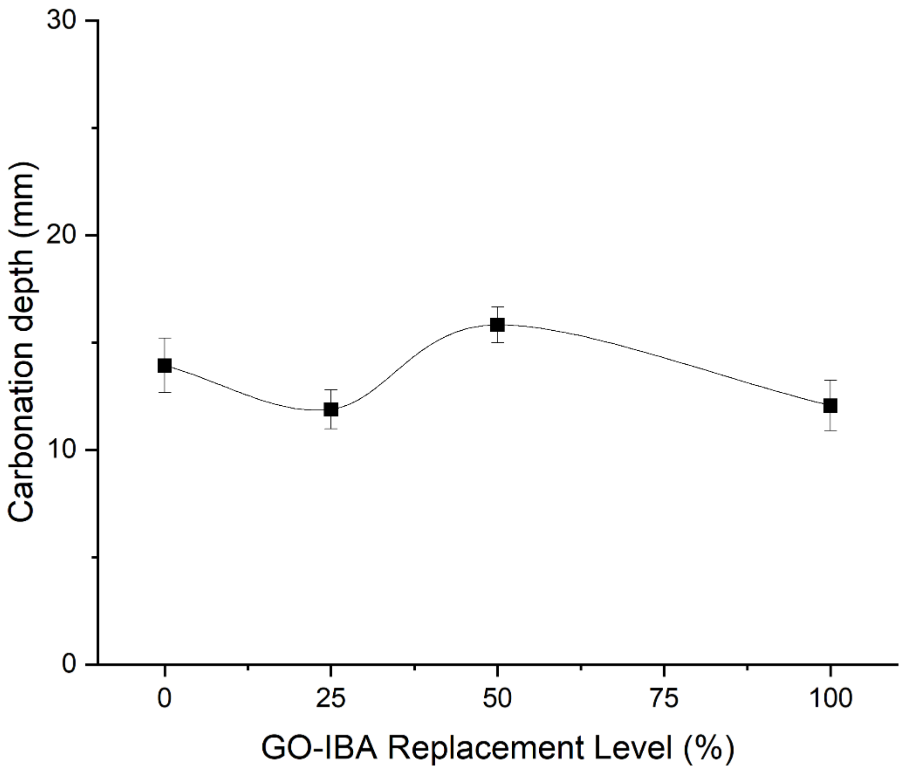


Figure 5.8: Carbonation results of PBFC mixes with GO-IBA™ replacement

5.5 Discussion on the Relationship of Different Concrete Properties between PBFC mixes and M Sand mixes

5.5.1 Fresh Properties of M Sand Mix vs PBFC Mixes

When comparing the slump results of PBFC mixes to M Sand mixes, PBFC mixes performed better than M sand mixes, as shown in Figure 5.1. By comparing the control mixes, P0 had 250mm and M0 had 190mm, showing a 60mm improvement. Even when comparing a 100% replacement level, it is generally considered better to use P100 at 60mm compared to M100 at 40mm. The results are in line with the findings of Oner & Akyuz (2007), who reported that the use of GGBS in concrete improves its workability.

Additional support of this phenomenon is given by the Air Pore content results shown in Figure 5.9. As shown experimentally, the air pore content of PBFC mixes is generally lower than that of M sand mixes. A comparison of P100 to M100 shows that the usage of GGBS improved air pore content from 4.1% to 3.4%. These results affect the improved workability of the PBFC mixes, allowing for higher compaction via tamping.

