

Advancing Low-Carbon Concrete: Performance Assessment and Optimization of Glass Powder, Biomass Fly Ash, and Shredded Rubber in Concrete Mixtures

By

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ABSTRACT

The production of conventional concrete has a substantial negative impact on the environment, underscoring the need for effective strategies to lessen this impact. One promising approach is the partial replacement of cement and/or aggregates with waste materials, which enhances the sustainability of concrete. This method reduces the volume of waste sent to landfills while also conserving natural resources and lowering environmental risks. Among various waste materials, glass powder (GP) and biomass fly ash (BFA) have shown promise as partial cement replacements, while shredded rubber (SR) can be used as a substitute for fine and coarse aggregates. However, designing concrete with such materials poses challenges in achieving the required mechanical and durability performance standards. This study aims to develop optimal mix designs incorporating SR, BFA, and GP to meet environmental, durability, workability, and mechanical performance requirements. Durability was assessed using tests such as freeze–thaw resistance test, rapid chloride migration (RCMT), rapid chloride penetration (RCPT), and surface/bulk electrical resistivity. The Global Warming Potential (GWP) and predicted service life were also evaluated to assess environmental impacts. In addition, the mechanical behavior of the developed mixes was studied using compressive strength (CS), splitting tensile strength (STS), and modulus of rupture (MOR). Response Surface Methodology (RSM) was used to model and optimize the mix variables, followed by the development of a meta-model enhanced by Monte Carlo back analysis to improve prediction accuracy and identify the target mix design. Large-scale reinforced beams were cast to evaluate the structural performance of the optimized mixes. The results demonstrate that GP not only improves concrete properties but also mitigates the negative effects of BFA and SR. Overall, the optimized use of GP, BFA, and SR effectively reduces cement content and carbon emissions while satisfying structural, durability, environmental, workability, and mechanical criteria.

CO-AUTHORSHIP

This thesis has been prepared in accordance with the regulations of the integrated article format stipulated by the Faculty of Graduate Studies at Lakehead University. Substantial parts of this thesis were either published in or submitted for publication to peer-reviewed technical journals and international conferences.

Journal Papers

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To my Mom and Dad,

Your endless love and support have been the foundation of my strength.

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List of abbreviations

SR	Shredded rubber
GP	Glass powder
BFA	Biomass fly ash
RSM	Response surface methodology
CS	Compressive strength
RCPT	Rapid chloride penetration test
RCMT	Rapid chloride migration test
AC	Air content
STS	Splitting tensile test
MOR	Modulus of rupture
GWP	Global warming potential
SL	Service life
FT	Freezing and thawing
BER	Bulk electrical resistivity
SER	Surface electrical resistivity
SEM	Scanning electron microscopy
EDX	Energy-dispersive X-ray spectroscopy
XRD	X-ray diffraction
XRF	X-ray fluorescence
AI	Artificial intelligence
C-S-H	Calcium silicate hydrate
OPC	Ordinary Portland cement

CHAPTER 1: INTRODUCTION

1.1 Background

In the last two centuries, emissions of carbon dioxide have significantly increased, which has led to a rise in global temperatures and subsequent climate change [1]. The increase in carbon emissions has caused the Earth to become 1.1°C warmer compared to 200 years ago. The negative impacts of global warming are widespread, affecting the economy, food and agriculture, health, nature, oceans, and animals. It can increase costs for businesses and lead to food shortages and higher prices for consumers, and also affect human health through disease-carrying insects and poor air quality. Natural ecosystems can be disrupted, leading to the extinction of certain species and a decline in biodiversity, and the world's oceans can be affected by rising sea levels and ocean acidification, in addition to changes in currents and temperatures. Animal populations can also be negatively impacted by changes in weather patterns and loss of habitat [2]. Additionally, higher temperatures have contributed to the intensification of various natural disasters such as storms, heat waves, floods, and droughts. A warmer climate would lead to greater retention and release of water, resulting in changes to weather patterns where wet areas become wetter and dry areas become drier [2].

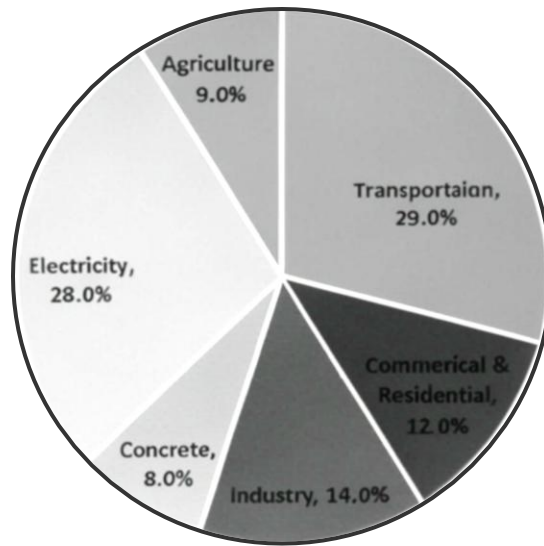


Figure 1.1: CO₂ emissions originate from different sources

Concrete is the most used man-made material worldwide. However, concrete is known to have a significant carbon footprint since its manufacturing/casting process is responsible for 8-10% of global carbon emissions (Figure 1.1) [3,4]. Concrete by volume is typically made up of 10-15% cement, 60-75% aggregate, and 15-20% water. The exact percentage of cement used can vary based on factors such as desired strength and durability, type of cement, and local availability of materials. Cement provides strength and durability to concrete and undergoes hydration when mixed with water, forming a solid matrix that binds the aggregate together and hardens to increase strength. According to estimates, the total volume of cement production globally reached 4.4 billion tons in 2021. Around 74% to 81% of the CO₂ emissions in concrete pertain to cement [5]. In particular, carbon dioxide is a by-product of cement production, where 40% of the CO₂ results from the burning of fossil fuels during the manufacturing process, and the remaining 60% is generated from natural chemical reactions. The manufacturing of cement involves the heating of a mixture of limestone, clay, and other materials in a kiln. Fuel-related CO₂ emissions are proportional to the energy required for the firing process, while calcination-related emissions are

produced when the raw materials are heated to over 2500°F and CO₂ is released from the minerals undergoing decomposition. Cement production is responsible for approximately 7% of the annual carbon emissions from the industrial sector [6]. Additionally, the rapid consumption of natural aggregates in construction has led to the depletion of these resources. Considering the current shortage of aggregates and advancements in the concrete industry, it is crucial to find suitable substitute materials for aggregate in durable concrete. These materials include but are not limited to recycled concrete, shredded rubber, fly ash, ground granulated blast-furnace slag, silica fume, and natural pozzolans. Fly ash, a by-product of coal-fired power plants, can be used as a partial replacement for cement in concrete, reducing the amount of cement needed while improving durability. Ground granulated blast-furnace slag (GGBFS), a by-product of iron production, GGBFS can be used as a partial replacement for cement in concrete, improving durability and reducing CO₂ emissions. Silica fume, a by-product of the production of silicon metal and alloys, can be used as a partial replacement for cement to improve durability and reduce the permeability of the concrete [7]. Given the negative environmental effects of concrete production on the environment, it is imperative to take steps to mitigate its impact. One viable solution to make concrete more eco-friendly is by replacing part of the concrete components, like cement, with waste materials. This can be accomplished by incorporating low-cost industrial by-products or solid waste in the production of concrete. A substantial amount of waste materials, such as 76% of discarded tires, 56% plastic, 76% glass, and 48% fly-ash powder, end up in landfills [8–10]. Utilizing these waste components in concrete production decreases the amount of waste that ends up in landfills, as well as reduces the depletion of natural resources and associated environmental risks.

1.2 Research Statement

Low-carbon concrete is concrete designed to minimize greenhouse gas emissions across its life cycle. This can be achieved by reducing the cement content through partial replacement with supplementary cementitious materials or industrial by-products, optimizing production processes such as in LC3 systems, or enhancing durability and service life through innovations like self-healing or smart concretes, thereby lowering the overall carbon footprint. The growing demand for low-carbon concrete in the construction industry is driven by increased regulations aimed at reducing carbon emissions, limiting greenhouse gas production, and conserving limited landfill space [11]. This complies with the general plan set by the government, where Canada has enacted the Net-Zero Emissions Accountability Act, which legally binds the country to achieve net-zero emissions by 2050. This Act guarantees transparency and accountability in the government's efforts to meet its targets. The Act mandates the involvement of the public and independent advisors to provide guidance to the Government of Canada as it works towards achieving its goals. In contrast to traditional concrete, low-carbon concrete offers numerous advantages, including reducing the unsustainable consumption of natural raw materials, improved compressive strength, and reduced environmental contamination [12]. The major obstacles to the widespread use of low-carbon concrete in construction are the lack of systemic lock-in, subpar quality of locally available materials, higher costs associated with construction, and technical difficulties [13].

Glass powder and biomass ash (from wood waste) have been identified as promising waste materials for use in low-carbon concrete. Research has shown that glass has a chemical composition that is similar to traditional SCMs like fly ash [14]. Due to the high volume of SiO_2 in glass, grinding glass into micro-meter scale particles increases its specific surface and can enhance the reaction between the glass and cement hydrates, resulting in significant energy,

environmental, and economic benefits when waste glass is used to partially replace cement in concrete production. Studies on the durability of concrete made with waste glass have shown improved performance against chloride permeability over the long term [15]. Moreover, the use of biomass ash generated by burning wood in home wood stoves or industrial power generation plants is becoming a common practice in the production of concrete. It is estimated that in the Province of Quebec, Canada, approximately 45,000 tons of wood ash were produced every year in the late 1980s by the pulp and paper industry. The spherical shape of the ash enhances the concrete's plasticity and creates a "ball bearing" effect, making it a suitable filler or partial replacement for cement. Using biomass ash in concrete production does not significantly affect the physical and mechanical properties of the resulting concrete, even when used in high quantities [16,17].

The rapidly increasing production of waste tires is a growing environmental concern. Waste tires pose various hazards, such as the risk of fires at landfills, attracting harmful creatures, spreading disease, and affecting human health. Currently, the global production of waste tires is estimated to be over 16 million tons per year, with Europe producing around 180 million worn-out tires and North America responsible for 150 million tires [18]. An appropriate method for recycling scrap tires can prevent it from polluting the soil, water, and air and threatening human life and various species. Grinding tires is a simple way to recycle scrap tires. Construction materials are the most applicable field for using shredded rubber, as they can partially replace the aggregate in concrete [19]. According to the research, although shredded tire deteriorates the mechanical properties of concrete (compressive and flexural strength), it has some benefits like improving toughness, impact, more elasticity and reducing plastic shrinkage cracks. Shredded rubber can improve the durability of concrete because the fine particles of rubber move to the surface of the concrete, and they hinder the permeation of sulphates [20]. By replacing natural aggregate with shredded rubber ,

it is possible to not only reduce the use of natural sand and coarse aggregate but also lower the construction cost. Recycling tires profited 4.2 billion dollars in 2019, and it is estimated that this value will increase to 6.21 billion dollars in 2027.

Concrete pavements, also known as rigid pavements, are widely used for various applications, including airports, ports, military facilities, parking lots, and high-traffic roadways [21]. These pavements have impressive mechanical characteristics, such as high bearing capacity, resistance to constant vehicular loads, and durability. To improve the sustainability of concrete pavements, researchers are exploring alternative raw materials to replace traditional aggregates. Options include burnt clay pozzolana, tire rubber waste, and palm oil fuel ash, among others. [16,22–25].

In this study, particular attention was given to incorporating waste materials that are locally available. Glass powder and shredded rubber can be collected and processed in most cities, while biomass fly ash was sourced from the Atikokan Generating Station, located near Thunder Bay where the concrete mixes were prepared. Utilizing these regional resources reduces the need for transporting raw materials over long distances, thereby lowering cost and associated emissions. At the same time, it diverts significant amounts of waste from landfills, supports a circular economy, and demonstrates the practical feasibility of producing low-carbon concrete for regional conditions.

The incorporation of waste materials in concrete mix design is a challenge, primarily due to the natural variability in their physical and chemical properties. This variability complicates the ability of consistent target mechanical and durability performance [26]. Nonetheless, the application of artificial intelligence (AI) is a viable approach to address such complexities. AI models can optimize mix proportions and predict concrete properties with higher accuracy, thereby making

the mix design values more efficient. By enabling data-driven decision-making, AI supports the development of high-performance low-carbon concrete mixture [27].

1.3 Main Objectives

This study aims to present a new mix design of low-carbon concrete in order to mitigate the negative impact of concrete on the environment and to reduce the amount of waste sent to landfills. This concrete mix, which includes waste materials such as shredded rubber, biomass fly ash, and glass powder, reduces the environmental impact of conventional concrete, along with satisfying the durability and mechanical properties of ordinary concrete. Although the use of waste materials in concrete mixture is beneficial to the environment, the design of a mixture that meets the mechanical and durability standards requires a thorough evaluation of the influence of the waste materials in the mix. The designed mix must have acceptable durability to resist harsh freeze and thaw conditions and chloride penetration. Also, acceptable mixes must have enough flexural and compressive strength to be suitable for different applications. This study investigated the durability, environmental assessment, and the mechanical behaviour of concrete containing biomass ash, glass powder, and shredded rubber to determine the optimum amounts of each waste material in the concrete and model their trends for different tests. There are some subjects that should be investigated by this study as follows:

1. Conducting physical and chemical characterization of the new materials used in this study (glass powder, cement, and biomass ash).
2. Evaluating the durability of concrete in terms of the chloride penetration resistance, freeze and thaw, and electrical resistivity. In addition, investigating the mechanical properties of concrete, such as the compressive strength, the tensile strength, and the modulus of rupture.

3. Evaluating the potential environmental impact of substituting cement/aggregate with glass powder, biomass ash, and shredded rubber, particularly regarding reducing carbon emissions and mitigating the effects of global warming.
4. Develop an “optimal design” for low-carbon concrete containing shredded rubber, glass powder, and biomass fly ash with mechanical, environmental, and durability constraints. And determining the sensitivity of each variable in the result tests.
5. Assessing the large-scale mechanical properties of the optimal mix designs, such as freeze and thaw resistance or chloride penetration resistance.
6. Investigating the early-age reactivity of waste material

1.4 Scope and Methodology

To fulfill the objectives of this study, the research was carried out in four phases, as depicted in Figure 1.2.

Phase I

In the first phase, the physical and chemical properties of the material, including cement, BFA, GP, and SR, were determined. X-ray Diffraction (XRD) and X-ray Fluorescence (XRF) were employed to determine the chemical composition of the waste material. Scanning electron microscope (SEM), mastersizer, and sieving analysis were used to measure particle size and particle size distribution of the waste material.

Phase II

This phase investigates the early-age effects of concrete containing (BFA, GP, and slag) by analyzing the results of various characterization techniques, including energy-dispersive X-ray spectroscopy (EDX), bulk and surface electrical resistivity measurements, and the setting time test, among others.

Phase III

a- Experimental work

In the first phase, various durability tests were conducted, including freeze-thaw cycles, rapid chloride migration (RCMT), rapid chloride penetration (RCPT), and bulk/surface electrical resistivity. Global Warming Potential (GWP) and the service life of the concrete were evaluated to examine the environmental impact. In addition, compressive strength, splitting tensile strength, modulus of rupture, and dynamic modulus were measured to investigate the mechanical properties. The air content and slump of all mixes were also recorded to evaluate workability.

b- Analytical work

Response Surface Methodology (RSM) was employed to derive equations for the results (freeze-thaw, RCMT, RCPT, bulk/surface electrical resistivity, GWP, service life, compressive strength, splitting tensile strength, modulus of rupture, dynamic modulus, air content and slump) and identify the most significant parameters. The models/equations provided the coefficient of each factor, allowing the detection of the most influential variables. The accuracy of the equations was evaluated using statistical criteria such as (Coefficient of Determination) R^2 , p-value, residuals, and Adeq Precision. For further validation, several random mixes were cast in the laboratory, and the experimental results were compared with the predicted values from the equations. After validation, results were plotted and acceptable mixes containing waste material were determined.

Phase IV

a- Analytical work

To build a more comprehensive and adaptable model than RSM, a meta-model was created using both data generated from the RSM equations and values gathered from the literature. Its predictive performance was evaluated using statistical metrics such as Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and R^2 . Back analysis was applied to optimize the mix design based on specific objectives, such as enhancing freeze-thaw resistance or reducing carbon emissions. Additionally, sensitivity analysis was conducted to investigate the influence of variables such as SR, BFA, and GP on outcomes like compressive strength, RCPT, and GWP.

b- Experimental work

Casting four reinforced concrete beams (2440 mm length and 250 mm by 250 mm in cross-section) involving waste material for performing a four-point bending test. Four beams were prepared, each

with a specific mix design: a control sample, a beam with improved chloride resistance, a beam with resistance to freeze–thaw cycles, and a beam designed to resist both chloride penetration and freeze–thaw damage. For each beam, specific performance constraints were applied to achieve optimized mix designs incorporating waste materials.

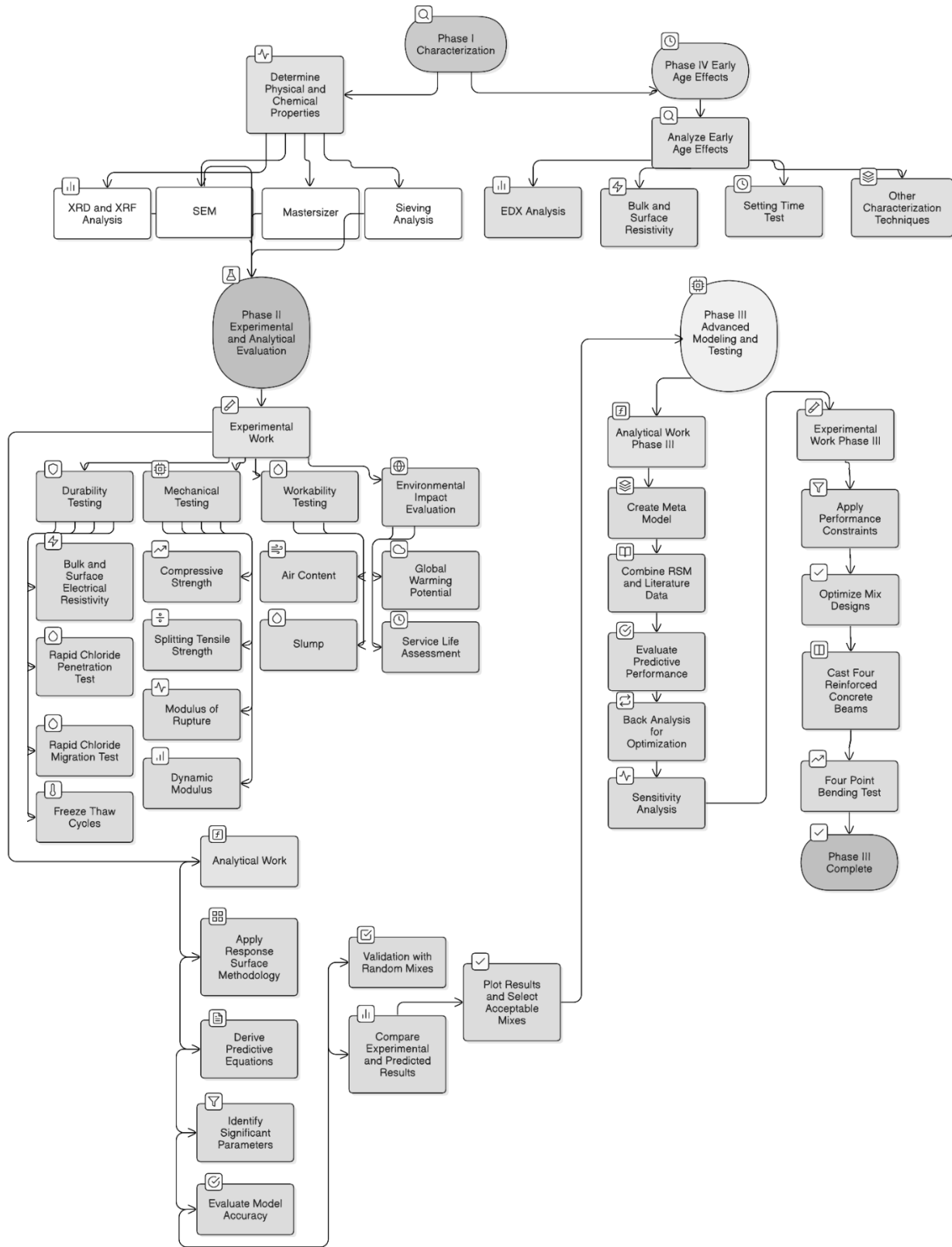


Figure 1.2: Flow chart showing the connections between the four phases

1.5 Thesis Structure

- Chapter 1 provides a brief overview of the research topic, outlines the problem statement and the extent of the study, defines the primary objectives, and summarizes the methodology employed.
- Chapter 2 provides an essential experimental background regarding the incorporating waste material (BFA, GP, SR) in concrete.

The following four chapters (Chapters 3 to 6) are presented in journal article format, where they were in published or under review

- Chapter 3 Sustainable concrete: impact of biomass fly ash, glass powder, and slag on early-age performance.
- Chapter 4 Multi-waste low-carbon concrete: synergistic optimization via response surface methodology for enhanced environmental and mechanical performance.
- Chapter 5 Durability performance of low-carbon concrete incorporating optimized ratio of multiple waste materials (glass powder, biomass fly ash, and shredded rubber).
- Chapter 6 AI-based meta model for predicting the performance of low-carbon concrete, considering the effects of multiple waste materials.
- Chapter 7 Conclusion and future work.