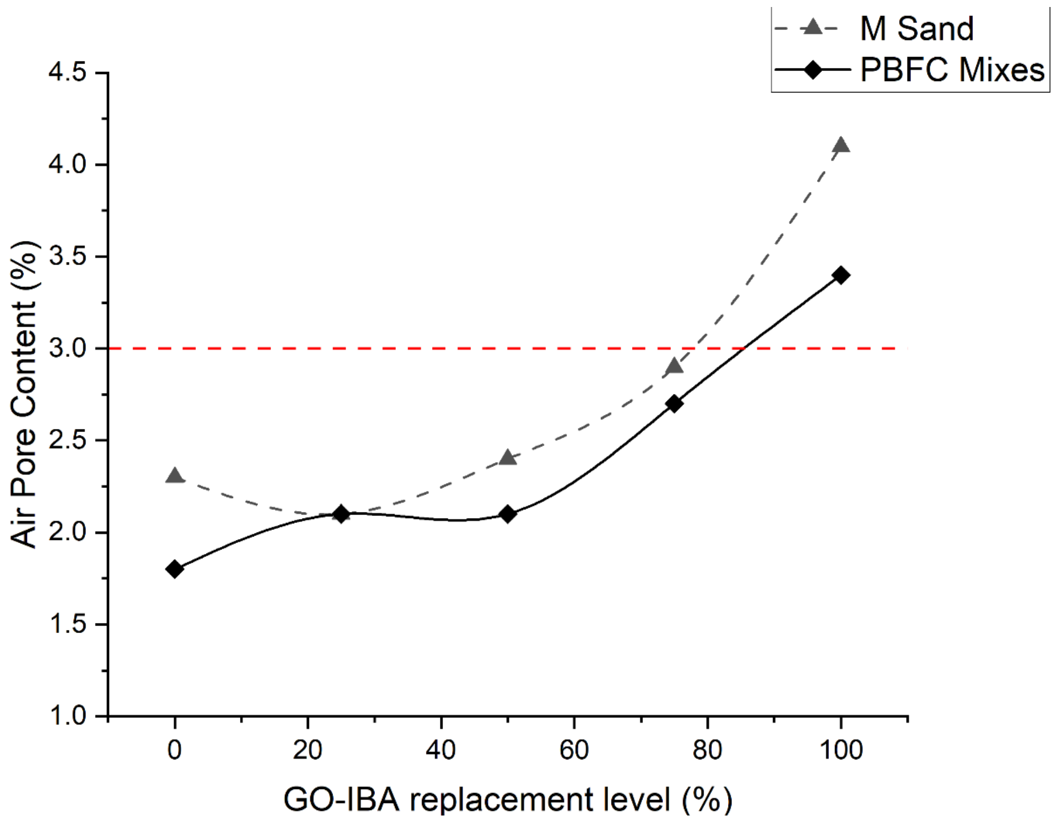


Figure 5.9: Air Pore Content results of M Sand mixes and PBFC mixes with GO-IBA™ replacement

5.5.2 Hardened Properties Compared to M Sand Mixes

As shown in Figure 5.10, while the average 91-day compressive strength for PBFC mixes is lower than that of M sand, it is notable that at 28 days, PBFC exhibited a decreasing trend. This observation has also been reported in the works of Dhir *et al*. (2002), Liu *et al.* (2022a), and Tang & Brouwers (2018), who reported that the round shape profile of GO-IBA™ was the leading cause for the declining strength.

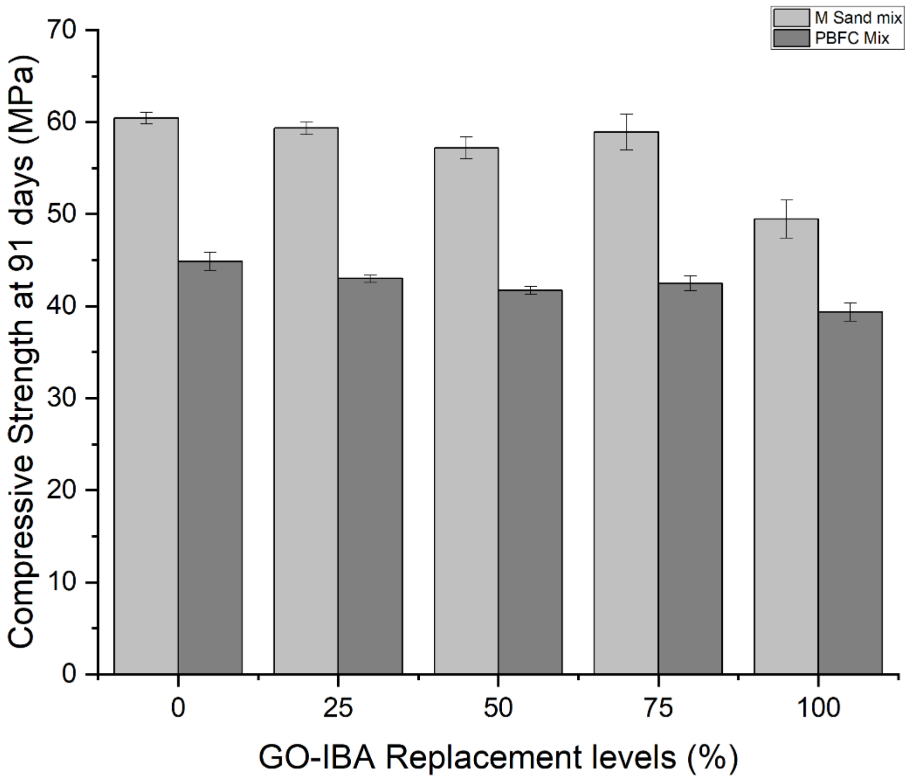


Figure 5.10: 91-day compressive strengths of M Sand mixes and PBFC mixes with GO-IBA™ replacement

A similar observation is noted for both mixes in terms of MOE, as shown in Figure 5.11, as the *Ecm* declined with increasing replacement levels. This further demonstrated that the round profile of GO-IBA™ promoted the propagation of microcracks, thereby decreasing the interlocking ability of the aggregates and the cement paste, which resulted in lower compressive strength and modulus of elasticity (MOE).