CHAPTER 2: LITERATURE REVIEW

2.1 Carbon emission and environmental impact

Although waste tires are considered a high-energy fuel and are referred to as Tire-Derived Fuel (TDF), their combustion results in substantial CO₂ emissions. For example, burning one ton of tires produces 2,890 kg of CO₂. To minimize this environmental impact, it is recommended to recycle the waste tires by grinding them and incorporating them into concrete (Figure 2.1).



Figure 2.1: Images of a landfill site, which is home to thousands of waste tires

Studies have shown that replacing cement with rubber powder in the concrete mixture reduces CO₂ emissions, as cement contributes significantly to the concrete's carbon footprint. The replacement of sand and gravel in the mixture has a limited impact on CO₂ emissions. Furthermore, using waste materials in concrete production helps conserve natural resources, as the replacement of coarse aggregate with rubber chips can save up to 10% of raw materials. The use of rubber crumb as a replacement in the concrete mixture results in a lesser raw material savings of less than 7% [28].

Most of the environmental impact from concrete and mortar comes from the production of Portland cement (Figure 2.2). The utilization of glass powder (GP) (Figure 2.3) as a substitute or partial replacement for Portland cement in concrete and mortar can significantly reduce the environmental impact of the cement. The ratio of Portland cement replacement and the production of Portland cement has a significant effect on the environmental impact of GP concrete. On average, GP mortar has a lower environmental impact compared to traditional mortar in all impact categories.

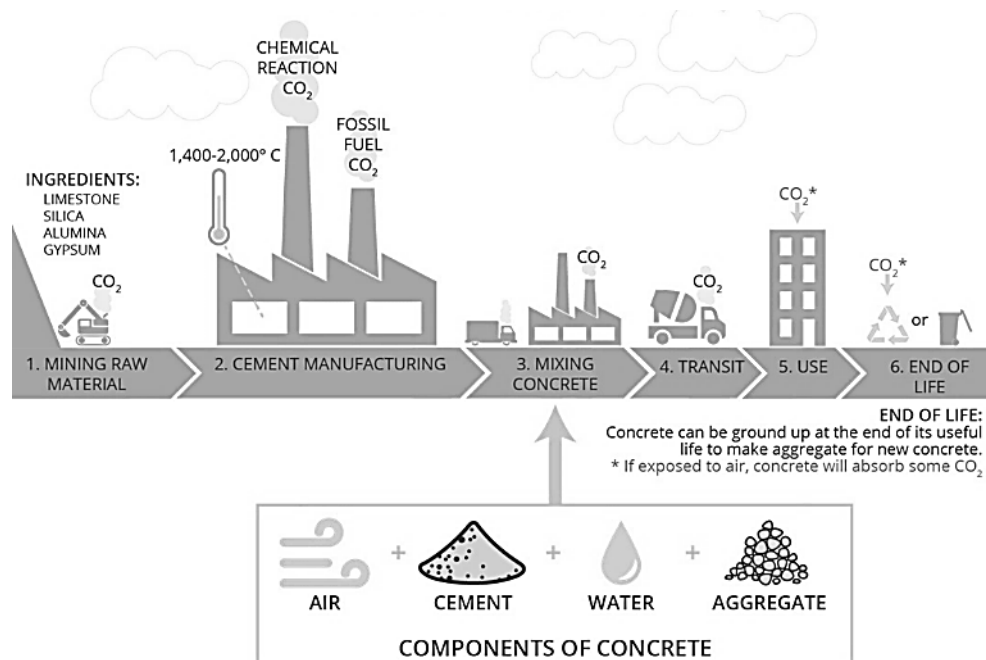


Figure 2.2: Carbon impact of concrete [29]

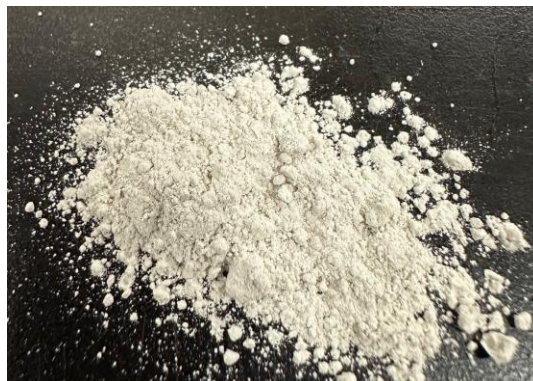


Figure 2.3: Glass powder

The inclusion of GP in mortar results in a reduction of 30-44% in greenhouse gas emissions, 27-42% less cumulative energy demand, 27-40% lower water usage and 24-45% reduced environmental toxicity potential [30]. Likewise, the use of biomass ash to substitute part of the cement instead of landfill disposal is an environmentally friendly alternative as it results in reduced greenhouse gas emissions, lower cumulative energy demand, less water usage, and decreased environmental toxicity potential. The study showed that blending biomass ash with cement reduced CO₂ emissions by 11-26% when compared to landfilling it. Additionally, there was a lower impact on global warming by 11-18% when 20% of the cement was replaced with biomass ash, and the reduction increased to 15-26% when 40% of the cement was replaced [30].

2.2 Durability of Concrete

The durability of concrete is its ability to resist weathering, chemicals, erosion, and other damage while retaining its shape and function. Achieving durability requires proper planning, mixing, placing, and curing. The required durability depends on environmental exposure, for example, seawater-exposed concrete needs more protection than indoor flooring [31–33]. The durability of concrete is vital for structural longevity, as exposure to salts, chlorides, seawater, and chemicals can lead to cracking and deterioration (Figure 2.4).





Figure 2.4: Chloride attack on reinforced concrete (Rees st, Toronto)

Thus, the low permeability of concrete is essential for its durability. Concrete must also resist physical stresses like volume changes from temperature fluctuations. In cold climates, freeze-thaw cycles and de-icing chemicals introduce additional challenges by expanding cracks and adding harmful chlorides. Ultimately, durability depends on material quality, proper construction, and resistance to environmental conditions [22,34].

Air-entraining agents improve concrete durability by forming tiny air pockets that absorb pressure and reduce freeze-thaw damage. A proper air void system is crucial for ensuring the durability of concrete in freeze-thaw conditions (Figure 2.5).



Figure 2.5: Damage to stairs at Lakehead University caused by freezing and thawing

The ideal air void content in concrete is about 6.5%, with 5.0% entrained air and 1.5% entrapped air. Entrained air, made of small, evenly spaced bubbles, improves freeze-thaw resistance, unlike larger entrapped air. Though entrained air can slightly reduce strength, this can be offset by increasing cement content or reducing water content [35].

The durability of concrete improves with proper design and execution. A well-planned mix considering aggregate type, cement type, and water-cement ratio ensures both strength and durability. Proper casting and curing help prevent cracking and promote correct hydration and hardening, supporting long-term performance [32]. Additionally, retrofitting existing structures can also restore their integrity and extend their lifespan. Freeze and thaw test, rapid chloride penetration test (RCPT), shrinkage, rapid chloride migration test (RCMT), and bulk electrical resistivity are the most frequent tests to assess the durability of concrete in North America.

2.2.1 Freeze and thaw

Damage to structures due to the freeze-thaw cycle is a common problem and is the primary cause of the deterioration of infrastructure (Figure 2.6). The impact of shredded rubber, biomass ash, and glass powder on freeze and thaw has been studied in many articles; the following paragraphs describe a few of these studies.

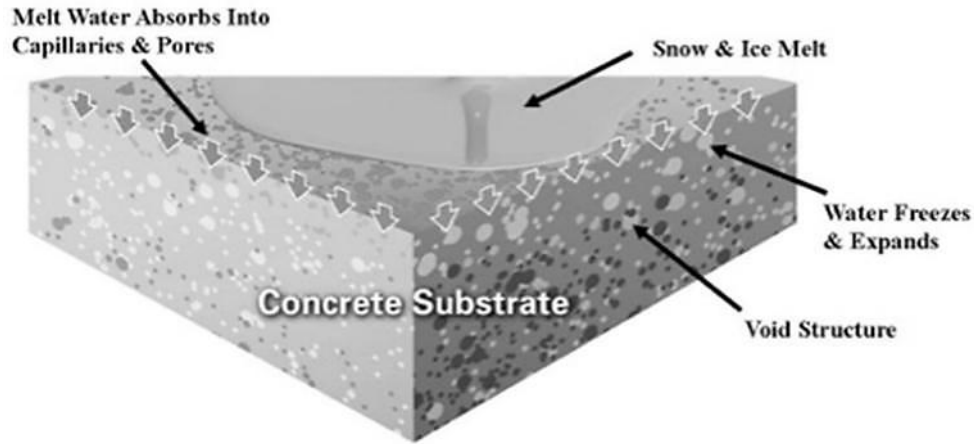


Figure 2.6: Schematic freeze-thaw process [36]

As the amount of ground rubber in concrete increases, its ability to withstand freeze-thaw cycles and maintain its strength decreases. However, even with up to 15% replacement of aggregate with ground rubber, rubcrete (rubberized concrete), mixtures still showed a durability factor of over 60% based on the ASTM C666 test [37], indicating that a certain capacity of freeze-thaw resistance is still maintained [34]. Research was carried out by Savas et. Al. [38] to examine the endurance of rubber concrete under rapid freezing and thawing conditions (according to ASTM C 666, Procedure A). They tested various mixtures that included 10%, 15%, 20% and 30% ground rubber as a proportion of the cement used in the control mixture, in an effort to find an ideal amount that could enhance durability without negatively affecting other properties. Based on their studies, they concluded that: air-entrainment did not result in a stronger performance against freezing and thawing for concrete mixtures containing various levels of ground tire rubber (10%, 20%, or 30%). And when the number of freezing and thawing cycles increased, there was also an increase in scaling (scaling is a method to assess the surface exposed to the freezing and thawing cycles and is determined by the loss of weight.)

Benazzouk and Queneudec [39] conducted research on the freeze-thaw durability of cement-rubber composites using two types of rubber aggregates: compact rubber aggregate (CRA) and expanded rubber aggregates (ERA). The volume of the rubber aggregates ranged from 9% to 40% of the total aggregate. The results indicated that the durability of the composites improved when they contained 30% and 40% rubber by volume. The improvement was more pronounced in the composites made with ERA aggregates compared to those made with CRA aggregates. The difference was particularly noticeable for composites made with ERA aggregates. Paine et al. [40] explored the possibility of using crumb rubber as an alternative to air-entrainment for enhancing the freeze-thaw resistance of concrete. They tested three sizes of crumb rubber, ranging from 0.5 to 1.5mm, 2 to 8 mm, and 5 to 25 mm. The findings showed that crumb rubber holds promise as a means of improving the freeze-thaw durability of concrete. The concrete containing crumb rubber performed notably better under freeze-thaw conditions compared to regular concrete. Furthermore, the concrete with crumb rubber had similar scaling performance to the air-entrained concrete. In addition, Naik et al. [41] investigated the effect of wood ash on the durability of concrete against freezing and thawing. The resistance was evaluated by measuring changes in the relative dynamic modulus, pulse velocity, and length variation. In the study, the wood ash content was set at 5%, 8%, and 12% of the total cementitious materials. After undergoing 300 freezing-thawing cycles, the results showed that the relative dynamic modulus of the concrete mixtures containing wood ash did not experience a significant change. The inclusion of wood ash in the concrete mixtures did not have a noticeable impact on the relative dynamic modulus. The control mixture without wood ash had a relative dynamic modulus of 97.7%, while the mixtures containing 5% wood ash had a relative dynamic modulus of 95.7%, the mixture with 8% wood ash had a relative dynamic

modulus of 97.8%, and the mixture with 12% wood ash had a relative dynamic modulus of 95.7% [42].

The addition of glass powder in roller-compacted concrete (RCC) has a positive effect on durability properties, such as resistance to freeze-thaw cycles and electrical resistivity. The water porosity and the volume of permeable voids in the hardened RCC can be decreased by incorporating glass powder into the RCC design. It's worth mentioning that a 14-day curing period before starting the freeze-thaw test may not be sufficient for significant hydration of the glass powder. It's likely that the performance of glass powder concrete will improve as it ages further.

2.2.2 Rapid chloride penetration (RCP)

The electrical indication of the resistance of concrete against chloride ion penetration is determined through the standard RCP test. The ASTM C1202, Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration, involves measuring the electrical current that passes through cylindrical specimens for a period of six hours. The total charge that passes during this time indicates the resistance of the specimen to chloride ion penetration. The following is a summary of the effects of crumb rubber, wood ash, and glass powder on the RCPT:

Nadi et al. discovered that the addition of crumb rubber (CR) in concrete can result in a rise in permeability. The increase was 35%, 60%, and 66% when the CR ratios were 5%, 10%, and 15%, respectively. This was due to the lower modulus of elasticity of the CR, which caused pores to form around the CR aggregates and result in cracks. However, the addition of CR reduced the compressive strength and durability of concrete samples. To improve these properties, the researchers suggested adding micro-silica, using magnetic water, and acidifying the rubber in a 2-hour H_2SO_4 solution [32].



Figure 2.7: Chloride penetration depths of concrete after 28 days

According to Subbaramaiah et al. [33], the chloride resistance of the concrete mix without wood ash was found to be moderate after 28 days and 90 days. There was a decrease in chloride permeability when 10% of the mix was replaced with wood ash, and this decrease was maintained at both 28 days and 90 days. However, when the replacement went beyond 10%, the chloride permeability of the concrete increased. Based on these results, it can be concluded that a replacement level of 10% wood ash is considered to be optimal [33].

The outcome of the RCP test is influenced by both the concrete's microstructure and the conductivity of the pore solution. If the pore solution conductivity is higher, even concrete with the same microstructure may exhibit increased RCP values (Figure 2.7). The presence of a certain amount of glass powder in the concrete mixture leads to the release of more alkali ions into the liquid phase, thereby increasing the pore solution conductivity. However, it has been observed that the glass powder modified concretes exhibit lower or similar RCP values compared to the control concrete at all ages, indicating that glass powder has a positive impact on the microstructure of the material [43]. When the particle size is sufficiently reduced (typically below 75 μm), the glass powder behaves predominantly as a pozzolanic material rather than a reactive aggregate. In this

state, the finely ground particles consume calcium hydroxide released during cement hydration, leading to the formation of additional C–S–H gel. This pozzolanic activity effectively mitigates the risk of alkali–silica reaction (ASR) expansion by binding alkalis and reducing pore solution alkalinity. Several studies have reported that glass powder not only decreases the likelihood of deleterious ASR but also improves long-term durability when used as a partial cement replacement, provided the fineness is adequate [44,45].

2.2.3 Rapid chloride migration (RCM)

For the design of concrete and mortar, the non-steady-state chloride migration coefficient D_{nssm} is a crucial parameter. At a global level, one of the accurate standard tests for measuring chloride penetration is NT Build 492 [46]. The NT Build 492 test specification outlines the required boundary conditions for conducting the test, including the casting and curing procedures for the specimens, as well as the technical parameters for the test. Strict adherence to these guidelines is crucial to ensure that the results obtained are comparable, and any deviation from them can lead to inconsistencies in the results [47].

Nadi et al.[32] found in their study that the addition of crumb rubber (CR) to concrete increases its permeability. This increase was more pronounced in samples with higher CR content, with 5%, 10%, and 15% CR resulting in permeability increases of 26%, 45%, and 59%, respectively. The researchers attribute the increase in permeability to the presence of pores caused by the lower modulus of elasticity of the CR compared to the surrounding concrete paste. In addition, cracks tended to form around the CR aggregates due to reduced adhesion between the CR and the concrete [32].

The plain ordinary Portland cement (OPC) mortar demonstrates the highest D_{RCM} of all samples. Binary binder samples, with cement replaced by high volumes of recycled waste glass, ground granulated blast furnace slag (GGBS), or fly ash, show lower D_{RCM} compared to OPC. Meanwhile, the incorporation of a high volume of fly ash in the specimen only shows an 18.1% reduction in D_{RCM} compared to OPC. The inclusion of 60% recycled waste glass provides excellent resistance to chloride migration, surpassing the GGBS and fly ash samples. Ternary binders that combine recycled waste glass with GGBS or fly ash also exhibit better performance than those that only use GGBS or fly ash. Interestingly, when the recycled waste glass is combined with fly ash in binders, the D_{RCM} experiences a significant decrease with an increased amount of recycled waste glass. The incorporation of waste glass powder in fly ash blended mixtures presents a more significant improvement of resistance to chloride migration than in GGBS blended mixtures. Other research has also shown that the inclusion of pozzolanic materials such as GGBS or fly ash can improve the resistance to chloride migration [48,49]. The interfacial transition zone (ITZ) in OPC concrete is typically rich in calcium hydroxide, which is a weak point for ion transportation. Pozzolanic materials, such as GGBS or fly ash, can be added to OPC concrete to consume calcium hydroxide and create a denser ITZ. Incorporating pozzolanic materials has been shown in multiple studies to improve the resistance to chloride migration. The RCM test is based on the electric conductivity method, which can be affected by the conductivity of the concrete pore solution. The ion dosage in the pore solution is determined by the chemical composition of the binder system. The consumption of calcium hydroxide in concrete containing pozzolanic materials can alter its chemical composition and influence the test results [50]. As the proportion of waste glass powder in blended binders increases, the calcium hydroxide content decreases after 91 days, which corresponds to the reduction in D_{RCM} . The observed variation in chloride migration can be

attributed to differences in pore size distribution. Previous research has shown that the use of supplementary cementitious materials (SCMs) in concrete can modify the pore structure, leading to varying levels of resistance to chloride penetration [51]. According to the current research, the coefficient of rapid chloride migration is mainly associated with the pores that are between 10 and 100 nm in size. Many studies have explored the link between the volume of capillary pores and the transport properties of concrete [52]. One example of a study that has addressed the relationship between pore volume and transport properties of concrete is Wu's research on microstructure and ITZ of blended cement. This study found that a decrease in the volume of pores between 10 and 100 nm was correlated with a reduction in chloride transport [53]. This finding is consistent with the results of the current study. Paiva et al. showed in their research on the microstructure-property of pozzolan-containing concrete that the pozzolanic reaction takes place within the capillary pores, leading to a densification of micro-pores as evidenced by MIP results [54]. This conclusion is in line with the results obtained from MIP, as discussed previously. The addition of 60% waste glass particles has the potential to create a similar microstructure to GGBS in concrete. However, while the 60% fly ash mortar shows a lower DRCM than OPC, it displays a pore size distribution curve similar to the OPC mortar. The decrease in DRCM of the high-volume fly ash-containing sample is primarily due to the decrease in electrical conductivity. The use of fly ash in concrete can reduce the alkalinity of the pore solution, leading to a reduction in alkaline ions and hydroxyl ions. Moreover, Friedel's salt in fly ash blended cement is also associated with improved resistance to chloride transportation [50,55].

2.2.4 Bulk electrical resistivity

The electrical resistivity of a solid material, such as mortar, is a useful indicator of its quality, microstructure, and porosity. It can be measured using bulk and surface electrical resistivity

instruments, as solid materials exhibit higher resistivity than air voids and capillary pores (Figure 2.8). This information can be used to evaluate the permeability class and durability of the mortar. By decreasing the permeability of reinforced concrete, its ability to withstand chloride ion attacks is improved, resulting in increased durability.



Figure 2.8: Bulk and surface electrical resistivity instruments

The quantity of rubber fibre powder (RFP) has a nonlinear impact on both the surface resistivity and bulk electrical conductivity, with the surface resistivity being more affected than the bulk resistivity. In a study conducted by Ghani [56], it was found that the mortar mixture with a 10% rubber powder ratio exhibited the highest surface and bulk resistivities. However, the mixture with a 25% rubber powder ratio showed the lowest surface and bulk resistivities due to the increased entrapped air that came with the rubber. In comparison, conventional mortar lacking RFP displayed a high level of chloride ion permeability, whereas rubberized mixtures with up to 15% RFP content exhibited a moderate level of chloride ion permeability. The results of bulk electrical resistivity can be used to determine the risk of steel rebars corrosion [57]. Specimens with a bulk resistivity

of 20 kΩcm or greater are considered to have a low risk of corrosion. The addition of rubber powder to mortar can further reduce the risk of steel corrosion. In particular, the study found that a mortar mixture with a 10% RFP replacement ratio demonstrated the most effective protection for reinforcement steel against corrosion. These findings suggest that rubberized mortar has the potential to be used as a repair and protective mortar [56].

According to data collected by Kasaniya et al. [58], incorporating 25% of inert filler or raw coarse bottom ash (BA) in concrete led to a considerable reduction in electrical resistivity. The 91-day results for mixes containing these materials were around 25% lower on average than the control mix that contained 100% Portland cement. Among the mixes containing pozzolans, only the mix with 25% metakaolin exhibited a significant increase in resistivity compared to the control mix at 7 days. However, all the mixes containing pozzolans showed notable increases in resistivity over time. By 28 days, most of the concrete mixes containing highly reactive or very highly reactive pozzolans had increased resistivity compared to the control mix, and by 91 days, all the concrete mixtures containing pozzolans showed increased resistivity [58].

2.3 Mechanical properties

2.3.1 Compressive strength

The compressive strength of rubberized concrete (RC) is typically less than that of an OPC concrete. Concrete with rubber content of 5-50% of natural aggregates, which may range in size from 0.075mm to 6mm, has shown a strength reduction of approximately 4-70% (Figure 2.9). The degree of strength reduction in RC depends on various factors such as the size, shape, mechanical properties, and percentage replacement level of RC. Several studies have demonstrated different explanations for the decreasing trend of RC's compressive strength with an increase in rubber content [59]. A significant reason for the decline in strength can be attributed to the poor adhesion

between the rubber and cement paste in concrete. This is due to the rubber acting as an empty space within the concrete matrix, resulting in a lower density. Another factor that leads to reduced strength is the development of tensile stresses along the surface of the rubber particles and the surrounding cement paste when the reinforced concrete (RC) is subjected to compressive stress, which causes premature cracking. These stresses arise from the softness of rubber particle cracks, which initiate near the joint of the rubber and cement paste in concrete and spread rapidly towards failure. Additionally, there is a wide and porous ITZ, which is the weakest part of the concrete mix, observed in RC because the hydrophobic nature of the recycled aggregate tends to repel the cement paste [59].