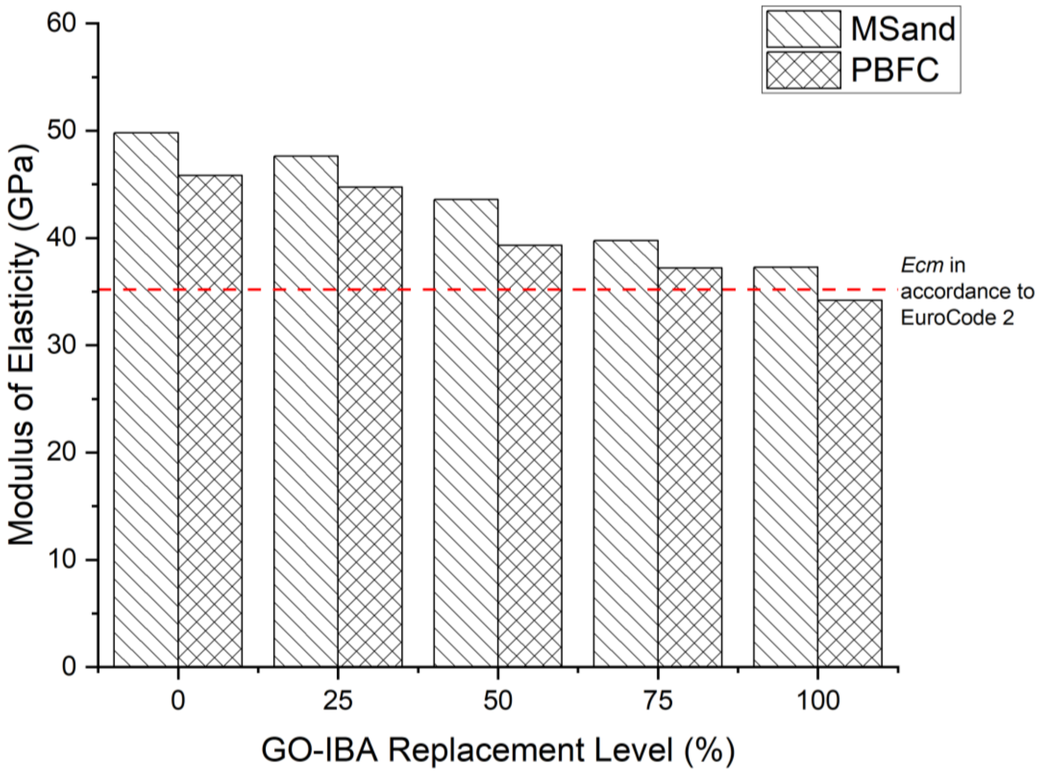


Figure 5.11: MOE results of M Sand mixes and PBFC mixes with GO-IBA™ replacement

With a 5% failure criterion set earlier in Section 5.3.2, only a 25% replacement for both PBFC and M sand mixes, and up to a 50% replacement level for C sand mixes, is recommended.

5.5.3 Durability Properties Compared to M Sand Mixes

In Sections 5.4.1 and 5.4.2, PBFC mixes exhibited higher WAT and WPT than M Sand due to a lower degree of hydration at the test ages. The explanation in Section 6.4.1 that the inclusion of GGBS is beneficial was based on the fact that it showed no significant difference between the two, with improvements noted at P75. However, based on the findings in Chapter 5 and considering the WAT results of PBFC mixes, it suggests the presence of other contributing factors. Ghostine *et al.* (2022) reported that concrete with a higher GGBS replacement (over 45% GGBS) exhibited greater porosity and permeability due to inadequate curing. Considering the results of WAT, the higher results of PBFC mixes may be attributed to the inadequate curing of the samples at test ages. Therefore, it is not possible to correlate these two test results with compressive strength.

RCPT results for PBFC are lower than those of M Sand, which was expected due to the well-known phenomenon of GGBS preventing chloride attack. However, the decreasing trendline persisted with increasing replacement levels, supporting the hypothesis that single-sized gradation of GO-IBA™ causes porosity, which remains unsaturated due to the sample preparation. As explained in Section 5.4.4, the accelerated carbonation test indicated that elevated carbonation is most likely due to the reduced availability of calcium hydroxide as GGBS hydrates. Due to this, the correlation cannot be made between the carbonation results and the compressive strength.

5.6 Summary

Although the use of GGBS could have resulted in a denser concrete structure, providing an extra layer of defence against the undesired properties observed in Chapter 4, most of the durability tests were conducted at 28 days, resulting in inadequate curing of the PBFC mixes, as GGBS possesses latent hydraulic properties and delayed microstructure densification.

The similar trends in the majority of the PBFC mixes to M sand mixes, signifying a possible cause closely related to the pore structure of GO-IBA™ replaced concrete. With the exception of WAT, WPT and Carbonation test, which are explained due to the nature of GGBS being used, the dominant effect is still the pore refinement observed in Chapter 4. This can be seen in the trendline exhibited in the results of slump, air pore content and RCPT. This warrants further research to study the pore refinement of GO-IBA™ replaced concrete and its effect on concrete properties, which lies beyond the scope of the research.

Chapter 6 - Conclusion and Recommendations

In this chapter, the concluding remarks of each chapter will be presented and the summary of the principal findings with the conclusions of the dissertation.

6.1 Conclusions

Chapter 1 introduces the problems associated with waste management, particularly with landfilling, as well as the unique situation that Singapore faces with sand importation. Thus, the appeal of using IBA as fine aggregates enhances both the sustainability and resource security aspects. This study proposes to use treated IBA as aggregate replacement in structural concrete. The influences of the concrete with treated IBA replacement on fresh properties, mechanical properties, and durability of the material will be investigated.

In Chapter 2, a detailed literature review has been conducted on utilising treated IBA in concrete, and challenges associated with this aggregate replacement. From the literature review, it is found that some results on concrete with IBA replacement are controversial, which indicates that the treatment method of IBA may significantly affect the properties of the concrete. It is also noticed that there is a scarcity of studies on replacing fine aggregates with treated IBA.

In Chapters 3 , an extensive experimental programme has been designed to study the fresh, mechanical and durability properties of concrete with untreated and treated IBA replacing the fine aggregates. Note that the treated IBA (GO-IBA™) employed in this study is treated using cold-bonded pelletisation technique. A baseline study of untreated IBA was being conducted. The materials used in this experiment and their geometric and material properties are presented in this chapter

Chapter 4 first reports aggregate properties of both untreated and GO-IBA™ were examined. Both exhibited a single gradation characteristic, given the process by which they were obtained. This will serve as a very important influencing factor for their concrete properties upon replacement. The environmental aspect was analysed, revealing that upon treatment, the majority of the harmful leachates were significantly reduced. This is imperative, given the characteristic of cement hydration coupled with the leaching behaviour of IBA; the mechanics of cement hydration could be affected. From the literature review, it is found that some results on concrete with IBA replacement are controversial, which indicates that the treatment method of IBA may significantly affect the properties of the concrete. It is also noticed that there is a scarcity of studies on replacing fine aggregates with treated IBA.

The effect of aggregate replacement with test results of rIBA mixes as a baseline study, followed by C Sand mixes and M Sand mixes. Most of the concrete properties of rIBA mixes showed a decline in performance. The most noticeable aspect is the compressive strength, which is often used as a key indicator for other concrete properties. The reduction in strength was attributed to the observation by Pera *et al.* (1997) of portlandite reaction with the aluminium phase in untreated IBA, which resulted in hydrogen emission and increased porosity within the concrete matrix. This porosity, combined with the presence of deleterious materials highlighted earlier, forms the basis for the reduction in rIBA mixes 'concrete properties and the reasons to avoid it in concrete applications, along with the importance of treatment before usage.

Given the foregoing results of the effects on concrete properties when utilising GO-IBA™ as a fine aggregate replacement of C Sand and M Sand, it is worth noting that the majority of concrete properties did not suffer a significant reduction compared to rIBA mixes. Fresh concrete properties were found to be hindered by the high-water absorption of the GO-IBA™. This can be mitigated by prewetting, which improves workability through the ball bearing effect, as explained in Section 5.3.1.2. The higher compressive strength of pre-wetted GO-IBA™ compared to surface dry GO-IBA™ was observed across all replacement levels. The MOE data showed that all replaced concrete shows a decreasing trend with increasing replacement level, owing to the spherical profile of GO-IBA™.

The single-sized gradation and round profile of GO-IBA™ showed the potential to create gap grading within the concrete. Strong evidence was observed in the WPT results of C Sand M Sand mixes, demonstrating decreasing water penetration till 75% replacement levels, but showed higher results than the control at100% replacement level. C sand mixes had higher WAT results across all replacement levels compared to the M sand mixes, with a declining trend, but still performed similarly in RCPT, with a decrease in chloride penetration with increasing replacement levels. This phenomenon may be explained by the pore refinement of the GO-IBA™ replaced concrete, as the lack of angularity in the fine aggregate of C sand mixes may have contributed to a larger amount of capillary pores.

Chapter 6 reports the effect of cement replacement using CEM III/B cement. Slump and Air pore content results of PBFC mixes performed better than M Sand mixes. Setting time for PBFC mixes were longer throughout all replacement levels compared to M Sand Mixes, which was typical behaviour of CEM III/B cement. Compressive strength for PBFC mixes showed a similar trend to M Sand mixes, with no statistical difference and deemed satisfactory till 75% replacement level. MOE for PBFC also showed a similar linear reduction with increasing replacement levels, with only the 100% replacement level not meeting the requirement set by Eurocode 2. Only 25% replacement level met the arbitrary value set earlier for PBFC mixes. Both WAT and WPT do not reveal a significant difference in trend at all replacement levels. It was deemed inconclusive as the slow hydration of GGBS resulted in a lower degree of hydration during the testing age. RCPT results of PBFC were reported to be in the very low chloride penetration regions, which was consistent with the well-known characteristic of GGBS. Carbonation results of PBFC showed elevated carbonation compared to M Sand mixes. It was reported in the works of Lye et al. (2016) that the hydration of GGBS consumed calcium hydroxide to form CSH, dropping the pH. As the majority of the concrete properties are similar to M Sand mixes in trend, the dominant effect remains with the replacement of fine aggregates with GO-IBA™.