Figure 2.9: Compressive Concrete cylinder

To address these issues, researchers have explored the use of additional materials. One approach is to add silica fumes to enhance bonding in the ITZ [60]. Another possibility is to use a non-homogeneous concrete matrix, as the recycled aggregate tends to rise to the upper surface of the mold when compacted due to its lower specific gravity. Turki et al. have proposed the use of mineral fillers such as siliceous or limestone in combination with rubber to improve the mechanical properties of reinforced concrete (RC). These measures can improve the bond strength within RC, leading to a more robust and dependable mechanical strength over time [61].

2.3.2 Flexural strength

The trend of decreasing flexural strength in rubberized concrete (RC) is nearly identical to the decline in compressive strength. Additionally, studies have demonstrated that replacing 20% of the sand with CR in concrete leads to a 25-27% reduction in flexural tensile strength. However, during the early age of concrete, the flexural strength of RC is not substantially lower than that of plain concrete (PC), even with up to 30% inclusion of rubber and a low water-cement ratio. One advantage of RC is that it does not exhibit sudden failure under bending, unlike ordinary concrete, and instead undergoes a certain amount of deformation before ultimately failing. Although the bond between rubber and cement paste is weak, resulting in a steeper decline in flexural strength compared to compressive strength, the failure mode of RC is less brittle than that of ordinary concrete (Figure 2.10) [62]. The reduction in strength of RC during bending tests can be lessened when smaller-sized RA is used, due to the high compact capacity of smaller materials. Additional filling materials can also increase the flexural strength of RC up to a certain limit for 20% rubber content. Silica fume can be added to reduce the strength reduction during flexural loading of RC. Researchers have also recommended the use of steel or synthetic fibers to improve the flexural strength and cracking resistance of RC [63,64].

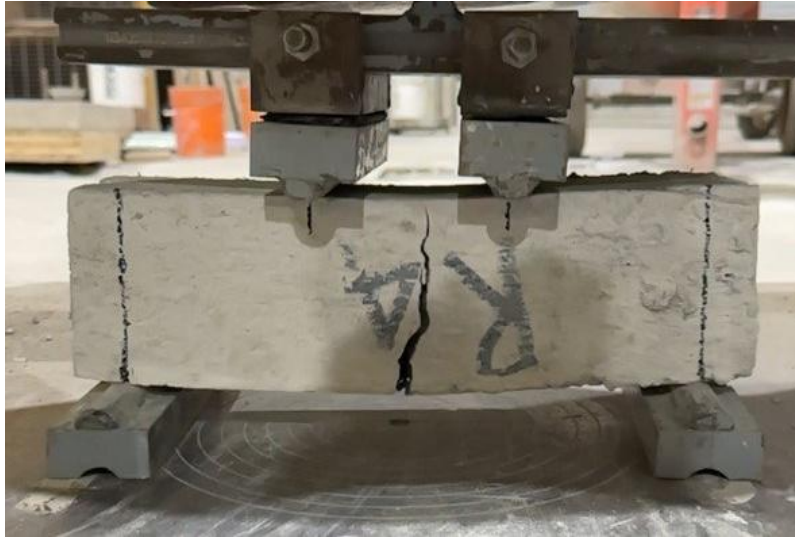


Figure 2.10: Flexural strength test of concrete

2.3.3 Vibration Damping

Ultrasonic techniques for evaluating concrete structures typically rely on measuring the velocity of ultrasonic waves passing through the material. This is accomplished using piezoelectric transducers that generate and receive the waves. Ultrasonic waves are sound waves with a frequency greater than 20 kHz, which is above the range of human hearing. When used on concrete, lower-frequency ultrasound can be used to detect faults and damage within the material [65].

Karaiskos et al. [66] developed an ultrasonic concrete tester that was specifically designed to assess the quality of concrete pavements. This tester utilized a higher frequency than the sonoscope due to the short path lengths in concrete pavements. Transducers with high-resonance frequencies ranging from 60 to 200 kHz were created and used to achieve the desired level of penetration. The transit time of the stress wave could be accurately measured within a range of $\pm 2 \mu\text{s}$. The tester was also used to explore the impact of various factors, such as water-to-cement ratio, aggregate type, and content, on pulse velocity. Additionally, the relationship between pulse velocity and compressive strength was investigated [66].

Khaloo and colleagues [67] conducted an ultrasonic analysis of tire-rubber concrete using the ultrasonic echo technique to study the sound absorption and ultrasonic modulus of the material. The researchers found that rubberized concrete is highly effective at absorbing sound and vibration energy. As the content of tire rubber in the concrete increased, the velocity of ultrasonic waves significantly decreased [67]. The transfer of wave velocity through a material is an important factor that affects mechanical wave energies. Therefore, tire-rubber concrete is a potentially suitable material for sound and vibration damping and can be used in noisy environments for sound insulation. Due to the significant reduction in ultrasonic modulus with increasing tire-rubber concentration, tire-rubber concrete is expected to have a porous composition.

A notable gap in the current literature is that most studies investigate merely one or two types of waste materials, typically assessing their effects in isolation rather than examining potential interactions, and focus on a narrow range of properties, most often compressive strength or slump [68–71]. Comprehensive evaluation of strengths, durability, workability, and environmental impact remains uncommon especially for multiple waste materials [72]. This is mainly because such assessments are resource-intensive, time-consuming, and require extensive experimental work [73–75]. This underscores the need for more efficient and integrative predictive models capable of addressing all four critical aspects of concrete performance, which is addressed in this study.

2.4 Response surface method

The response surface method (RSM) was first introduced in 1951 by Box and Wilson as a tool for the design of experiments, and it remains widely used today. RSM has a strong connection to linear regression analysis and seeks to estimate interactions between the second-order equation and the local shape of the response surface through a well-designed experimental program. If the applied surface provides an adequate approximation of the actual response surface, the response surface

analysis can be compared to similar approximations of the actual system analysis [76–78]. For a complex and nonlinear system, in equation (2.1) Y and the variables of X_i can be calculated according to the following equation, as employed in previous studies [76,77,79,80]:

$$Y = \beta_0 + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \beta_{ii} X_i^2 + \sum_{i < j}^k \beta_{ij} X_i X_j + \epsilon \quad (2.1)$$

The predicted response, which can be slump flow, RCPT, RCMT, bending strength and compressive strength, is denoted by Y in the equation. The intercept is represented by β_0 , the first-order (linear) coefficient by β_i , the second-order (quadratic) coefficient by β_{ii} , and the coefficient of interaction effect by β_{ij} . The independent variables are X_i and X_j , and the associated random error is ϵ . The second-order model has the advantage of flexibility, as it can encompass a wide variety of functions [76].

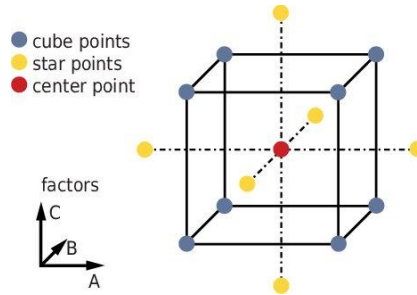


Figure 2.11: Schema of a central composite design with three factors [81]

The central composite design (CCD) is a well-known branch in response surface methodology (RSM). This design involves a set of 2^k factorial points, which includes n_F factorial runs, as well as $2k$ axial (star) runs and n_C central runs (Figure 2.11). The factorial runs are used to fit the first-order model, while the axial runs are employed to fit the second-order model. The value of α determines the distance between the axial points and the center point. The rotational symmetry of the design is a desirable characteristic because the aim of RSM is optimization, and using a design that provides accurate estimation in all directions is beneficial, especially when the location of the

optimal point is not known in advance. The CCD can be rotated by choosing an appropriate value for alpha, which depends on the number of factorial points. Various formulas have been proposed for calculating alpha, and in some cases, it is determined experimentally. The most commonly used formula is $\alpha = (nF)^{1/4}$, where nF is the number of factorial points[76,82,83].

2.5 Meta model

AI meta models deploy sophisticated machine learning methods to increase the precision and effectiveness of the prediction of concrete properties. Meta models, particularly artificial neural networks (ANN) and hybrid frameworks, have presented robust potential toward minimizing dependency upon conventional laboratory test methods while optimizing mix designs for the concrete. ANN models have been successfully utilized to predict compressive strength as well as other performance characteristics of concrete, including mixes containing supplementary cementitious materials (SCMs) such as metakaolin and fly ash. For example, one ANN model outperformed others in predictive accuracy, with a near-simulation of experimental results [84].

AI-based meta models offer significant insights into the relationships among variables in concrete mixes, enhancing decision-making in mix design, especially when incorporating waste materials. However, developing accurate models remains challenging due to the variability in experimental data. Concrete properties are influenced by many factors, including material types and proportions, curing conditions, and testing methods, making generalization of the datasets difficult [85]. The accuracy of artificial neural network (ANN) models depends on the quality and volume of training data, the variety of input factors, and the optimization of network architecture. While the number of hidden nodes affects model accuracy, the relationship is not always linear. Other machine learning techniques, such as support vector machines and genetic programming, have also been

used for predicting concrete properties. Nevertheless, ANN models remain among the most broadly used due to their capability to capture complex, non-linear relationships [85].

ANNs have also been used to predict the properties of fly ash self-compacting concrete (SCC). It was trained with parameters like binder content and fly ash replacement ratio, and it was able to predict outputs like slump flow and compressive strength [86]. The artificial neural network (ANN) model developed within this study appropriately predicts the fly ash properties for self-compacting concrete (SCC), with acceptable correlations between the input parameters (e.g., cement, water, and quantity of fly ash) and the output properties (e.g., V-funnel, slump flow, and compressive strengths).[87]. The comparison between the ANN model predictions and experimental data indicates its high potential for predicting SCC performance with various fly ash contents, offering a tool for SCC mix design optimization [87].

In continuation, various types of Machine Learning models such as Generalized Linear Models, Decision Trees, Random Forests Regression (RFR), Support Vector Machines, Back Propagation Neural Network (BPNN), and also different Deep Learning models have gradually been utilized for predicting concrete properties include basic approaches. Among these, Miao et al. [88,89] used hybrid machine learning (SSA-BPNN, SSA-XGB, SSA-RFR) to predict mechanical properties of recycled aggregate concrete with SCMs, based on a large datasets and demonstrated that the SSA-XGB model excelled in accuracy. Miao et al. [90] proposed an intelligent framework for designing eco-friendly glass powder concrete by combining machine learning, generative adversarial networks, and multi-objective optimization. Using 1,279 samples, their model achieved high predictive accuracy ($R^2 \approx 0.95$) for slump, strength, and durability.

The previously noted gap, focusing on isolated waste materials without considering their interactions, also applies to AI-based models, limiting their ability to perform simultaneous optimization of multiple performance metrics.

CHAPTER 3: SUSTAINABLE CONCRETE: IMPACT OF BIOMASS FLY ASH, GLASS POWDER, AND SLAG ON EARLY-AGE PERFORMANCE

Abstract

The massive use of cement has led to significant carbon dioxide emissions worldwide, prompting researchers to explore sustainable alternatives. Replacing cement with waste materials such as biomass fly ash, glass powder, and slag can reduce the negative environmental impacts of cement production and the problems caused by the disposal of these waste materials. While the previous studies have examined the long-term mechanical properties of concrete using these waste materials, there is limited research on the early age properties of concrete incorporating waste materials. Thus, this paper focuses on understanding the impact of each waste material at replacement levels of up to 30%. A total of ten mixtures were prepared, and the results of various tests were compared, including fresh tests (slump, air content and setting time), mechanical test (compressive strength), and durability indicators (surface and bulk electrical resistivity) at 7 and 14 days. Additionally, results were further corroborated through Energy Dispersive X-ray spectroscopy (EDX) analysis and Scanning Electron Microscopy (SEM). The experimental results revealed that 30% slag (SL) as a replacement improved compressive strength by 2.15% compared with the control sample at 14 days, making it the most effective substitute for early age strength of concrete. Glass powder (GP) contributed to moderate strength but was less effective compared to SL. GP at 30% replacement showed the highest bulk and surface resistivity values. In contrast, biomass ash exhibited the lowest performance among the waste materials used to replace cement. These results highlight that SL is the most effective cement replacement for compressive strength.

Key words: *Early age, low carbon concrete, Slag, Glass powder, Biomass fly ash*

3.1 Introduction

Understanding the early-age mechanical properties of concrete is essential for ensuring structural integrity, optimizing construction schedules and minimizing maintenance costs. Early-age concrete is a complex material that undergoes rapid chemical and physical changes that impact its strength, stiffness and durability. During hydration, concrete experiences volumetric changes that, if uncontrolled, can lead to cracking and reduce its long-term durability [91]. The proper selection of ingredients and mix proportions is crucial for producing concrete that meets strength and durability standards. However, high-quality concrete may be difficult to achieve if its early-age properties are overlooked. Therefore, a fundamental grasp of concrete's early-age properties is vital [92]. Also, for the concrete to acquire its intended qualities, adequate moisture and temperature must be maintained during the curing process [92]. Additionally, the rapid temperature rise due to exothermic hydration can lead to thermal stress, especially in large structures or mass concrete applications. If thermal stresses are not managed, they may exceed the early-age tensile strength, resulting in cracking [93].

Supplementary cementing materials (SCMs) such as glass powder (GP) [94,95], biomass fly ash (BFA)[96], and slag (SL)[97,98] have earned increasing recognition in recent years for their potential to improve both the sustainability and performance of concrete [99]. The early-age compressive strength and setting time are challenging to predict and assess due to unique hydration processes, pozzolanic reactions, and interactions within the cement matrix. These complexities often lead to slower strength development, increased curing demands, and varied water requirements, all of which can impact the concrete's durability and performance in later stages [100].

GP obtained from recycled waste glass is acknowledged for its pozzolanic properties, which enhance the mechanical strength of concrete while reducing the cement consumption [101]. Studies have demonstrated that using GP (size less than 300 μm) not only improves compressive strength but also reduces the risk of alkali-silica reactions [102,103]. When GP is introduced as a partial replacement for Portland cement, it exhibits pozzolanic reactions at early stages, reacting with calcium hydroxide to form additional calcium silicate hydrate (C-S-H) gel, which enhances strength development [104]. The initial strength gained by GP concrete was observed to be slower than that of conventional cement-based concrete, with the GP contributing to long-term strength rather than early-age performance. The research highlighted the potential for using GP to enhance durability and reduce environmental impacts [105]. It was found that concrete containing waste glass as a partial cement replacement exhibited lower compressive strength at early ages compared to conventional Portland cement concrete and observed that the strength of concrete incorporating waste glass did not match that of control mixes at day 7 and day 14, indicating the potential need for extended curing periods for optimal performance [106]. Predicting the long-term performance of concrete based on early-age strength poses challenges, especially for mixtures incorporating SCMs.

BFA, a byproduct of agricultural waste incineration, has shown potential to significantly reduce environmental impacts by replacing cement, thereby contributing to lower carbon emissions [107]. Concrete containing 5% and 10% BFA as cement replacement increased its compressive strength by 1.66% and 2.97% respectively (negligible change), at the 28-day curing age [108]. However, at higher replacement levels (above 25%), there tends to be a decrease in early-age strength by 50% compared to the control mix [104,109]. Nonetheless, concrete containing BFA also exhibits reduced heat of hydration, which can be beneficial in preventing thermal cracking in mass concrete

applications. It was found that concrete incorporating 30% BFA achieved only 50-70% of the strength of control mixes at day 7 [110]. The variability in the BFA composition, influenced by its source, can lead to inconsistent hydration and strength results [111].

Slag (SL), a byproduct of steel manufacturing, is another highly effective SCM known for improving the durability and longevity of concrete, especially in aggressive environments [112]. The addition of SL enhances both the mechanical and chemical resistance of concrete, making it suitable for sulphate and chloride-rich environments [113]. Moreover, studies have shown that SL significantly reduces the permeability of concrete, thereby improving its resistance to water and chemical attacks [114,115]. SL's latent hydraulic properties contribute to early-age strength gain when it reacts with calcium hydroxide during hydration. Research showed that replacing 40% of Portland cement with SL can increase the 28th-day compressive strength by approximately 23.9% compared to the control mix [116], while lower SL content (20-30%) results in a more gradual strength development. It was reported that SL improves the workability of fresh concrete while providing a steady increase in early-age compressive strength, particularly in mixes exposed to sulphate-rich environments, where SL-based concrete exhibits superior resistance to chemical attack. In the Xu et.al study, the early-age strength performance of SL-blended concrete was highlighted that SL-blended concrete exhibits improved early-age strength at elevated curing temperatures, the long-term durability and mechanical properties require further investigation to fully understand their behaviour beyond initial assessments, the variability in hydration reactions and long-term performance necessitates continuous monitoring to ensure accurate assessments of supplementary cementitious materials (SCMs) in concrete systems under varying environmental conditions [117]. Both GP and Ground Granulated Blast Furnace Slag (GGBFS) also tend to increase water demand in concrete mixes. Concrete mixes containing GP exhibit reduced

workability and may require the use of superplasticizers to achieve acceptable flow properties [118]. It was found that GGBFS, when used in higher proportions, can also lead to increased water requirements, which negatively impact early-age strength development if not properly compensated [119]. Over the past decades, extensive research has sought to improve our understanding of early-age concrete properties. Earlier, research focused primarily on achieving optimal curing techniques to ensure proper hydration [120]. More recent studies have leveraged advanced techniques, such as the application of nanotechnology and the use of SCMs to better control the hydration process and improve early-age [121].

Projection of early-age concrete mechanical behavior still remains difficult due to using waste material in concrete. Despite significant advances in research conducted on supplementary cementitious materials (SCMs), some gaps have remained in the earlier studies. The majority of the studies concerning SCMs like biomass fly ash (BFA), glass powder (GP), and slag (SL) considered the long-term mechanical properties for the most part (28 days or more). Previous research generally confined its investigation to a few types of mechanical or durability tests without covering the wide range of performance parameters. Few studies have investigated the early-age properties of concrete containing biomass fly ash, and these studies generally did not include testing of fresh properties (such as setting time), microstructure (such as EDX analysis), and durability indicators (such as electrical resistivity) to entirely assess early-age reactivity [96,107,122]. These gaps in knowledge hinder the ability to predict the performance of SCMs in early-age uses and their effects on long-term concrete behavior.

This research investigates the influence of GP, SL, and BFA on the early-age behaviour of concrete through 10 concrete mixtures containing these waste materials. SL was selected because its performance in concrete has been extensively studied and well established in the literature. Its

inclusion in this chapter was intended solely to provide a benchmark for evaluating the early-age properties of concrete containing BFA and GP. Unlike BFA and GP, which represent the main focus of this study, slag was not considered a primary subject of investigation. By measuring the effects of these SCMs on the air content, slump, electrical resistivity (bulk and surface), compressive strength, setting time, Scanning Electron Microscopy (SEM), and energy dispersive x-ray spectroscopy (EDX) at 7 and 14 days, the research aims to provide a full overview regarding the chances of substituting these materials for a conventional cement mix for early-age application purposes. This study is part of an ongoing research project at Lakehead University. The current phase focuses on evaluating the individual effects of each waste material on concrete performance, which will provide the necessary foundation for the second phase, where Response Surface Methodology (RSM) will be employed to optimize the combined use of multiple waste materials.

3.2 Material and test method

3.2.1 Materials

In this study, commercial type GU Portland cement according to ASTM C150 [123] was used. The chemical properties of the cement, biomass fly ash, glass powder and slag are tabulated in Table 3.1. Particle size distribution (PSD) of the cement, biomass fly ash, glass powder and slag are shown in Figure 3.1. The D90 of glass powder is 13.40 microns, while the D90 of slag is 33.84 microns. The D90 of cement is coming out as 53.60 microns, and the largest of all the four materials is biomass fly ash, at 115.37 microns. (The D90 means that 90% of the total particles are smaller than the given size)

Polycarboxylate ether-based superplasticizer, which meets ASTM C 494/C 494M [124] has been used. The gradient diagram for aggregate is given in Figure 3.2.