6.2 Recommendation and Future Works

The recommendation for optimal usage is as follows;

1. GO-IBA™ is recommended to be at least in a moist state prior to mixing to further enhance its properties.
2. For the use case of C sand replacement with GO-IBA™, it is recommended to keep it at a 25% level.
3. If replacement of M Sand, 25% is conservatively recommended, with 50% usage still showing promising results.

With the usage of higher replacement levels of GGBS, a maximum of 25% replacement level is recommended.

The current scope of the research was to conduct a parametric study of GO-IBA™ replacement in light of natural fine aggregate materials. However, the test results, especially durability properties, require further research to understand and predict their properties fully.

The microstructure feature of GO-IBA™ also warrants further research as it influences the macro properties such as RCPT. Scanning electron microscopy (SEM) imaging and optical microscopy could give further insights into how the porosity of the GO-IBA™ and the surface topology give rise to its physical properties. Bulk electrical resistivity of the concrete can be employed to measure the electrical conductivity of GO-IBA™ replaced concrete. The particle sizing of GO-IBA™ could also be graded properly to better assess the concrete properties in the most ideal conditions, instead of the single-sized gradation of this research.

As explained in Section 5.4.2, the topic of pore structures is largely divided in the literature. While they are difficult to experiment with and understand, they are quintessential for understanding GO-IBA™ replaced concrete. This will give further credibility to the test results above and the fundamentals of the reasons for the test results. Mercury Intrusion Porosimetry (MIP) and X-ray computer tomography (X-Ray CT) could be employed to determine the pore structures and the location and distribution of the pores and voids.

Although RCPT test results were used as a measure of chloride attack, tests that utilise embedded rebar in concrete could actually simulate concrete under realistic service conditions.