Table 3.1: Chemical composition of Cement, Biomass Fly Ash, Glass Powder and Slag

Materials	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	L.O.I
Biomass fly Ash	2.79	5.2	2.3	42.49	5.21	0.55	29.68
Glass Powder	70.07	1.57	0.34	10.46	1.47	12.85	1.11
Slag	33.4	13.4	0.76	42.70	5.3	0.3	-
Cement	19.9	5.2	2.3	62.34	2.27	0.23	2.93

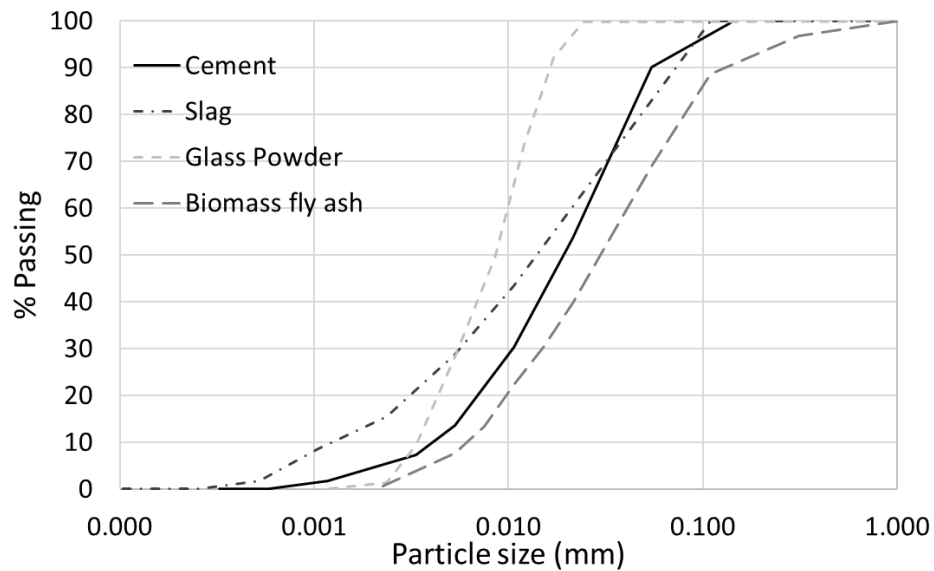


Figure 3.1 Particle size distribution of Cement, Slag, Glass powder, and Biomass fly ash

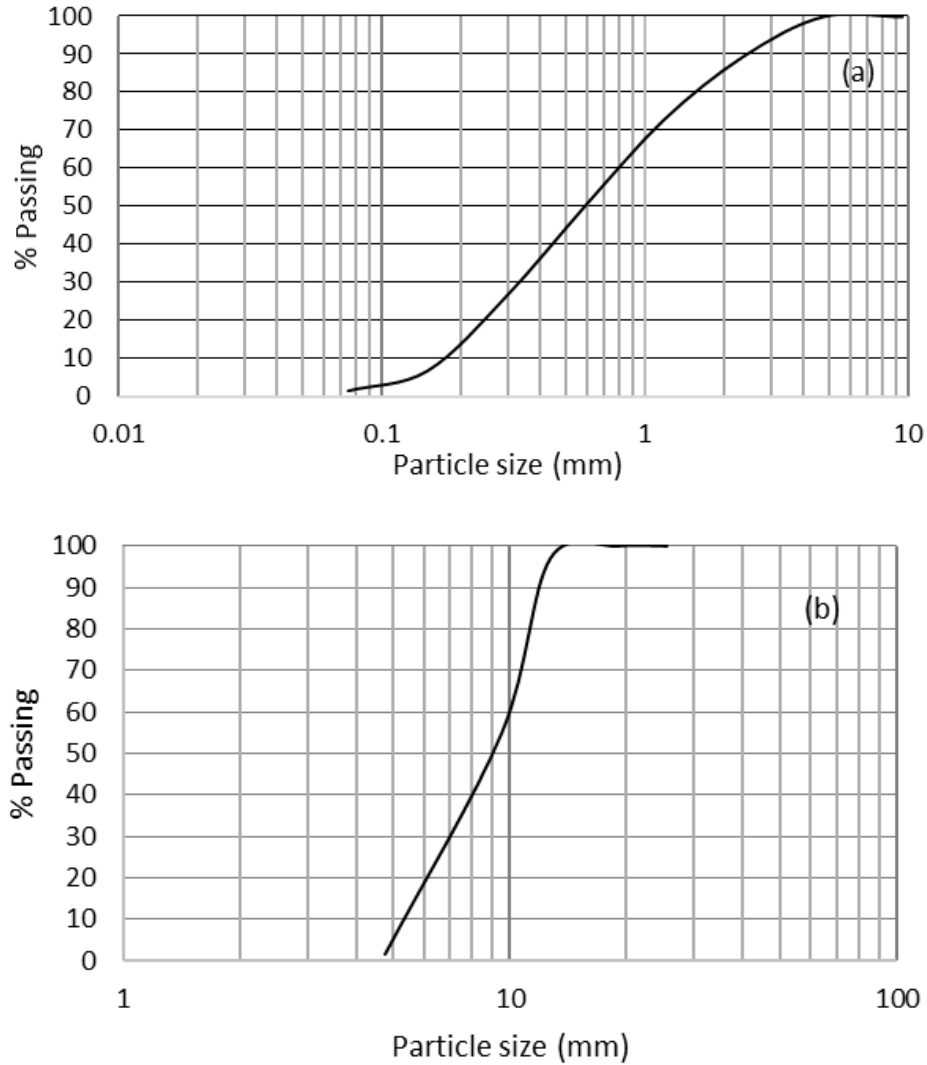


Figure 3.2 Gradient diagram of a) Sand and b) Gravel

3.2.2 Preparation of samples and test procedure

The aggregates, cement, biomass fly ash, glass powder and slag were combined in mixer and mixed (dry) for 1 min. Afterward, the water and the super plasticizer were gradually added to the mixture, which was mixed for 5 min after adding water. Immediately after preparing the mortar, the slump flow test and the air content test were performed according to ASTM C143/C143M-12 and ASTM C231-09a, respectively [125,126]. The setting time test for the concrete was also performed [127]. Concrete cylinder samples, 4×8 in., were cast for surface electrical resistivity [128] and bulk

electrical resistivity [129], and compressive strength [130] after 7 and 14 days curing period. The ten concrete mix designs used in the experimental program are reported in Table 3.2. In the ten mixes with varying levels of SL, GP, and BFA, the SP dosage was kept constant to isolate the effect of these pozzolanic materials on workability. This ensured that any change in workability resulted from the type and content of SCMs rather than SP variation. The fixed SP dosage was based on control mix trials, which achieved adequate workability without segregation or bleeding.

For the air content test, the measuring container was filled in three layers of approximately equal volume by rodding each layer of concrete by 25 strokes of the tamping rod; after rodding, the sides of the container were tapped 10 to 15 times with a mallet. After the consolidation of concrete, striking off the top surface by sliding the strike-off bar across the top flange until the container was just level full. Moisten the bowl's rim, and the cover assembly was attached, ensuring it was clamped securely. The main air valve was closed, and both petcocks were opened. Water was injected through one petcock with a rubber syringe until water came out from another petcock. The air bleeder valve was closed, and air was pumped into the air chamber. Allow for a few seconds and stabilize the gauge hand and close both petcocks. Open the main air valve and tap the sides of the measuring bowl and pressure gauge. The percentage of air was read on the dial of the pressure gauge .

For the setting time test, a mortar sample was obtained by wet sieving a sample of fresh concrete. through a 4.75mm No. 4 sieve. The mortar was placed and placed in a wooden test container up to a depth of at least 5-1/2 inches, compacted by means of a tamping rod. After completion of rodding, tap the sides of the container lightly to close voids left by the tamping rod. The container was stored at a specified ambient temperature within the range 20-25 °C and covered with a suitable material to avoid excessive evaporation. At regular time intervals, insert a suitable needle (bearing

area: 645, 323, 161.3, 64, 32 and 16 mm²) .) in penetration resistance apparatus and bring the bearing surface of needle in contact with the mortar surface by gradually applying a vertical downward force on the apparatus until needle penetrates to a depth of 25.4 mm . Continue the test until at least one penetration resistance of at least 4000 psi is recorded. The penetration resistance of mortar was measured by recording force and dividing this recorded force by the bearing area of the needle .

Surface electrical resistivity measurement was performed by a commercially available 4-point probe surface resistivity meter. In this study, electrical resistivity was measured on 7,14 days for 100×200 mm cylinders. Three cylinders were tested for each concrete mixture. The equipment measures the current flowing between the outer electrodes and the potential difference between the two inner electrodes [128].

Bulk resistivity measurement was performed on the same cylinder sample as surface electrical resistivity measurement. This test was also non-destructive and simple to perform. A cylinder was placed on the support, and two ends were wet with a wet sponge. This test method consists of applying a potential difference to the cylindrical specimen, thereby producing a current flow through the cylinder [129].

The compressive strength test of the cylindrical concrete specimen was conducted according to ASTM C39 [130] for 7 and 14 days. This test method consists of applying a compressive axial load to molded cylinders at a rate which was within a prescribed range until failure occurs. The compressive strength of the specimen was calculated by dividing the maximum load attained during the test by the cross-sectional area of the specimen .

For SEM and EDX Analysis, samples of concrete measuring about 3mm³ were collected from the cylindrical concrete specimen for all ten mixes after curing the specimen for 14 days in water. These small samples were then analyzed using a scanning electron microscope for each mix. The calcium to silica ratio of all the mixes was examined and compared with the control mix.

Table 3.2: Mix proportions of concrete with different cement levels for ten concrete mixtures per cubic meter

Mix No.	W/B	Water	Sand	Gravel	Cement	Biomass fly ash	Glass Powder	Slag	Binder	SP
Control	0.45	153	953.5	953.5	340	0	0	0	340	3.4
BFA 5%	0.45	153	953.5	953.5	323	17	0	0	340	3.4
BFA 10 %	0.45	153	953.5	953.5	306	34	0	0	340	3.4
BFA 15%	0.45	153	953.5	953.5	289	51	0	0	340	3.4
GP 10%	0.45	153	953.5	953.5	306	0	34	0	340	3.4
GP 20%	0.45	153	953.5	953.5	272	0	68	0	340	3.4
GP 30%	0.45	153	953.5	953.5	238	0	102	0	340	3.4
SL 10%	0.45	153	953.5	953.5	306	0	0	34	340	3.4
SL 20%	0.45	153	953.5	953.5	272	0	0	68	340	3.4
SL 30%	0.45	153	953.5	953.5	238	0	0	102	340	3.4

3.3 Results and Discussion

3.3.1 Slump

Figure 3.3 highlights the slump results for the concrete samples, categorized into three distinct groups alongside the control mix. The control mix, with a slump value of 150 mm, exhibited superior workability, reflecting its ease of handling. In contrast, the samples including BFA exhibited a substantial decrease in slump values. At BFA 5% (5% of the binder), the mix presented lower workability with a slump of 40 mm, while the BFA 10% and 15% mixtures showed zero slump. This trend suggests that increasing biomass fly ash content leads to a significant reduction in workability. This reduction is primarily attributed to the higher water demand of BFA compared to cement, which is due to its greater porosity and higher loss on ignition (LOI) [131] (Figure 3.4 a). Conversely, the concrete mixtures containing GP exhibited a gradual increase in the slump as the GP content increased. A mixture with GP of 10% (10% of the binder) showed an increase of 20% in the slump (180 mm) as compared with the control sample. Similar results are appreciated with the GP 20% with a slump of 170 mm (13% more than the control). Finally, the mixture with GP of 30% matches the slump value of the control. This enhancement in workability is attributed to the smoother texture and spherical nature of the glass powder particles, which reduce internal friction and improve the flowability of the mix (Figure 3.4b). Similarly, the SL group maintained high slump values across all replacement levels. In particular, the SL 10% with 160 mm, which is 7% higher, SL 20% with 180 mm or 20 % more than the control and SL 30% with 180.5 mm or 20 % more, confirming improved workability with higher slag content. The addition of glass powder reduces concrete workability due to high surface tension, strong capillary forces and an increase in mix viscosity, which lowers slump [132]. Conversely, slag improves workability by enhancing fluidity and reducing viscosity and yield stress, aided by its favourable interaction with water and cement and the early formation of beneficial hydration products [133,134].

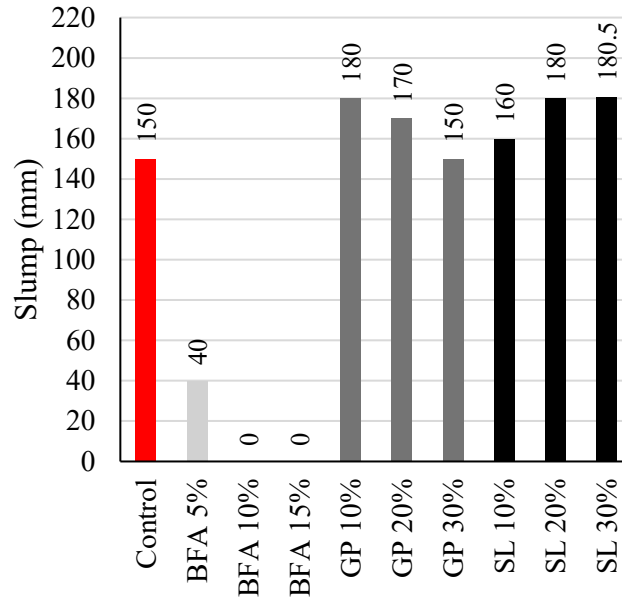


Figure 3.3: Slump test of fresh concrete incorporating biomass fly ash, glass powder and slag as a partial substitution of cement compared with a control mix

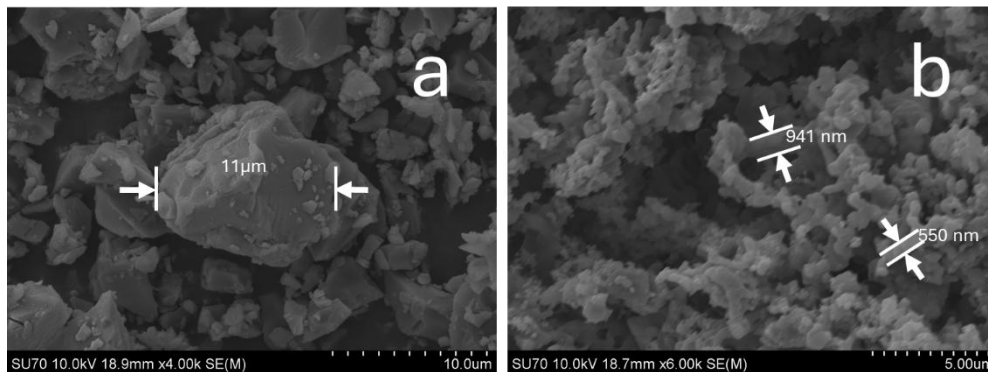


Figure 3.4: SEM images of a) biomass fly ash b) glass powder

3.3.2 Air Content

Figure 3.5 illustrates the effect of material composition on air content, a critical factor in determining the concrete's durability and resistance to freeze-thaw cycles. The air content test, as specified by ASTM C231 [125], utilizes the pressure method to assess the volume of air entrained in freshly mixed concrete. It should be noted that no air-entraining agents were used in the mixes; therefore, the measured air content reflects only the entrapped air during mixing. The control mix

has 3.4% air content, which is not between the 4% and the 8%, and is not an acceptable range of conventional concrete according to the ACI PRC-211.1-22[135]. In the BFA mix, there is a noticeable increase in air content, except BFA 5% that has also 3.4%, matching the control group, particularly at 10% and 15% BFA, BFA 10% with 8.4%, which is 147% higher than the control, and BFA 15% with 6.2% (an increase of 82% than the control). Experimental studies show that increasing biomass fly ash content 30% raises the air content in concrete. This is mainly due to the porous, irregular BFA particles trapping air, which hinders air release. Additionally, carbonaceous residues in BFA can alter the surface free energy of water, promoting air entrapment by reducing air bubble coalescence and further increasing the amount of entrapped air [136].

Conversely, the GP group shows a consistent reduction in air content across all tested percentages, each of which is lower than the control mix: GP 10% with 3.2% (5.9% lower than the control), GP 20% with 3.3% and GP 30% with 2.8%. This indicates that glass powder contributes to denser concrete formulations by reducing air entrapment. This behaviour is likely due to the spherical shape and low porosity of glass powder particles, which minimize the spaces for air to become trapped [137].

Finally, the SL group shows air content levels that are close or slightly lower than the control mix. For instance, the SL 10% mix has an air content of 2.6%, lower than the control, while the SL 20% mix shows a slight increase to 2.8%, and the SL 30% mix maintains air content comparable to the control with 3.4%. At low replacement (10-30% SL), research shows almost no change in air content compared to the control mix. The ACI education bulletin E3-13 [138] notes that slag cement generally does not cause fluctuations in air content, unless it is extremely finely ground [130]. A research reported samples with 20,40, and 60% SL replacement, which had an entrapped

air content very close to the control mixture [139]. This finding supports that a low replacement yields air content nearly identical to the control.

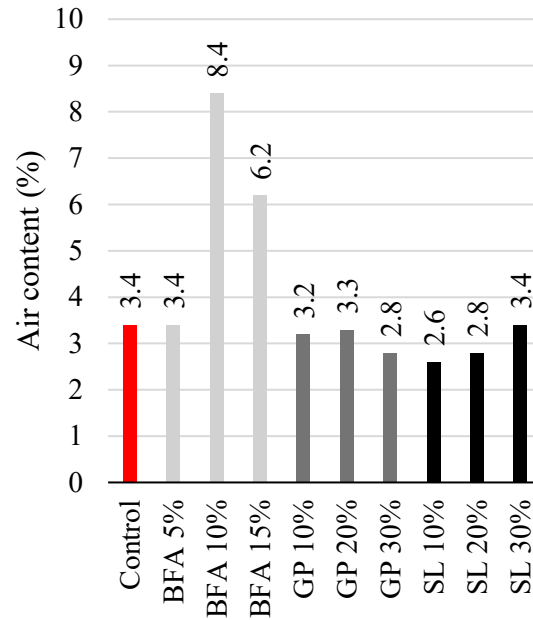


Figure 3.5: Air content of fresh concrete incorporating biomass fly ash, glass powder and slag as a partial substitution of cement compared with a control mix.

3.3.3 Surface resistivity

The concrete surface resistivity, as defined by the AASHTO T 358 [128] standard, measures the electrical resistance of concrete surfaces, primarily using cylindrical specimens. Figure 3.6 presents the resistivity data at 7 and 14 days. The control mix's resistivity values for 7 and 14 days were $13.07 \text{ k}\Omega\cdot\text{cm}$ and $14.62 \text{ k}\Omega\cdot\text{cm}$, respectively (11.85% increase from 7-14 days). According to AASHTO T 358 [128] (Table 3.3), this indicates a moderate surface resistivity and a slight increase in resistivity over time, which is normal for concrete as hydration continues and the microstructure densifies. However, in the mixtures with BFA, the surface resistivity decreases as BFA content increases. For the concrete mixture with BFA of 5%, the resistivity was $12.62 \text{ k}\Omega\cdot\text{cm}$ for 7 days and $13.39 \text{ k}\Omega\cdot\text{cm}$ for 14 days (lower than the control values by 3.44% at 7 days and

8.41% at 14 days). In the mixture with BFA of 10%, the resistivity was 10.09 k Ω ·cm at 7 days and 13.96 k Ω ·cm at 14 days (i.e., lower than the resistivity of the control by 22.76% at 7 days and 4.51% 14 days). The decrease in the surface resistivity was more apparent with BFA of 15%, which shows resistivity values of 7.64 k Ω ·cm at 7 days and 9.90 k Ω ·cm at 14 days, reaching 43.84% and 32.28% reduction as compared with the control. These trends indicate for BFA 5% and BFA 10% a rate of surface resistivity between high and moderate, and BFA 15% high rate of resistivity. Similar studies observed that replacing cement with BFA led to a decrease in mechanical strength as well as surface resistivity; however, mortars with lower BFA content presented the best results for most of the tests [140].

In contrast, the GP mixes exhibit an opposite trend, as the surface resistivity increases with the increase in the glass powder. The addition of GP 10% initially decreased the surface resistivity by 16.59% compared to the control after 7 days (10.90 k Ω ·cm), then it increased up to 16.01% compared to the control after 14 days (16.96 k Ω ·cm), conferring a moderate to high resistivity rate according to AASHTO T 358. GP 20% with surface resistivity values of 13.84 k Ω ·cm and 21.93 k Ω ·cm at 7 and 14 days, respectively, showing an increase of 5.89% at 7 days and 58.4% at 14 days compared with the control, and a moderate rate of resistance. The GP 30% mix shows the highest resistivity values at both 7 and 14 days, with 20.10 k Ω ·cm and 38.64 k Ω ·cm respectively, demonstrating values in a rate of moderate to low surface resistivity according to the standard, 53.79% higher at 7 days and 164.15% at 14 days compared with the control mix. This significant increase is attributed to the densification of the microstructure, which reduces pore connectivity and is reflected by the elevated surface resistivity values. The improvement in microstructural density results from the pozzolanic activity of the GP, as further confirmed by the EDX analysis presented later in this manuscript.

Similarly, the mixtures with SL show increased surface resistivity as the slag content rises. SL 10% indicates resistivity values of 15.98 k Ω .cm and 17.50 k Ω .cm at 7 and 14 days, respectively. Thus, an increase of 22.28% at 7 days and 19.70% at 14 days was recorded compared with the control. The surface resistivity in mixtures with SL of 20% has values of 19.12 k Ω .cm at 7 days and 22.53 k Ω .cm at 14 days, demonstrating an increase of 46.29% and 54.12% at 7 and 14 days, respectively. Likewise, the SL 30%" mix exhibits higher resistivity at both 7 and 14 days, with values of 18.34 k Ω .cm and 35.93 k Ω .cm, indicating 40.30% and 145.76% higher at 7 and 14 days compared with the control mix. This phenomenon is attributed to the pozzolanic reaction between SL and calcium hydroxide, which leads to the formation of additional CSH gel [141].