Appendices

Appendix A: Slump Photos

Figure A.1: C0 Slump Photo

Figure A.2: C25 Slump Photo

Figure A.3: C50 Slump Photo

Figure A.4: C75 Slump Photo

Figure A.5: C100 Slump Photo

Figure A.6: M0 Slump Photo

Figure A.7: M25 Slump Photo

Figure A.8: M50 Slump Photo

Figure A.9: M75 Slump Photo

Figure A.10: P0 Slump Photo

Figure A.11: P25 Slump Photo

Figure A.12: P50 Slump Photo

Figure A.13: P75 Slump Photo

Figure A.14: P100 Slump Photo

Figure A.15: W25 Slump Photo

Figure A.16: W50 Slump Photo

Figure A.17: W75 Slump Photo

Figure A.18: W100 Slump Photo

Appendix B: Carbonation Test photos

Figure B.1: M0-1 Carbonation cubes photos

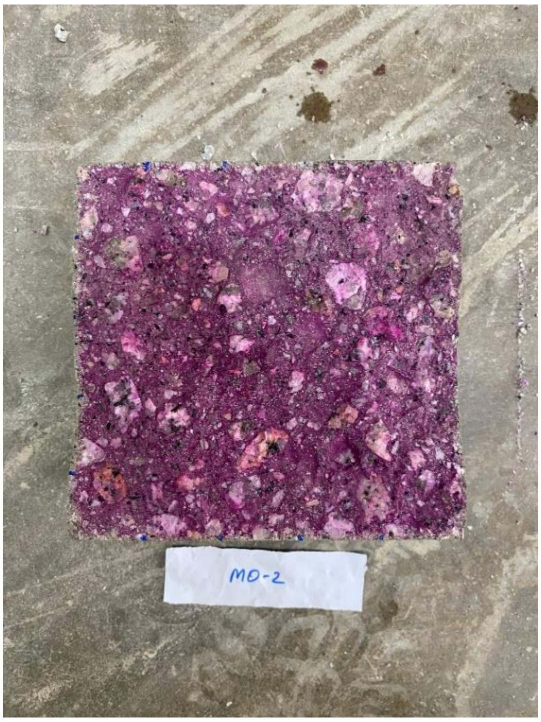


Figure B.2: M0-2 Carbonation cubes photos

Figure B.3: M25-1 Carbonation cubes photos

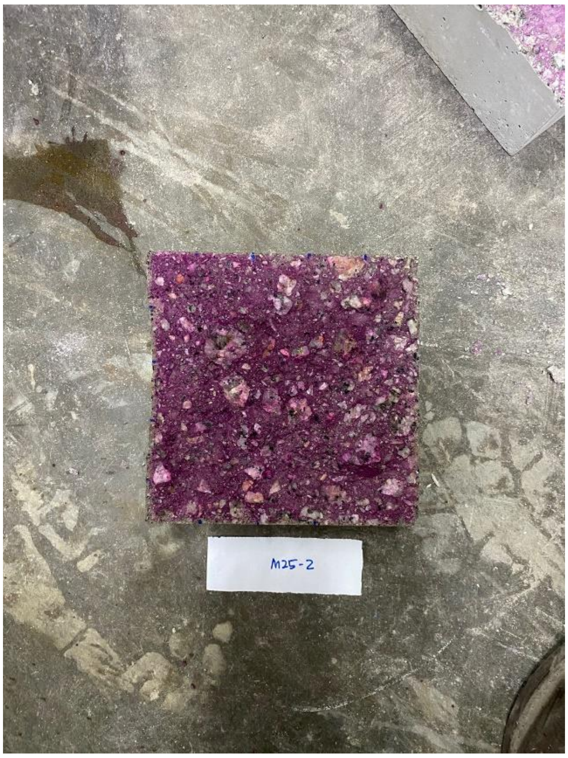