Table 3.3: Surface Resistivity and Chloride Penetrability Classification (AASHTO T 358[128])

Chloride Penetrability	Surface Resistivity(k Ω .cm)
High	< 12
Moderate	12 – 21
Low	21 – 37
Very Low	37 – 254
Negligible	> 254

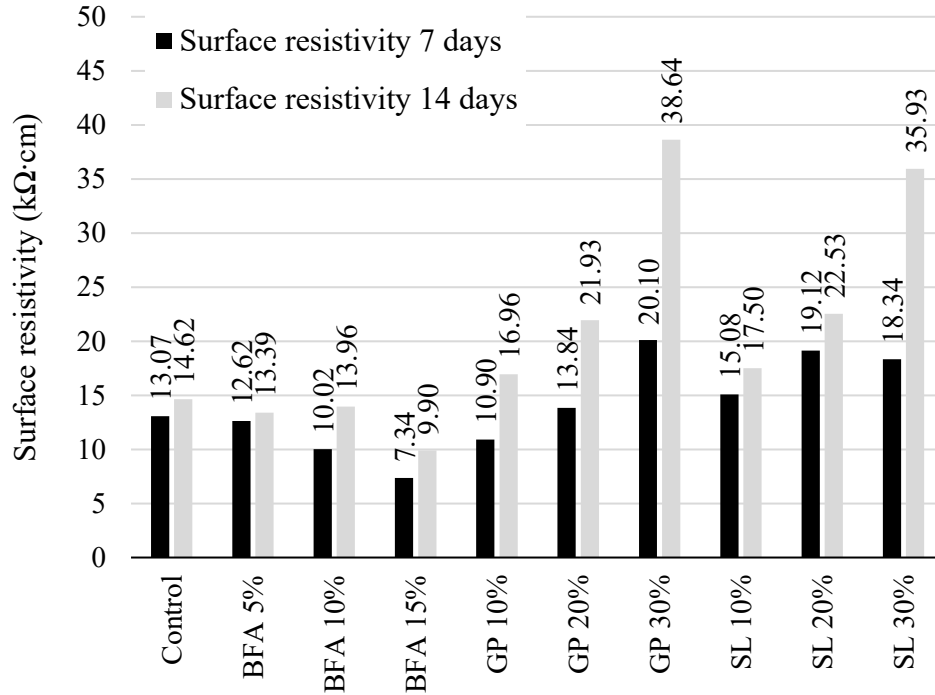


Figure 3.6: Surface resistivity test of fresh concrete incorporating biomass fly ash, glass powder and slag as a partial substitution of cement compared with a control mix.

3.3.4 Bulk electrical resistivity

The bulk electrical resistivity (BER) of the concrete mixes shown in Figure 3.7 is performed based on the ASTM C1876 [129] standard, which describes a non-destructive method to evaluate concrete's electrical current resistance. This test serves as an indicator of concrete's permeability, providing insight into both its short-term and long-term durability. As established by the ACI 222r [142], resistivity higher than 20 kΩ·cm correlates with lower corrosion rate, signifying enhanced durability against penetration of corrosive agents like chlorides.

The results show trends similar to those observed in the surface resistivity test. The control sample has values of 5.22 kΩ·m for 7 days and 6.09 kΩ·cm for 14 days, indicating a low to moderate electrical resistivity. In the BA group, an increase in biomass fly ash content leads to a marked reduction in BER values, particularly at higher content: BER 5% present 5.33 kΩ·cm (3.44% less

to control) for 7 days and $5.96 \text{ k}\Omega\cdot\text{cm}$ (2.13% less compared to control) for 14 days, showing a low to moderate electrical resistivity. The decrease in bulk electrical resistivity with higher BFA concentrations is due to increased porosity and changes in the concrete's microstructure, which facilitate ion movement [143].

Conversely, the GP mixes demonstrate a clear upward trend in resistivity with increasing glass powder content. The mix with GP of 10% has a bulk resistivity of $4.80 \text{ k}\Omega\cdot\text{cm}$ (13.04% less to control) for 7 days and $7.06 \text{ k}\Omega\cdot\text{cm}$ (15.91% higher than control) for 14 days. However, the mixes with 20% and 30% GP exhibit significant increases in the resistivity. Thus, a mix with GP of 20% presents $5.55 \text{ k}\Omega\cdot\text{cm}$ (0.54% higher than control) for 7 days and $8.97 \text{ k}\Omega\cdot\text{cm}$ (47.23% higher than control) for 14 days, and GP 30% with $7.98 \text{ k}\Omega\cdot\text{cm}$ (44.75% higher than control) for 7 days and $14.07 \text{ k}\Omega\cdot\text{cm}$ (147.37% higher than control) for 14 days, indicating an enhanced durability with the increase in GP.

Similarly, the mixes with SL show a moderate to high increase in resistivity with increasing slag content. The SL 10% mix shows $6.24 \text{ k}\Omega\cdot\text{cm}$ (13.04% higher than control) for 7 days, and $7.49 \text{ k}\Omega\cdot\text{cm}$ (23% higher than control), and the SL 20% mix presents $7.38 \text{ k}\Omega\cdot\text{cm}$ (33.7 higher than control) for 7 days and $9.27 \text{ k}\Omega\cdot\text{cm}$ (52.29% higher than control) for 14 days. The SL 30% mix achieves the more resistivity values, with $7.61 \text{ k}\Omega\cdot\text{cm}$ (37.87% higher than control) for 7 days and $13.01 \text{ k}\Omega\cdot\text{cm}$ (113.67% higher than control) for 14 days. The observed increases in resistivity with higher SL or GP dosage, particularly notable at 14 days compared to 7 days, are attributed to ongoing pozzolanic reactions that generate additional calcium silicate hydrate (C-S-H) over time. SL reacts with calcium hydroxide $[\text{Ca}(\text{OH})_2]$ to form additional C-S-H, which progressively enhances resistivity as hydration advances [144]. Similarly, GP, rich in amorphous silica, actively

consumes $\text{Ca}(\text{OH})_2$ to produce C-S-H gel, reducing pore connectivity and further increasing resistivity with curing age [145]. Both SL and GP reduce ionic mobility in the pore solution by chemically binding calcium and alkali ions and decreasing capillary pore size and connectivity, thereby improving concrete durability as these reactions improve [144]. In contrast, biomass fly ash exhibited largely inert behavior, showing minimal pozzolanic activity and resulting in decreased resistivity due to increased porosity and microstructural changes that facilitate ion transport.

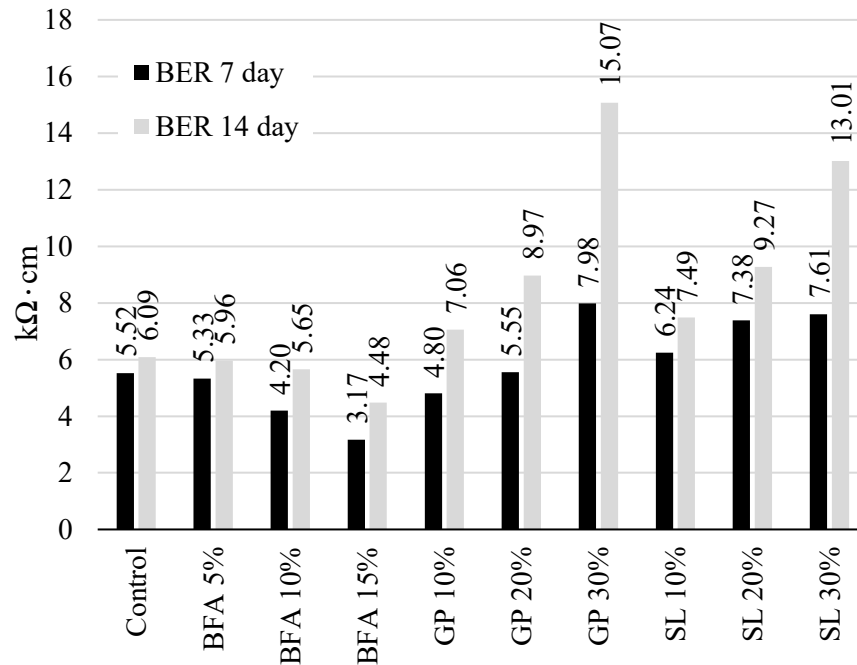


Figure 3.7: Bulk electrical resistivity test of fresh concrete incorporating biomass fly ash, glass powder and slag as a partial substitution of cement compared with a control mix.

3.3.5 Compressive strength test

The compressive strength of the mixes, categorized into three distinct groups alongside the control mix at different curing ages, that is, 7 days and 14 days, are shown in Figure 3.8. The compressive strength of the control mix was shown to be 40.3 MPa and 45 MPa after 7 days and 14 days of

curing, respectively. It can be seen from the Figure 3.8 that compressive strength for the control sample after 14 days increased by almost 12% as compared to the 7-day strength.

For the samples where BFA is used by 5%, 10% and 15%, the value of compressive strength is less than the control mix after both 7 and 14 days of curing. The maximum value of compressive strength for BFA samples is for 5% cement replacement at 14 days of curing which is 38.1MPa, 15.4% lesser than the control sample for same duration of curing whereas the lowest value is recorded for 15% which is 18.9 MPa, 57.9% lower than control sample and 50.3 % lower than 5% BFA replacement concrete sample. Several factors contribute to this phenomenon: the incorporation of BFA can increase the porosity of the concrete matrix, higher porosity means more void spaces within the concrete, which affects its density and strength [143]. Additionally, BFA exhibits lower SiO_2 content and a reduced pozzolanic reactivity. This means that less additional CSH is generated during hydration, which limits the development of compressive strength [110].

In the samples where cement is substituted by GP in the order of 10%, 20% and 30%, the values obtained are increasing as the substitution percentage increases for both 7 days and 14 days of curing. The sample with 30% substitution percentage gives 42.2 MPa, which is the maximum in this group, but it's 6.2175% less than the control sample for 14 days of curing. The value recorded with 10% substitution gives the least value as 39.7 MPa, 11.9% less than the control sample and 6.10% less than 30% GP substitution for the same age of concrete. The fine particles of GP fill voids within the concrete matrix, reducing porosity and leading to a denser, more cohesive structure. This contributes to increased compressive strength [146].

The last group of samples is prepared with cement being replaced with slag at 10%, 20% and 30% which gives a higher value than the other two groups. 30% slag replacement gives the value of compressive strength as 46MPa, which is slightly higher than the control sample by 2.1% whereas

the lowest value recorded after 14 days is with 10% substitution as 42.2 MPa, 6.3% lower than the control sample. This improvement is primarily due to the pozzolanic and latent hydraulic properties of slag, which contribute to the formation of additional CSH gel during the hydration process, which is the primary compound for strength development in concrete [147].

Compressive strength achieved with 30% SL is 8.9 % higher than the one obtained with 30% glass powder. While the value recorded with 5% BFA is 17.2% lower than the 30% SL substitution.

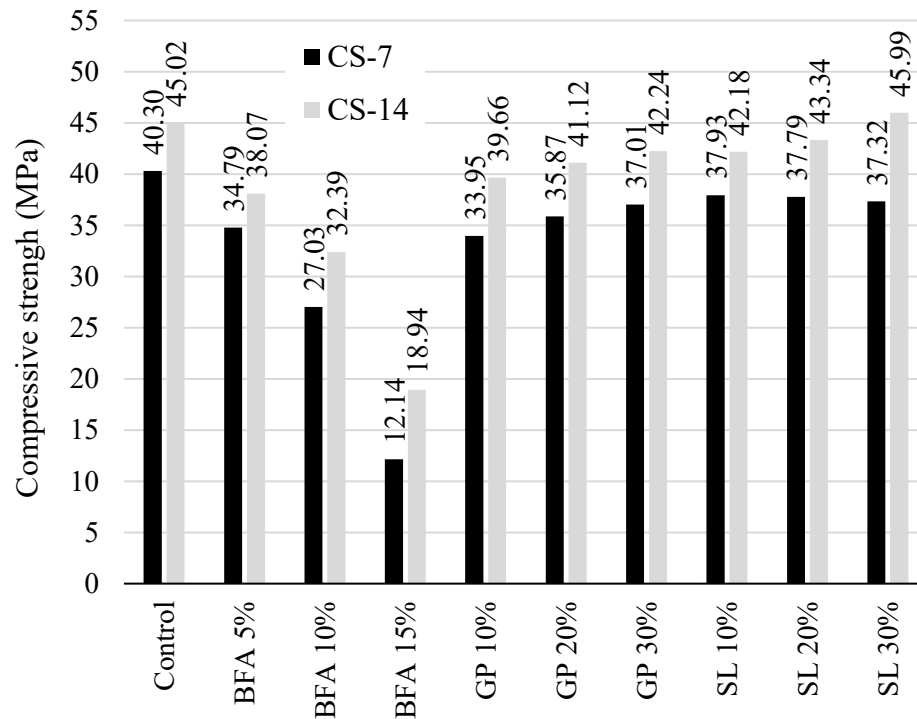


Figure 3.8: Compressive strength test of hardened concrete incorporating biomass fly ash, glass powder and slag as a partial substitution of cement compared with a control mix.

3.3.6 Setting time test

Figure 3.9 shows the penetration resistance (psi) of concentrated mixes with different compositions of BEA, GP, and SL versus the elapsed time (min). This graph shows a general view of all the different mixes separated into three groups compared with a control mix following the standard

ASTM C403/403M [127]. The test is designed to determine the initial and final setting times, which aid in understanding the behaviour and the hardening of mortar with time, which is important for the timing of placing, finishing, and curing operations.

As shown in Figure 3.9, the control mix exhibits a delayed rise in penetration resistance, until around 210 minutes the resistance starts increasing but remains below 1000 psi until around 360 minutes and begins to sharply increase after this point reaching around 5000 psi. The control mix seems to have the fastest rate of increase in penetration in the final phase.

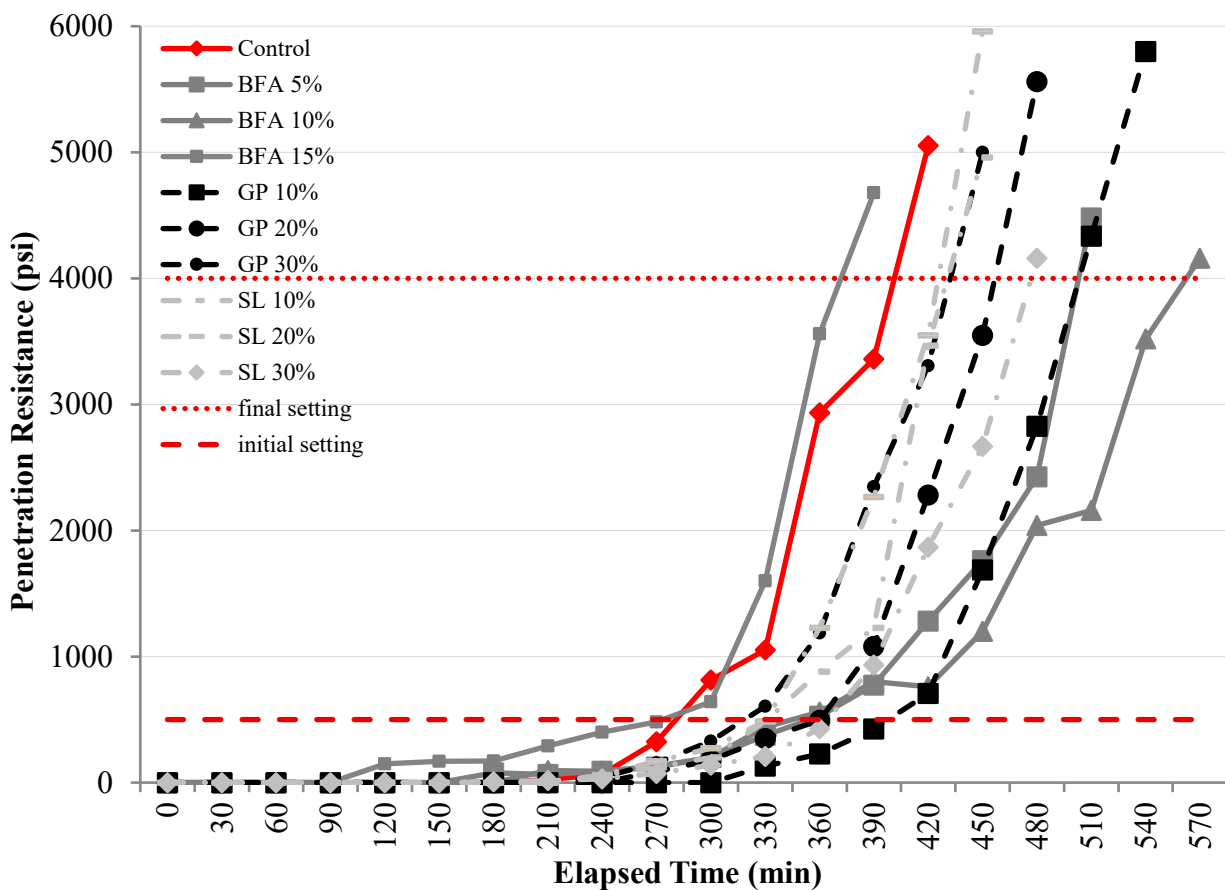


Figure 3.9: Setting Time test of fresh concrete incorporating biomass fly ash, glass powder and slag as a partial substitution of cement compared with a control mix.

The mix with 5% BFA behaves similar to the 10% BFA mix in the initial resistance. BFA 5% and 10% mixes show a smoother and gradual buildup compared with the control mix. This slowdown is attributed to calcium ions in the ash, the high concentration during early ages of hydration, and delays in the cement from reacting [148]. At the end, the mix with 15% BFA shows the most behind start in resistance increase, around 330 minutes. Furthermore, a 15% BFA mix shows similar behaviour to the control in the initial phase with low resistance values. After 210 minutes, the penetration resistance starts increasing gradually, and between 360 and 20 minutes, there is a sharp rise reaching under 4000 psi.

The mix with a 10% GP mix exhibits the most delayed penetration resistance within the GP group. In contrast, the 20% GP mix demonstrates a shorter hardened development than the 10% GP yet follows a similar initial penetration pattern. Finally, the 30% GP mix exhibits an initial delay in the development of its penetration resistance. However, as the testing period progresses, the 30% GP mix demonstrates an accelerated rate of resistance development, ultimately surpassing other mixes by reaching its final resistance earlier than both 10% and 20% GP mixes. In the GP group, as the percentage increased, the penetration resistance developed earlier. Research has shown that the addition of GP decreases the heat release rate during hydration but provides sites for C-S-H nucleation, aiding in microstructural development [146].

Finally, the control mix and SL mixes are compared with varying percentages of SL (10%, 20% and 30 %). The 10% SL mix shows an increase in penetration after 240 minutes; the rate of increase is slower than the control mix, and it remains below 4000 psi until around 450 minutes. This mix demonstrates delayed strength development compared to the control mix. The 20% SL mix also shows a slow start in resistance, indicating that the higher SL concentrations slow down the setting process. The 30% SL mix shows the slowest initial increase in penetration, rising after about 300

minutes. While crossing the 4000 psi with 450 minutes, it lags significantly behind the control and other SL mixes. In a general aspect, the mixes that have the slowest behaviour are the BFA mixes, especially the BFA 10%.

3.3.7 EDX Analysis

The calcium to silica (Ca/Si) ratios were determined using EDX analysis at day 14 for all mix samples to evaluate the hydration products and pozzolanic reactivity of the mixtures (Figure 3.10). The Ca/Si ratio is a key factor to show the pozzolanic reactions, as it reflects the consumption of calcium hydroxide (CH) and the formation of additional calcium silicate hydrate (CSH) gel. A lower Ca/Si ratio typically indicates higher pozzolanic activity and greater CSH formation, while a higher ratio suggests limited reactivity and unreacted CH presence. The analysis was conducted at 14 days to ensure sufficient time for pozzolanic reactions to develop, as such reactions typically progress more slowly than primary cement hydration. This age also provides a reliable basis for comparison with other tests and helps capture the more pronounced differences in pozzolanic behavior. The control sample, consisting of Portland cement without any replacement, exhibited a Ca/Si ratio of 1.265 (Figure 3.10). In the samples where cement was partially replaced with biomass fly ash, the Ca/Si ratios showed a significant increase compared to the control sample, varying from 1.483 to 2.057 for 5% to 15% replacement of cement. The results indicate that the partial replacement by biomass fly ash reduced the reactivity and led to less CSH gel formation.

In the case of the samples where slag was used as a partial cement replacement, the Ca/Si ratios were lower than the control but higher than those observed in the glass powder samples in the range of 1.183 to 0.936 for 10% to 30% of cement substitution level. The result indicates that the

partial replacement with slag has augmented reactivity as compared to biomass fly ash but lower than glass powder.

Whereas the samples in which cement was partially replaced by glass powder showed lower Ca/Si ratios than the control sample in the range of 0.981 to 0.672 for 10% to 30% replacement of cement. This indicates that the glass powder led to increased reactivity compared to control samples, thus forming more CSH gel in the concrete.

Figure 3.11a displays the highest Ca/Si ratio (2.057) for the mixture with 15% BFA. Figure 3.11b shows a medium ratio of 0.936 for the mixture containing 30% SL, while Figure 3.11c presents the lowest ratio (0.672), observed in the mixture with 30% GP. In the 15% BFA sample, the area associated with Si is relatively low, while the Ca area is higher. However, in the 30% GP sample, EDX analysis shows a significantly larger Si area compared to Ca.

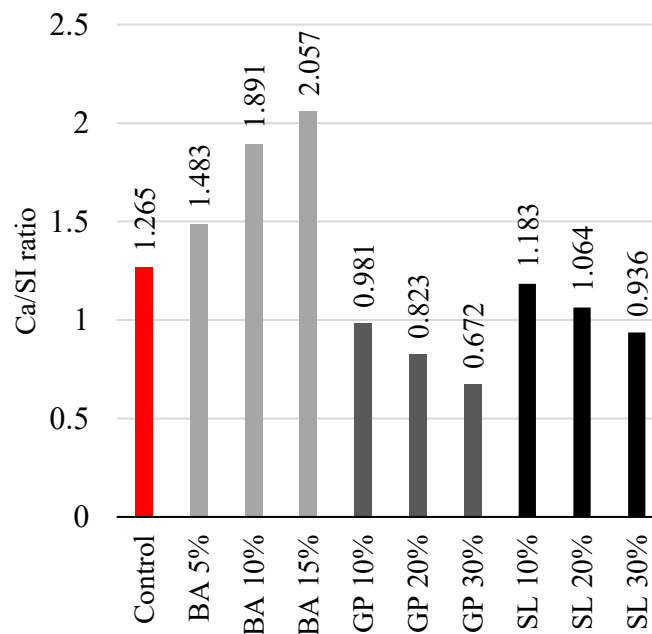
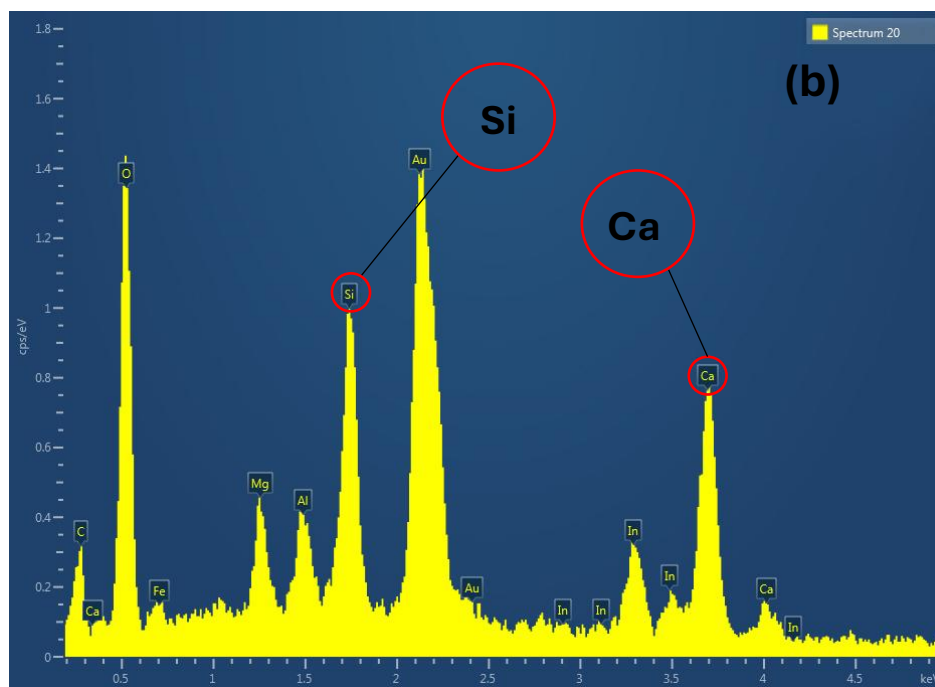
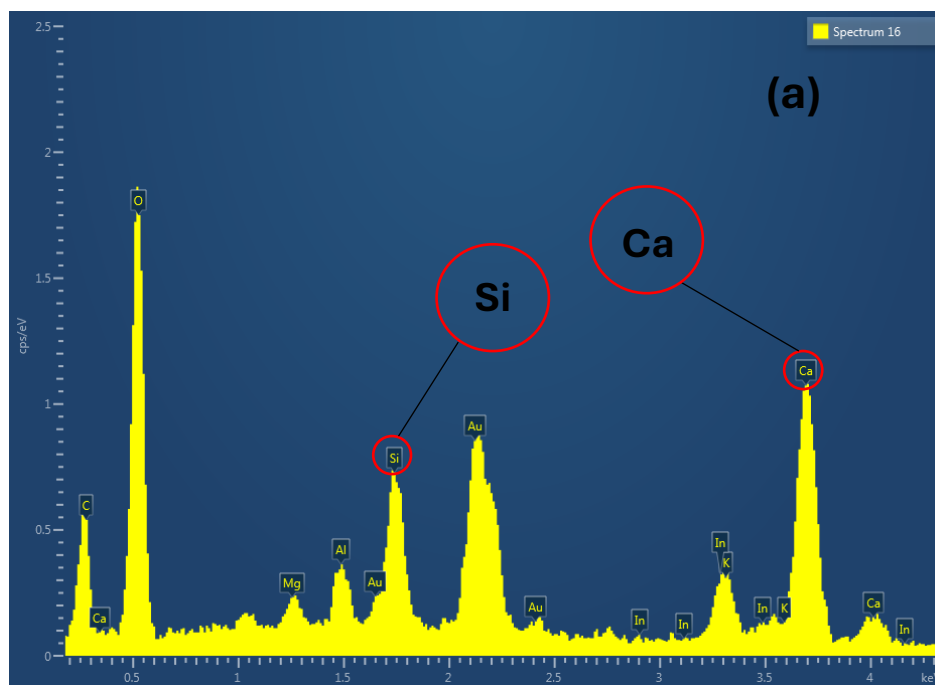


Figure 3.10: Ca/Si ratios obtained with the help of EDX Analysis for all mixes



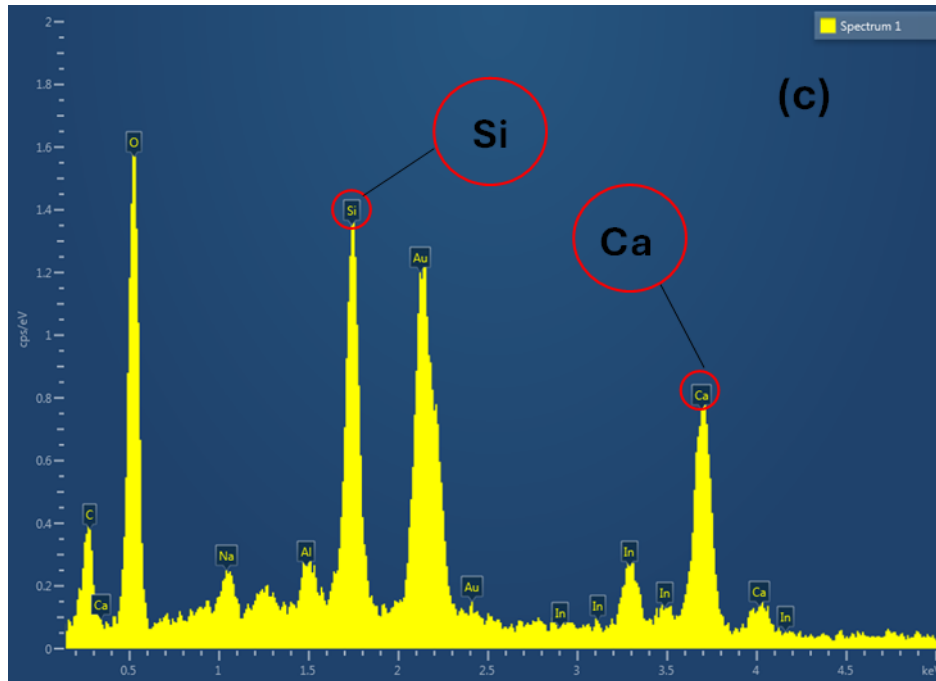


Figure 3.11: EDX analysis results of a) BFA 15%, b) SL 30%, c) GP 30%

The observed variations in strength and resistivity for GP, BFA, and SL indicate their significant effects on concrete. In addition to the variations in the Ca/Si ratio observed across different concrete mixes, the inverse relationship between the Ca/Si ratio and both Bulk Electrical Resistivity (BER) and Surface Electrical Resistivity (SER) shows the significant role of the calcium to silica ratio in influencing the properties of cementitious materials.

The increased reactivity of glass powder due to its pozzolanic character was confirmed in the samples containing glass powder with a lower Ca/Si ratio. Also, the increase in surface and bulk electrical resistivity with the incorporation of glass powder was attributed to the pore-filling effect of the C-S-H gel. However, the resulting CSH gel was not structurally hard enough to improve compressive strength in early ages. The results in this study are consistent with previous findings (Hongjian Du and Kiang Hwee Tan) [149,150]. For biomass fly ash samples, both reactivity and resistivity were on lower than the control sample, which is indicated by a higher Ca/Si ratio and less CSH gel formation. This lack of sufficient CSH gel led to reduced strength at the early age of

7 and 14 days, making biomass fly ash less effective as an early strength enhancer when used as partial replacement of cement. In addition, many microcracks were observed on the surface of the BFA samples, which further contributed to their reduced compressive strength (Figure 3.12). These microcracks are likely caused by the high-water absorption of BFA, leading to internal stresses during hydration and drying.

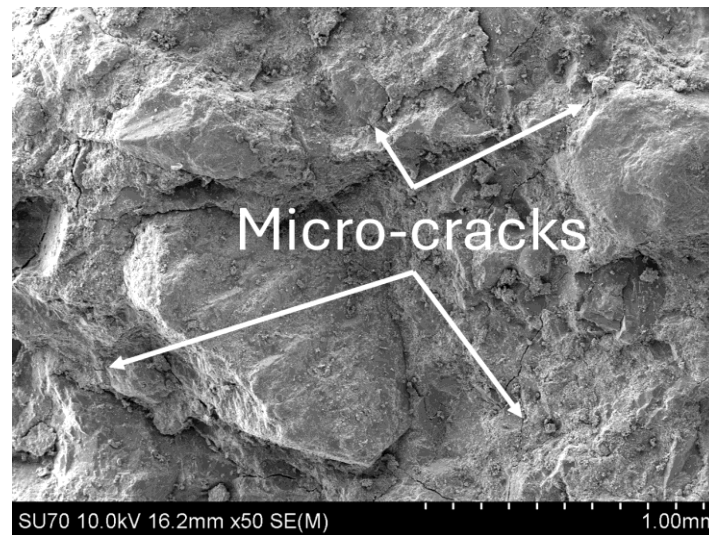


Figure 3.12. SEM image of surface micro cracks in the BFA sample

In the case of slag, the increased resistivity suggested denser microstructure, and higher hydration process resulted in high strength at early ages. The notable increase in strength at 14 days for the 30% slag replacement suggests that longer curing duration would improve overall strength.

Biomass fly ash (BFA) increases the Ca/Si ratio significantly with increasing replacement levels due to its higher calcium oxide content. Conversely, glass powder (GP) consistently reduces the Ca/Si ratio, likely due to its high silica content and limited calcium contribution. Slag (SL) demonstrates a balanced behaviour, with a modest decrease in the Ca/Si ratio, reflecting its relatively lower calcium-to-silica ratio compared to the control. As shown in the Scanning Electron Microscopy (SEM) in Figure 3.13, while a significant presence of C-S-H gel can be frequently

observed in the GP and SL samples, the BFA specimen lacks noticeable formation of C-S-H gel. From a performance perspective, a higher Ca/Si ratio may reduce early strength development and could deteriorate durability due to increased porosity. Conversely, lower Ca/Si ratios, as observed with GP and SL, are associated with improved pozzolanic reactions and reduced permeability, which can contribute to enhanced durability and compressive strength. These findings emphasize the importance of selecting SCMs based on the desired balance between early strength and durability in concrete design.



Figure 3.13: SEM images of a) BFA 15%, b) SL 30%, c) GP 30%

3.4 Conclusion

This study aimed to evaluate the early-age mechanical properties of concrete incorporating glass powder (GP), biomass fly ash (BFA), and blast-furnace slag (SL) added individually as partial replacements for Portland cement. Through comprehensive experimental investigations, including slump, air content, compressive strength, setting time, electrical resistivity, and EDX analysis, the distinct effects of each supplementary cementitious material (SCM) were clearly outlined on the following conclusions:

- The findings indicate that slag proved to be the most effective in terms of early strength development; concrete with 30% slag replacement achieved a 14-day compressive strength that was slightly higher than the control mix, indicating that slag can be used at relatively high

levels without compromising early-age strength. This superior performance is attributed to slag's latent hydraulic and pozzolanic reactivity, which contributed to additional calcium silicate hydrate formation and a denser microstructure by 14 days.

- Glass powder, while moderately affecting early compressive strength negatively, significantly enhanced electrical resistivity, indicating its potential for improving concrete durability through reduced permeability and refined pore structure.
- Conversely, biomass fly ash exhibited lower effectiveness in the early stages, at low replacement levels (5–10%) BFA led to a small strength decline relative to the control, and at higher replacement levels the early-age strength reduction became pronounced, this implies that the pozzolanic reaction of BFA is quite slow within the first two weeks, and its incorporation (especially in larger quantities) results in a more porous matrix with less extensive early hydration products.
- EDX observations show that mixes with GP and SL exhibited a denser matrix with well-distributed hydration products, whereas BFA mixes showed more unreacted particles at the early ages. These findings highlight the importance of selecting and proportioning SCMs based on the desired balance between early-age strength and durability in concrete design.

This study was only focused on the early age behaviour of these materials as cement replacement individually with certain percentages. It is recommended to (1) investigate the different replacement levels on mechanical and durability performances on concrete; (2) assessing the effect of interaction of GP, BFA, and SL on the early age of concrete; and (3) calculating the released carbon emission by replacing GP, BFA, and SL by cement.

CHAPTER 4: MULTI-WASTE LOW-CARBON CONCRETE: SYNERGISTIC OPTIMIZATION VIA RSM FOR ENHANCED ENVIRONMENTAL AND MECHANICAL PERFORMANCE

Note:

The manuscript had been slightly altered from the original paper by renumbering the tables and figures to include the chapter number. In addition, the reference list and list of notations have been moved to the appropriate sections in the thesis as indicated in the table of contents.

Abstract

The adverse environmental effects of conventional concrete manufacturing demand sustainable solutions, including the substitution of Portland cement and aggregates with waste materials. This approach not only minimizes landfill waste but also mitigates resource depletion and environmental risks. Incorporating multiple waste materials like biomass fly ash (BFA) and glass powder (GP) in place of cement, along with shredded rubber (SR) as aggregate, has the potential to enhance cement substitution and support more sustainable concrete production. However, achieving optimal environmental, mechanical and durability standards remains challenging when using multiple waste materials. This study, as part of an ongoing project at Lakehead University, investigates optimal concrete mix designs that incorporate shredded rubber, biomass fly ash, and glass powder. Nineteen mixtures were developed using the Response Surface Method (RSM) to model the interactions between these materials. Workability and mechanical properties were evaluated through slump and compressive strength tests, while durability was assessed using Rapid Chloride Migration (RCMT) and bulk electrical resistivity tests. Environmental impact, including

Global Warming Potential (GWP) and service life, was also examined, contributing valuable insights toward the development of sustainable concrete solutions. The results demonstrate that GP enhances concrete properties and, when combined with BFA and SR, partially offsets their adverse effects. This allows a greater proportion of waste materials to replace cement, potentially reducing carbon emissions by 30% per 1m³ during the life cycle compared to the control sample.

Keywords: Green Concrete, Net-Zero Emission, Waste Materials, Response Surface Methodology, Environmental impact

4.1 Introduction

In the last two centuries, carbon dioxide emissions have significantly increased, leading to a 1.1°C rise in global temperature compared to 200 years ago, which has intensified climate change [1]. This will be translated to a severe negative impact affecting the economy, food and agriculture, health, nature, oceans, and animals [151]. As a result, by 2070, the total area in North America experiencing freezing days is projected to shrink by about 6% [152]. Depending on the location, the number of freezing days will decline by 10 to 90 days. Higher temperatures would also intensify natural disasters such as storms, heat waves, floods, and droughts [2,152].

Concrete is the most commonly used man-made material worldwide [153]. Concrete is known to have a significant carbon footprint since its manufacturing/casting process is responsible for 8-10% of the global carbon dioxide emissions [4]. One cubic meter of concrete is typically made up of 10-15% Portland cement, 60-75% fine and coarse aggregates, and 15-20% water. Recent estimates indicate that 4.68 G tons of Portland cement will be produced globally in 2025, accounting for 74% to 81% of concrete's CO₂ emission [5,154]. In particular, 40% of the carbon dioxide produced during the manufacturing of Portland cement comes from the combustion of

fossil fuels, with the remaining 60% generated from natural chemical reactions [6]. Furthermore, the rapid consumption of natural aggregates in construction would lead to the depletion of these natural resources [155]. The overutilization of sand (fine aggregates), especially from rivers, lakes, and shorelines, is worsening the scarcity of suitable construction sand [156]. Even with moderate population and economic growth, it is predicted that global use of sand will increase by 45% by 2060; that was further confirmed by [156], who illustrated that the sand demand is projected to decline slightly in the middle and high-income regions by 2060. However, in lower-middle-income regions, demand is expected to be three times higher than the current demand.

The rapidly increasing dumping of waste materials is a growing environmental concern. For instance, a significant portion of waste materials, including 76% of discarded tires, 56% plastic, 76% glass, and 48% fly ash powder, wind up in landfills [8–10]. Specifically, a sizable amount of glass waste is not used each year, even though it can be recycled. Although it may take thousands of years for glass to break down naturally, recycling is a very effective way to save resources and cut down on waste. Globally, only 21% of the 130 million tonnes of glass produced annually is recycled [157]. In Ontario, around 600,000 tonnes of glass waste is collected each year, which presents a substantial opportunity to recycle glass fines [158]. Additionally, waste tires pose various hazard impacts, such as the risk of fires at landfills, attracting harmful creatures, spreading disease, and affecting human health [159]. Worldwide, over 26 million tons of waste tires are produced annually [160], where 437,000 tons of worn-out tires were collected in Canada, according to the Canadian Association of Tire Recycling Agencies [161]. Moreover, with restrictions on coal power plants threatening the future supply of coal fly ash for the cement industry, biomass combustion is emerging as a promising alternative. This shift highlights the urgent need to explore alternative materials. As biomass use increases, it will generate significant

quantities of biomass fly ash, making it essential to develop efficient management strategies for its incorporation into cement production, as landfill disposal poses environmental risks [162,163].

Given the harmful impact of concrete production combined with the environmental degradation caused by the disposal of tires, fly ash, and glass wastes on the environment, it is imperative to take significant actions to reduce these effects by using these waste materials in the concrete production industry. In addition to decreasing the amount of waste sent to landfills, this would also lessen the impact on the environment by reducing the depletion of natural resources. It is important to note that this approach aligns well with the overall strategy established by the Canadian government, which has passed the Net-Zero Emissions Accountability Act, requiring the nation to attain net-zero emissions by 2050 [164]. The Act mandates the involvement of the public and independent advisors to provide guidance to the Government of Canada as it works towards achieving its goals [165,166].

In this context, extensive research has been conducted to assess the potential of using the previously mentioned waste materials as a substitute for the ingredients of the concrete. Both glass powder and biomass fly ash (from wood waste) have been identified as promising waste materials to be used to produce green concrete [95,167]. The mechanical properties [107,168], workability [169,170], and durability of concrete [171,172] containing biomass fly ash were studied extensively. Rumman et al [21] investigated the characterization of wood fly ash and its impact on the production of low-carbon concrete. Their findings showed that while adding wood fly ash reduced the compressive strength, particularly when a high dosage of wood ash was used; however, replacing up to 15% of the cement with wood fly ash produced a concrete with strength similar to the control sample. However, in this research, the carbon equivalent emissions of the low-carbon concrete were not measured. Research has shown that glass has a chemical composition that is

similar to the traditional supplementary cementitious materials (SCMs) like fly ash [14]. Deschamps et al. [173] conducted a life cycle assessment of glass powder in concrete, advocating for the use of post-consumer mixed glass as SCM, confirming that it can reduce environmental impacts by 20%. Du and Tan [149] assessed the compressive strength of concrete with a high glass powder content over a year. However, in this research the effect of combining multi waste material was not evaluated. Also, the applicability of using crumb rubber as a partial replacement to the aggregate in concrete was reported by many researchers [174–177]. The electrical resistivity [178], chloride ion diffusion [179], and compressive strength [180] of rubberized concrete were studied. In addition, the findings indicate that incorporating up to 15% of shredded tires in the concrete matrix enhances its overall durability characterization. None of these studies explored the durability, mechanical properties and environmental impact comprehensively to optimize a concrete mix design containing multiple waste materials. The synergy between GP and SR helps mitigate the strength loss caused by SR. While SR reduces mechanical performance, GP refines the pore structure through its pozzolanic activity, improving durability properties such as water absorption, capillarity, and porosity. This combination enhances impermeability and thermal insulation, making SR-GP mortars suitable for applications where these properties are prioritized over high strength [181]. However, even in the study by Gerges et al. [44] or Letelier et al. [181], which explored the use of BFA, GP, and SR in concrete, the durability, global warming potential (GWP), and optimized mix were not addressed.

Optimizing the amounts of three waste materials or more, which may significantly impact concrete performance, is understudied. Additionally, another critical research deficiency is the lack of evaluation of the environmental impact through Global Warming Potential (GWP), which was not assessed. There is considerable potential to utilize multiple waste materials to enhance cement

replacement while still meeting the required mechanical, durability, workability, and GWP criteria. Addressing this gap is essential for assessing the true low-carbon potential and feasibility of these waste materials in concrete mixtures. Thus, this study represents the initial phase of an extensive ongoing research project at Lakehead University on developing low-carbon and sustainable concrete using multiple waste materials. This study comprised two sets of experiments. The first set involved 19 concrete mixtures used to establish equations for various tests, encompassing workability, mechanical properties, durability, and environmental impact. The second set of four mixtures was used to validate the accuracy of the equations. A total of 19 concrete mixtures incorporating shredded rubber, biomass fly ash, and glass powder were designed and produced using the Response Surface Methodology (RSM). RSM applies statistical techniques to analyze the interactions between variables and their responses, as detailed in the experimental program section. The workability and mechanical properties of the mixtures were assessed through slump tests and compressive strength evaluations. Durability was examined using the Rapid Chloride Migration Test (RCMT) and bulk electrical resistivity (BER) measurements. Additionally, the environmental impact of the concrete mixtures was evaluated by assessing their Global Warming Potential (GWP) and projected service life.