Figure B.4: M25-1 Carbonation cubes photos

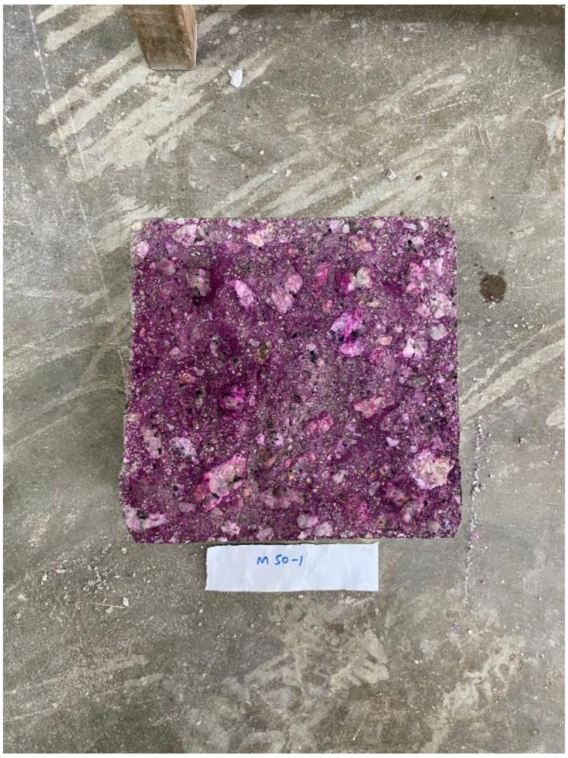


Figure B.5: M50-1 Carbonation cubes photos

Figure B.6: M50-2 Carbonation cubes photos

Figure B.7: M100-1 Carbonation cubes photos

Figure B.8: M100-2 Carbonation cubes photos

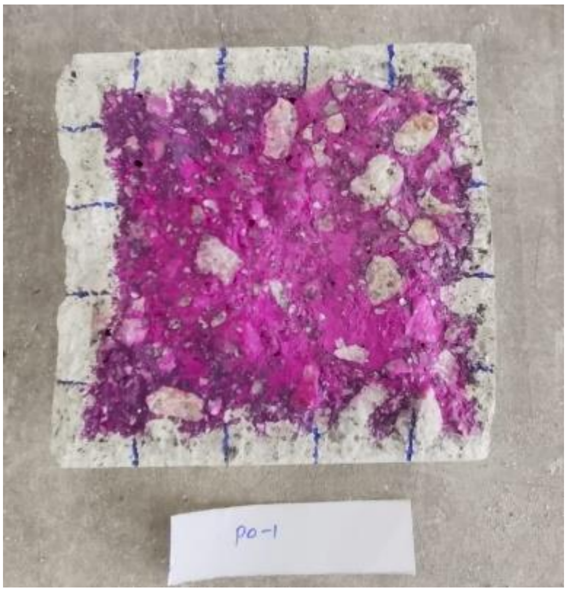


Figure B.9: P0-1 Carbonation cubes photos

Figure B.10: P0-1 Carbonation cubes photos

Figure B.11: P25-1 Carbonation cubes photos

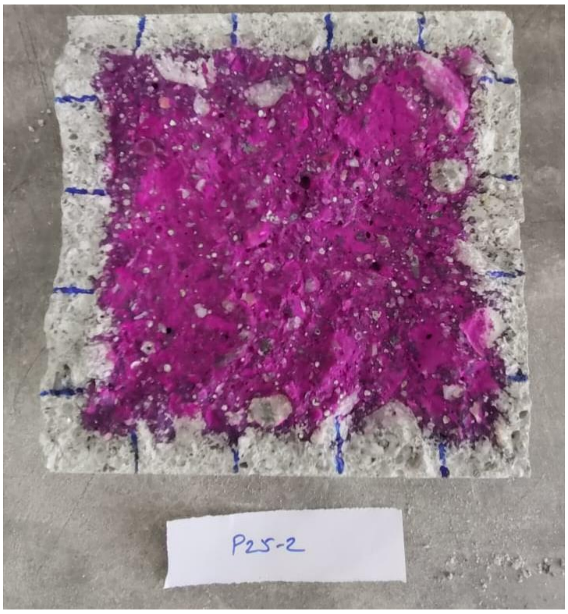


Figure B.12: P25-2 Carbonation cubes photos

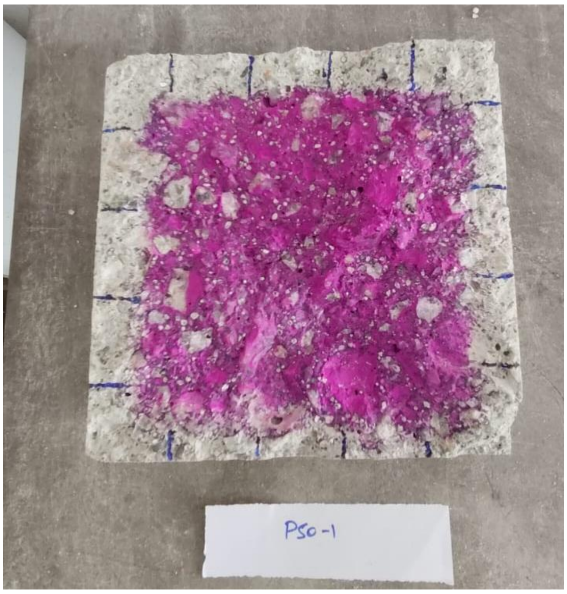


Figure B.13: P50-1 Carbonation cubes photos

Figure B.14: P50-2 Carbonation cubes photos

Figure B.15: P100-1 Carbonation cubes photos

Figure B.16: P100-2 Carbonation cubes photos

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