4.2 Experimental Program

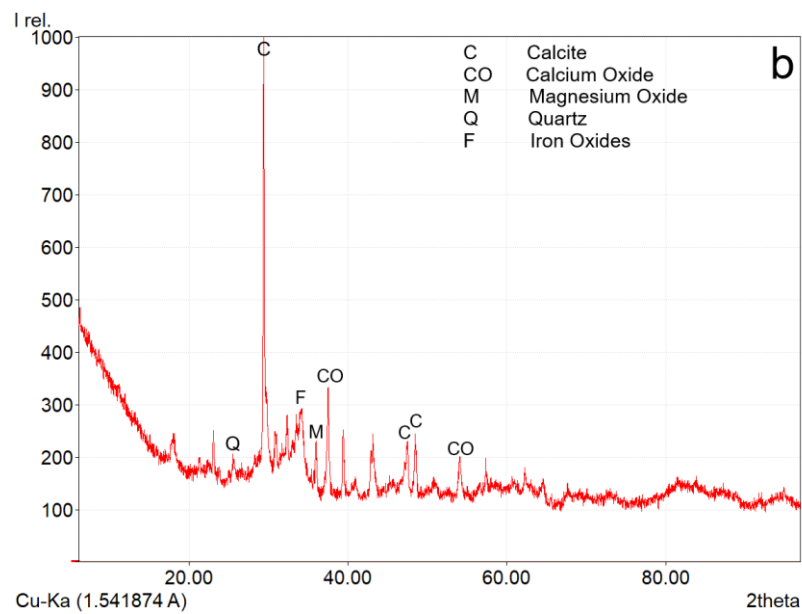
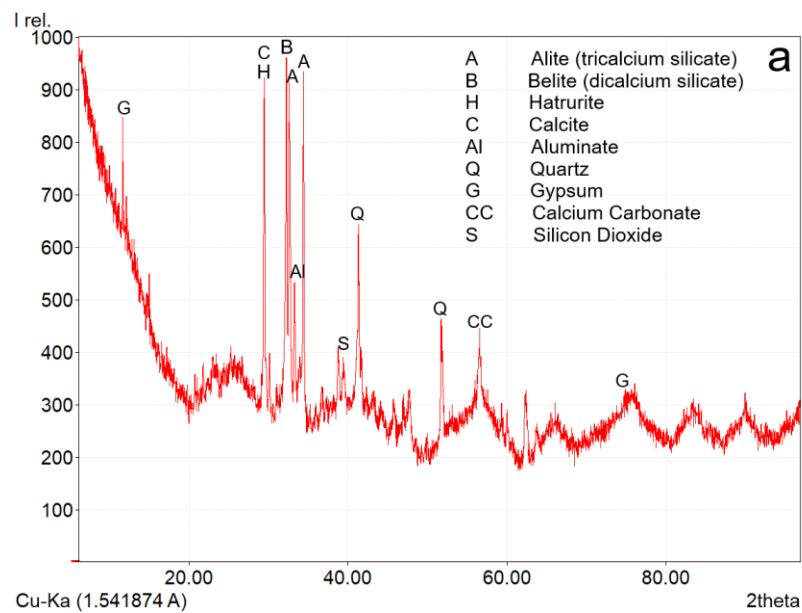
4.2.1 Materials

In this research, general-use (GU) Portland cement utilized is complying with the requirements of CSA-A3001 standard [182]. Glass powder (GP) with the requirements of ASTM C1866 [183] standard and biomass fly ash (BFA) were employed as supplementary material. Table 4.1 presents the chemical composition of the GU cement, GP, and BFA. Also, X-ray Diffraction (XRD) was employed to identify and quantify the crystalline phases in cement, BFA and GP from diffraction

patterns obtained when X-rays interact with their crystal structures. The Intensity vs. 2θ angle chart produced displays peaks whose intensities and positions reveal the phase composition of the material. As shown in Figure 4.1a, compounds like alite, belite, hatrurite, calcite, aluminate, quartz, gypsum, calcium carbonate, and silicon dioxide were detected in cement. Similarly, the BFA analysis shows crystalline phases such as calcite, calcium oxide, magnesium oxide, quartz, and iron oxides (Figure 4.1b). Contrarily, no particular crystalline phases could be established in GP (Figure 4.1c), showing its very amorphous nature. The particle size distribution of cement, GP, and BFA was tested by a Mastersizer device. According to the results, D_{90} (90% of the total volume) for GU, GP, and BFA is 50 μm , 13.2 μm and 120 μm , respectively. The particle size distribution of the materials is shown in Figure 4.2. The grain size and shape of BFA and GP are also presented in Figure 4.3 through an SEM image. The superplasticizer utilized is a polycarboxylate ether, with a specific weight of 1.08. The aggregate with a maximum size of 20 mm was used, and the particle size distribution of sand and gravel is shown in Figure 4.4, where the gradations were compatible with the specification of the ASTM C33 [184] standard. The gradation curve of the shredded rubber (SR) was obtained using the sieve analysis, and the curve fits within the ASTM limits, as shown in Figure 4.4 (c).

Table 4.1: Chemical composition of Portland cement, glass powder, and biomass fly ash

	SiO₂	Al₂O₃	Fe₂O₃	CaO	MgO	Na₂O	LOI
Cement (%)	19.9	5.2	2.3	62.34	2.27	0.23	2.93
Biomass fly ash (%)	2.79	0.83	1.92	42.49	5.21	0.55	29.68
Glass powder (%)	70.07	1.57	0.34	10.46	1.47	12.85	1.11



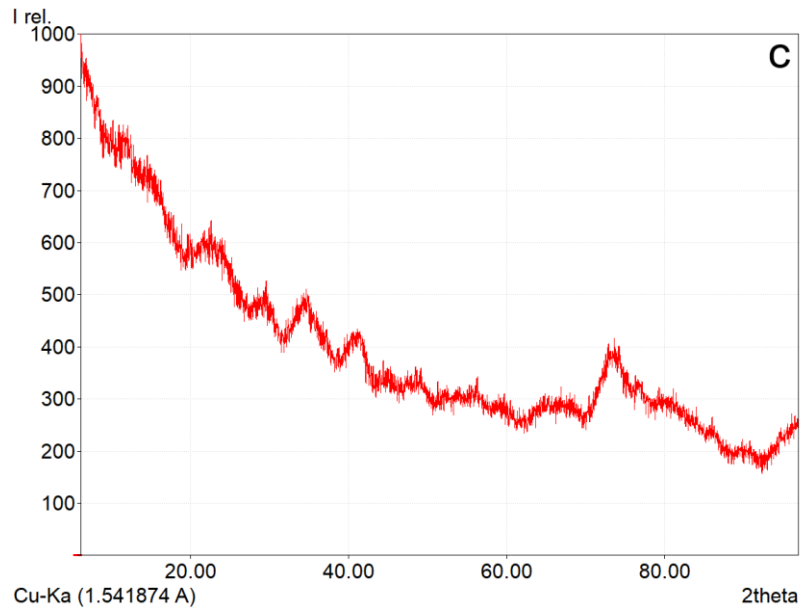


Figure 4.1: XRD graph of a) Cement, b) Biomass fly ash, and c) Glass powder

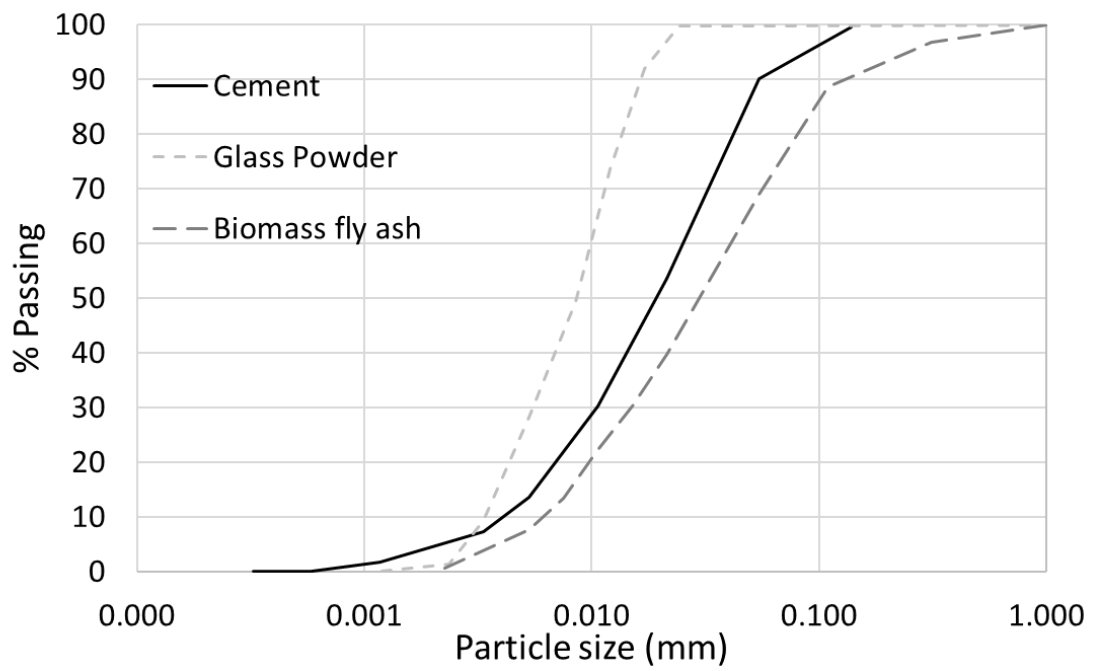


Figure 4.2: Particle Size Distribution of Cement, Glass powder, and Biomass fly ash

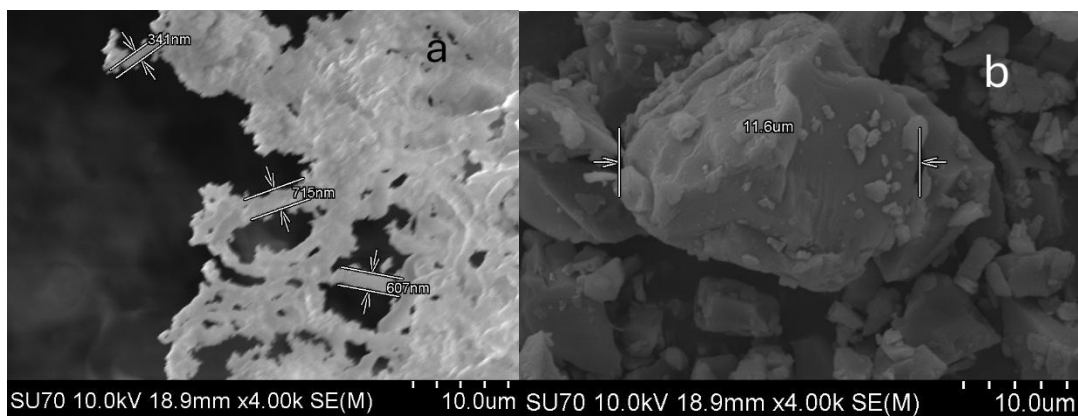


Figure 4.3: Scanning electron microscope (SEM) of a) Glass powder and b) Biomass fly ash

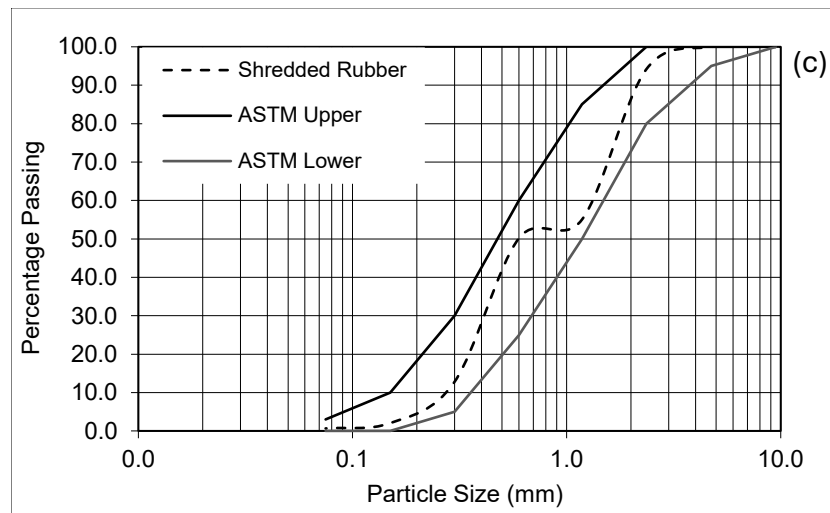
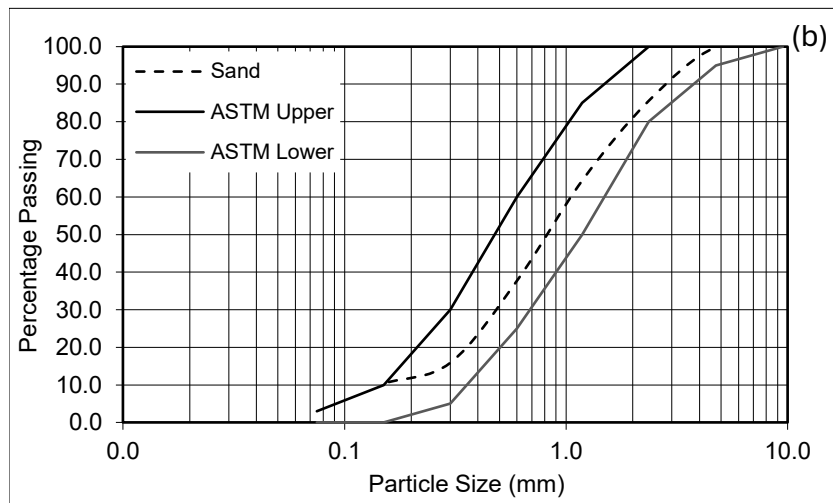
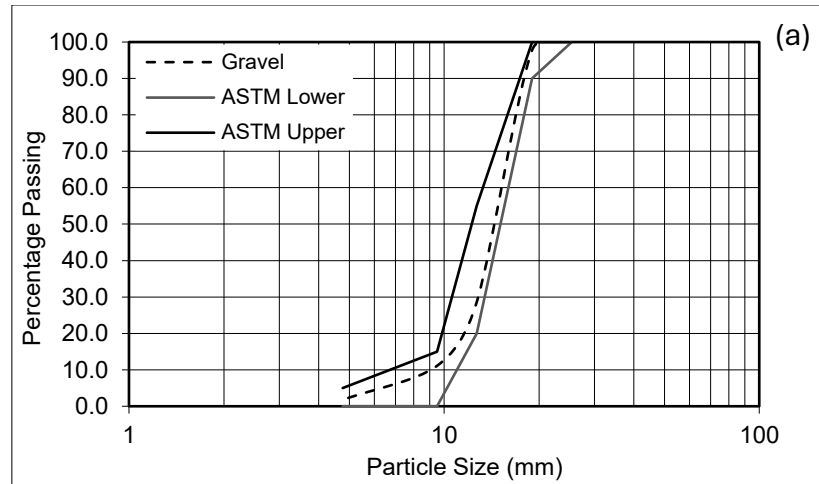


Figure 4.4: Particle size distribution of (a) Gravel, (b) Sand, and (c) Shredded Rubber

4.2.2 Sample preparation

The concrete mixtures were prepared in accordance with ASTM C192 [185]. Initially, the aggregates and cement were mixed for 1 minute. Subsequently, water and the superplasticizer were gradually added, and the mixer was operated for 3 minutes after the water was introduced. The mixer was then paused for 3 minutes, followed by an additional 2 minutes of mixing. Upon completion of mixing, a slump test was conducted before the concrete was poured into molds. After casting, the specimens were covered in plastic sheeting for 24 hours and then transferred to a curing tank for 28 and 90 days prior to further testing. The water-binder ratio (with the binder comprising cement, BFA, and GP) was maintained at 0.46 for all mixtures, with a binder content of 340 kg/m³, and BFA and GP replacing cement. A 50/50 sand-to-gravel ratio was used for mixtures, except when SR replaced sand.

4.2.3 Tests

The workability of the fresh concrete mixtures was assessed by the slump as per the ASTM C231[126]. Nine cylindrical samples, 100 mm in diameter and 200 mm in height, were cast for each mixture and tested at 28 and 90 days to determine the compressive strength according to the standard ASTM C39, 2023. A total of 114 cylinders of concrete were made for 19 mixtures.

NT BUILD 492, 1999 code was followed to perform the rapid chloride migration test (RCMT). At 28 days of curing, two cylindrical discs with a diameter of 100 mm and a height of 50 mm were cut for each mix. The outermost 10-20 mm of each core was removed before slicing. A total of 38 samples were tested across 19 designed mixtures, with two specimens tested for each mix. The specimens were stored in water and saturated with limewater under vacuum conditions one day prior to testing. During the vacuum saturation process, the samples were placed in a desiccator

connected to a vacuum pump, where a pressure of 40 mbar was applied for 3 hours. The desiccator was then slowly filled with limewater while maintaining the vacuum for an additional hour, after which air was allowed to re-enter the desiccator. The samples remained in the solution for approximately 18 hours. The RCM test was performed on the saturated samples at 28 and 90 days, using power sources with constant voltage outputs. The test setup included two concrete samples, with a catholyte volume of approximately 12 L and an anolyte volume of about 0.3 L per test specimen. The electrolytes were refreshed after each series of experiments (Figure 4.5). Since physical observations provide a better representation of the penetrability of chloride ions only into concrete, the physical penetration depth of chloride ions was measured in this study immediately after the completion of the test by spraying 0.1 M AgNO_3 (silver nitrate) solution onto the surface of equally split discs. The discs were allowed to sit under fluorescent light for approximately 15 min to obtain the whitish precipitate of silver chloride.

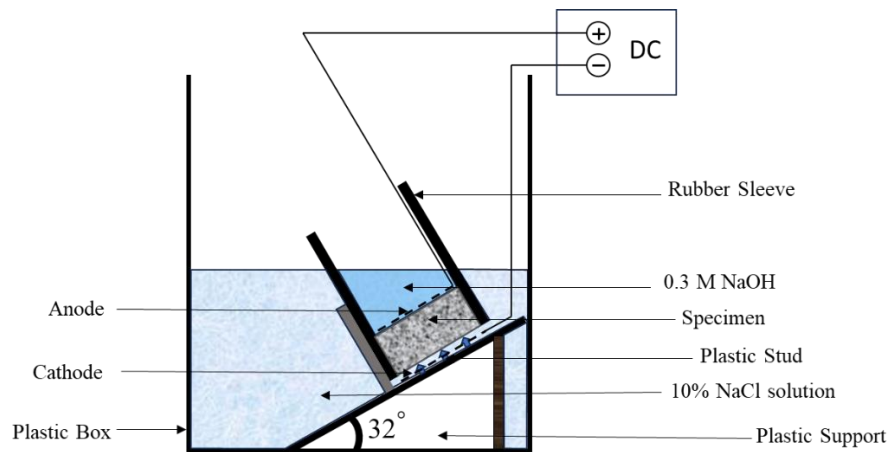


Figure 4.5: Schematic of RCM test setup

Finally, the bulk resistivity measurement was conducted on cylindrical specimens (three 100×200 mm) using the RCONTM bulk electrical resistivity testing (Figure 4.6) following the ASTM C1876-19 standard [129]. This method is non-destructive and straightforward, providing

results within 2 seconds, with the entire process, including preparation, taking less than 30 minutes. During the test, the cylinder was placed on supports, and both ends were moistened using a spray bottle. The specimens were positioned between the electrodes, and an alternating current of 1 KHz frequency was applied through them using the control box. The resistance, measured in ohms, is the apparatus's raw output. To calculate the electrical resistivity in $K\Omega.cm$, equation (1) was used, where L represents the specimen's length in centimetres, and A represents the specimen's cross-sectional area. three measurements were taken for each cylinder by swapping the end faces.

$$\left[Bulk\ resistivity = Bulk\ resistance \times \frac{A}{L} \right] \quad (1)$$

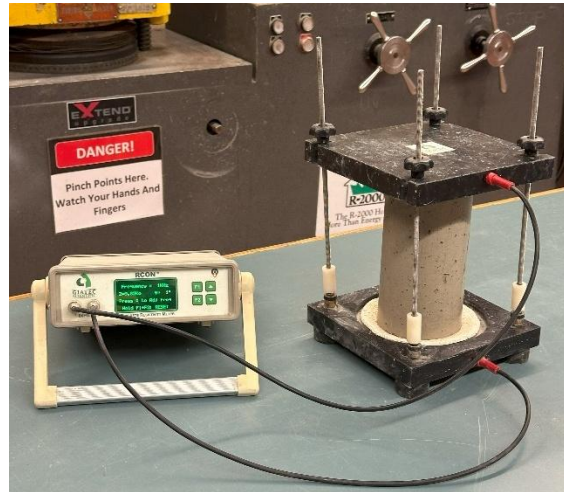


Figure 4.6: Bulk electrical resistivity setup

Global Warming Potential (GWP) serves as a metric for assessing and contrasting the contributions of various greenhouse gases to global warming over a specified period, typically 100 years [186,187]. These gases are compared to carbon dioxide (CO_2) based on their capacity to trap heat and persist in the atmosphere. GWP values are extensively employed in greenhouse gas inventories and climate change evaluations to quantify the collective impact of diverse gases on global warming. In this particular research, the 100-year Global Warming Potential (GWP100 year) was

determined using the guidelines provided by the International Plant Protection Convention (IPPC 2006) [186], which involves the calculation (3.1):

$$\text{GWP100year}(\text{kg CO}_2 - \text{eq}) = 1 \times \text{CO}_2 + 21 \times \text{CH}_4 + 310 \times \text{N}_2\text{O} \quad (3.1)$$

GWP100 year was measured for each run to assess the global warming potential of concrete samples, including GP, SR, and BFA.

Regarding concrete's service life, the fib model [188] plays a significant role in advancing knowledge and understanding of durability-related issues. The fib 2015 model utilizes chloride migration data from RCMT as a main input for service life prediction. The RCMT chloride migration coefficient is used to estimate the rate of chloride penetration into concrete, a basic parameter to calculate the time for chloride concentration to reach the corrosion initiation threshold at reinforcement depth. The fib 2015 model is employed to determine the expected lifespan of concrete mix designs as equation (3.2):

$$C_{(x=a,t)} = C_0 + (C_{\text{crit}} - C_0) \left[1 - \text{erf} \frac{a - \Delta x}{2\sqrt{D_{\text{app},c}(t) \cdot t}} \right] \quad (3.2)$$

Where $C_{(x=a,t)}$ is the chloride content at a certain time and depth, C_0 is the initial chloride content of the concrete (wt.-%/CM), C_{crit} is critical chloride content (wt.-%/CM), erf is the error function, a is the concrete cover (mm), Δx is the depth of the convection zone (mm), $D_{\text{app},c}(t)$ is the chloride diffusion coefficient (mm^2/years), and t is time (year).

The chloride diffusion coefficient is calculated based on the equation (3.3).

$$D_{\text{app},c}(t) = k_e D_{\text{RCM},0} k(t) A(t) \quad (3.3)$$

Where k_e represents the environmental transfer variable, $D_{\text{RCM},0}$ is the chloride migration coefficient with units of Dnssm ($\text{E}^{-12} \text{ m}^2/\text{s}$), $k(t)$ denotes the unitless transfer variable, and $A(t)$ is

the aging function. The calculation of the environmental transfer variable and aging function is done by equations (3.4, 3.5):

$$k_e = \exp \left[be \left(\frac{1}{T_{ref}} - \frac{1}{T_{real}} \right) \right] \quad (3.4)$$

The variable represents the regression coefficient with units of k, while T_{ref} is the standard test temperature in kelvin. T_{real} is the actual temperature of the concrete's environment in Kelvin.

$$A(t) = \left(\frac{t_0}{t} \right)^\alpha \quad (3.5)$$

The variable t_0 represents the time period taken as a reference point in years, while α is an exponent used to determine the degree of aging.

The values of the parameters used in the calculation are: $C_{crit} = 0.6$ wt.-%/CM, $C_0 = 0.1$ wt.-%/CM based on [189], $\Delta x = 0.1$ -50 mm, $C_{s,0} = 3.0$ wt.-%/CM, $kt = 1$ (according to fib 2006), $be = 4800$ k, $T_{ref} = 293$ K, $T_{real} = 297.0$ K, $t_0 = 0.0767$ years (28 days), and $\alpha = 0.3$.

A 100-year duration was taken into consideration to accommodate diverse environmental and material factors influencing the structural elements.

4.3 Response surface method

Response Surface Methodology (RSM) encompasses statistical and mathematical techniques for modelling and optimizing processes by examining the relationships between multiple independent and dependent variables. Its objectives are to optimize conditions, develop predictive models, and understand variable interactions, producing regression equations, response surface plots, and optimal results. RSM utilizes various experimental designs, including Central Composite Design (CCD), Box-Behnken Design (BBD), three-level factorial designs, and Doehlert Design. CCD is frequently chosen for its flexibility, efficiency in delivering extensive information with fewer

experiments, rotatability for consistent precision, capability to estimate curvature using axial points, and inclusion of central points to evaluate experimental error and reproducibility [190–193]. These attributes make CCD particularly effective for accurately modeling and optimizing complex processes.

The CCD design involves a set of 2^k factorial points, that includes n_F factorial runs, a $2k$ axial (star) runs and n_c central runs, as depicted in Figure 4.7 [81]. The factorial runs are used to fit the first-order model, while the axial runs are employed to fit the second-order model. If the applied surface provides an adequate approximation of the actual response surface, the response surface analysis can be compared to similar approximations of the actual system analysis [76–78]. For a complex and nonlinear system, the equation Y can be calculated according to equation (3.6):

$$Y = \beta_0 + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \beta_{ii} X_i^2 + \sum_{i < j}^k \beta_{ij} X_i X_j + \mathcal{E} \quad (3.6)$$

Y is the predicted response, which can be a slump, RCMT, electrical resistance, global warming potential (GWP) index, Service life, or compressive strength. β_0 is the intercept, β_i is the first-order (linear) coefficient, β_{ii} is the second-order (quadratic) coefficient, and β_{ij} is the coefficient of the interaction effect. On the other hand, the independent variables are X_i and X_j (glass powder, shredded rubber, and biomass fly ash), and the associated random error is $\mathcal{E}$. The rationale behind selecting the second-order model is its flexibility, as it can encompass a wide variety of functions [76]. The distance between the axial points and the center point is defined by another parameter known as α . It ensures that the design is rotatable, meaning the prediction variance remains constant at any point equidistant from the center. For a rotatable design, the value of α is calculated as $\alpha = (n_F)^{1/4}$, where n_F is the number of factorial points [76,82,83].

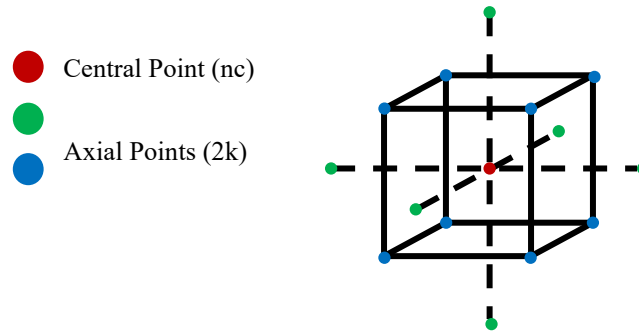


Figure 4.7: Schema of a central composite design with three factors [81]

4.4 Results and discussion

4.4.1 Model fitting

The framework of the optimization process can be explained as follow: the factors/levels were established and the test program was designed, the tests were carried out, and the responses were recorded to establish several models between variables and results. The models were statistically substantiated/modified by assessing the P-value, residual of results, A_{deq} Precision, and correlation coefficient. After the statistical adequacy of the resulting model was confirmed, the validity of the models/equations was tested by comparing the theoretical output of the equations to the real/actual results of new mixtures that were randomly selected. In the final phase, contour graphs were generated after the equations' accuracy was verified, and the optimum ranges were identified.

The first step in creating an RSM design is to determine the value of factors and levels. This study was conducted in the form of three factors and five levels, with five midpoints, eight factorial points, six-axis points, and an alpha value of 1.682. In CCD, the number of midpoints (center points) is not predetermined but is selected based on the desired level of accuracy. In this study, five center point replications were incorporated to obtain a more precise estimate of pure error, detect potential curvature in the response surface, ensure reproducibility, and enhance the robustness of the statistical analysis. The factors (glass powder, biomass fly ash, and shredded rubber) and the levels are shown in Table 4.2. To cover a wide spectrum of variability, SR was

varied from 0-15% of the sand volume, while GP and BFA were varied from 0-20% and 0-15% of the cement mass, respectively. The responses in this study were adopted to cover different dimensions of the concrete properties (fresh, hardened, durability and environmental properties), which would be translated to slump, compressive strength, RCMT, electrical resistivity, Global warming potential, and service life. The design and analysis of the RSM were carried out using the Design Expert software. The desired CCD with three factors/parameters and 5 levels, including 19 mixtures, and the mix design for each run/mix was calculated and shown in Table 4.3. Since the 19 mixtures did not include a control mix (sample without any waste material), an additional reference sample was cast for comparison purposes. Table 4.4 presents a comprehensive summary of all test results, including, slump, compressive strength, RCMT, service life, GWP, and BER. These results were utilized in the subsequent steps to develop the model/equation.

Table 4.2: Variables and range of variation.

Factors		Levels				
Actual	Coded	1.682	-1.000	0.000	1.000	1.682
Shredded rubber	$X_1=A$	0	3.040	7.500	11.960	15.000
Glass powder	$X_2=B$	0	4.054	10.000	15.946	20.000
Biomass fly ash	$X_3=C$	0	3.040	7.500	11.960	15.000

Table 4.3: Components of the Concrete Mixtures

Run Order	SR ¹ (%)	GP ² (%)	BFA ³ (%)	W/B	Water kg/m ³	Cement kg/m ³	Sand kg/m ³	Gravel kg/m ³
1	7.50	20.0	7.50	0.46	157	246.5	867.7	938
2	7.50	10.0	7.50	0.46	157	280.5	867.7	938
3	0.00	10.0	7.50	0.46	157	280.5	938.0	938
4	11.96	4.05	3.04	0.46	157	315.9	825.8	938
5	11.96	4.05	11.96	0.46	157	285.6	825.8	938
6	11.96	15.95	3.04	0.46	157	275.5	825.8	938
7	7.50	10.0	7.50	0.46	157	280.5	867.7	938

8	7.50	10.0	0	0.46	157	306.0	867.7	938
9	15.0	10.0	7.50	0.46	157	280.5	797.3	938
10	7.50	10.0	7.50	0.46	157	280.5	867.7	938
11	7.50	10.0	15	0.46	157	255.0	867.7	938
12	3.04	4.05	11.96	0.46	157	285.6	909.5	938
13	11.96	15.95	11.96	0.46	157	245.1	825.8	938
14	7.50	0	7.5	0.46	157	314.5	867.7	938
15	3.04	15.95	11.96	0.46	157	245.1	909.5	938
16	3.04	4.05	3.04	0.46	157	315.9	909.5	938
17	3.04	15.95	3.04	0.46	157	275.5	909.5	938
18	7.50	10.0	7.50	0.46	157	280.5	867.7	938
19	7.50	10.0	7.50	0.46	157	280.5	867.7	938

¹ Shredded Rubber, ² Glass Powder, ³ Biomass Fly Ash

Table 4.4: Summary of the results

No	Slump (cm)	Day 28 CS (MPa)	Day 90 CS (MPa)	RCMT Day 28 (10 ⁻¹² m ² /s)	RCMT Day 90 (10 ⁻¹² m ² /s)	28- BER (kΩ- cm)	90- BER (kΩ- cm)	GWP (Kg CO ₂)	Service life (year)	GWP/Service life
1	19.50	23.97	30.07	4.70	2.46	17.68	32.33	259.41	70.09	3.70
2	19.00	19.62	23.77	9.20	5.23	8.52	19.02	287.41	58.02	4.95
3	17.00	30.80	35.33	8.19	3.63	11.35	19.89	291.14	60.30	4.83
4	23.00	15.82	18.64	11.47	8.49	6.88	10.46	315.73	53.37	5.92
5	2.00	21.95	24.14	10.71	9.62	7.00	10.34	288.85	54.88	5.26
6	23.50	19.69	21.89	3.12	1.98	13.65	25.73	281.73	75.92	3.71
7	19.20	19.32	23.27	7.77	5.02	8.68	19.72	287.41	61.31	4.91
8	24.00	16.86	20.64	12.21	6.91	8.42	20.04	310.31	51.91	5.98
9	20.50	17.89	20.74	6.09	4.05	10.33	19.72	284.08	65.75	4.32
10	19.00	19.60	23.57	8.97	5.50	9.95	19.56	287.41	58.53	4.69
11	0.00	19.47	25.63	6.53	4.57	8.17	17.13	264.52	64.52	4.10
12	1.50	26.23	30.13	11.52	10.55	6.48	10.80	293.10	53.26	5.50
13	2.00	23.66	27.16	4.61	3.01	16.61	24.93	254.85	70.38	3.62
14	21.00	19.45	21.98	13.12	12.75	5.99	7.53	316.41	50.12	6.31

15	1.50	25.55	31.41	6.90	3.07	16.62	23.43	259.10	63.51	4.08
16	23.00	25.40	29.46	12.09	8.11	6.12	9.93	319.98	52.15	6.14
17	23.00	25.01	29.09	5.16	1.82	13.72	25.63	285.98	68.57	4.17
18	19.5	19.2	23.80	8.50	5.00	8.60	19.50	287.41	58.94	4.87
19	19.2	19.5	23.30	9.00	5.31	9.20	19.23	287.41	57.95	4.96

4.4.2 Modification of equations according to statistical criteria

In CCD procedures, an iterative model-fitting approach is employed to develop an accurate model for each response. Initially, a second-order polynomial model is selected to estimate the relationship between the variables (i.e. BFA, GP, and SR) and the response (i.e. slump, RCMT, electrical resistance, GWP, GWP/Service life Index, and compressive strength) based on the experimental results. Subsequently, insignificant terms are eliminated from the model through a series of t-tests. After each term is removed, the fitting process is repeated until all insignificant terms are excluded. Finally, an appropriate transformation may be applied to normalize the equations. All equations and their statistical responses (P-value and coefficient of parameters), for slump, compressive strength, RCMT, service life, GWP, and BER, were listed in Appendix 4.1/4.2, due to space restrictions.

Afterwards, the models/equations' adequacy/accuracy were statistically evaluated through assessing the R^2 , Adj- R^2 , Pred- R^2 , A_{deq} Precision, and p-values, as displayed in Table 4.5. It is worth mentioning that R^2 (R-Squared) represents the proportion of the variance in the dependent variable that is accounted for by the independent variables in a regression analysis. It ranges from 0 to 1, where 0 means the model explains none of the variance and 1 means it explains all the variance. A higher R^2 value signifies a better model fit. Adjusted R^2 (Adj- R^2) modifies the R^2 value to account for the number of predictors in the model, offering a more accurate comparison when different models with varying numbers of predictors are used. It can decrease if additional

predictors don't significantly improve the model. Predicted R^2 (Pred- R^2), also known as Cross-Validated R^2 , evaluates the model's ability to predict new, unseen data. A higher Pred- R^2 suggests that the model performs well in predicting new data and generalizes effectively. The p-value measures the likelihood of observing the data (or something more extreme) if the null hypothesis is true. A low p-value (usually ≤ 0.05) indicates that the results are statistically significant, whereas a high p-value suggests that the evidence is insufficient to reject the null hypothesis. A_{deq} Precision represents a signal-to-noise ratio, which assesses the predicted values' range at the design points in relation to the average prediction error. All the R^2 values are approximately 90% or higher, demonstrating that the models exhibit an excellent fit. The p-values for the equations are 0.0001 or lower, indicating only a 0.01% probability that the observed results, or more extreme ones, could occur by chance under the null hypothesis. Furthermore, the difference between the adjusted R^2 (Adj- R^2) and predicted R^2 (Pred- R^2) for all equations is less than 20%, with both parameters undergoing cross-validation. Adequate Precision values exceeding 4 suggest satisfactory model discrimination, and according to Table 4.5, all values surpass 10. In addition, the equations/models accuracy was further assessed via residual analysis. Appendix 4.3 depicts the residuals versus predicted graph for slump, RCMT, electrical resistance, GWP, GWP/Service life Index, and compressive strength. A visual inspection of the residuals versus predicted graph was conducted to ensure constant variance. For constant variance (homoscedasticity), residuals should be randomly scattered around zero without any noticeable pattern, and the spread of residuals should be uniform across all levels of the predicted values. Deviations from this randomness, such as distinct patterns or shapes, indicate issues like heteroscedasticity (non-constant variance). A megaphone pattern suggests increasing variance with the level of the fitted values, indicating heteroscedasticity. A frown (U-shaped pattern) implies that the model underfits in the middle range

and overfits at the extremes, suggesting the need for a higher-order term in the model. Conversely, a smile (inverse U-shaped pattern) indicates that the model overfits in the middle range and underfits at the extremes, suggesting non-linearity. In summary, residuals should scatter randomly and should not exhibit patterns such as clustering, funnel shapes, pronounced curves, or unusually large values. If the residuals display any of these patterns, it indicates potential errors or biases in the data, which must be investigated and addressed. It can be seen that the residual scattering shows homoscedasticity, and they were not follow the heteroscedasticity shapes.

Table 4.5: The results for full regression models

Responses	R² (%)	Adj-R² (%)	Pred-R² (%)	(Adj-R²) - (Pred-R²) (%)	P-Value	A_{deq} Precision
Slump (cm)	96.00	94.28	84.68	9.6	0	30.48
Day 28 CS ¹ (MPa)	91.48	86.38	68.51	17.87	0	15.06
Day 90 CS (MPa)	96.53	93.06	75.74	17.32	0	19.46
RCMT ² Day 28(10 ⁻¹² m ² /s)	89.56	83.29	69.10	14.19	0.0002	12.16
RCMT Day 90(10 ⁻¹² m ² /s)	95.53	91.56	82.95	8.61	0	16.95
Day 28 BER ³ (kΩ-cm)	96.95	93.04	80.03	13.01	0.0002	16.95
Day 90 BER (kΩ-cm)	97.34	96.72	95.20	1.52	0	40.80
GWP ⁴ (Kg CO ₂)	99.98	99.98	99.97	0.01	0	637.09
Service life (Year)	89.21	82.74	67.34	15.40	0.0003	12.01
GWP/ Service life	92.03	90.19	85.16	5.03	0	21.02

¹ Compressive Strength, ² Rapid Chloride Migration Test, ³ Bulk Electrical Resistivity, ⁴ Global Warming Potential

4.4.3 Verification of models

To assess the model's precision, four randomly selected mixtures were cast and examined, none of which was part of the original runs/mixtures, as listed in Table 4.6. Following the testing and recording the results of the selected mixes, the precision of the presented equations was assessed by determining if the experimental results fell into the model's 95% confidence interval boundaries.

The design points and corresponding responses are presented in Table 4.7. As shown in Table 4.7, all the experimental values lie within the 95% confidence interval boundaries established by the model. The position of the obtained value within the 95% confidence interval provides a meaningful indication of where the true population parameter might lie relative to the sample data. Whether it is closer to the lower or upper limit, this positioning offers valuable insights into the tendencies and variability of the data. If the obtained value is close to the upper limit of the 95% confidence interval (CI), this implies that the true population parameter may lie towards the higher end of the estimated range, and vice versa. If the accuracy of the equations is confirmed, contour graphs are created to determine the optimal ranges.

Table 4.6: Mix design of samples for verification

Run Order	Water/Binder	Water kg/m³	Cement kg/m³	Sand kg/m³	Gravel kg/m³	SR¹ kg/m³	GP² kg/m³	BFA³ kg/m³
1	0.46	157	276.25	938	951.000	0.00	51.00	12.75
2	0.46	157	246.5	797.3	951.000	52.89	68.00	25.50
3	0.46	157	284.75	895.79	951.000	15.86	17.00	38.25
4	0.46	157	289	902.825	951.000	13.22	51.00	0.00

¹ Shredded Rubber, ² Glass Powder, ³ Biomass Fly Ash

Table 4.7: Confirming the model results versus experimental outcomes.

		Runs			
		E1	E2	E3	E4
SR (%)		0	15	4.5	3.75
GP (%)		15	20	5	15
BFA (%)		3.75	7.5	11.25	0
Tests	Comparison	Results			
Slump (cm)	Exp	21.50	14.60	5.10	22.00
	95% CI high	28.33	23.35	7.23	28.63
	95% CI low	14.77	10.56	3.57	14.99
Day 28 CS ¹ (MPa)	Exp	30.16	22.23	24.24	21.39
	95% CI low	29.26	20.78	21.04	21.87
	95% CI high	35.62	28.20	24.29	27.02
RCMT ² Day 28(10 ⁻¹² m ² /s)	Exp	7.32	3.12	11.39	7.48
	95% CI low	3.50	0.00	8.88	4.59
	95% CI high	9.14	3.73	12.02	9.26
Day 28 BER ³ (kΩ-cm)	Exp	12.68	16.70	7.28	10.52
	95% CI low	11.67	16.31	5.64	8.87
	95% CI high	18.04	26.57	7.91	14.50
GWP ⁴ (Kg CO ₂)	Exp	288.13	255.39	291.83	297.72
	95% CI low	287.85	255.07	291.62	297.44
	95% CI high	288.41	255.70	292.03	298.00
GWP/Service life	Exp	4.61	3.36	5.45	4.80
	95% CI low	4.32	2.72	5.12	4.47
	95% CI high	5.06	3.56	5.66	5.21

¹ Compressive Strength, ² Rapid Chloride Migration Test, ³ Bulk Electrical Resistivity, ⁴ Global Warming Potential

4.4.4 Slump

The slump test was carried out to assess the workability of various mixtures. Figure 4.8 illustrates the results of slump incorporating BFA, GP, and SR and their combinations. For the mixtures

containing BFA, the considerable presence of unburned carbon (LOI) in BFA was proved to highly absorb the free water [122]. Consequently, the incorporation of BFA resulted in a significant reduction in slumps as shown in Figure 4.9. Figure 4.8 (a) shows that the slump reaches zero when BFA exceeds 12%, resulting in a 100% decrease compared to the control sample. Using 12-15% biomass fly ash, irrespective of the level of SR or GP incorporated, resulted in zero slump. On the other hand, the inclusion of approximately 7.5% SR yielded the maximum slump by 27%, an increase in comparison to the control sample (from 180 to 230 mm). SR, at a higher level, more than 7.5 up to 15%, demonstrated a slump reduction of 9% in comparison to the reference mixture. This might be attributed to its role as a physical barrier impeding the movement of concrete particles, Figure 4.8 (b). This impediment diminished the overall fluidity of the mix, resulting in a stiffer consistency. The introduction of 20% GP had an insignificant impact on the slump, causing only a 1% increase compared to the reference mixture Figure 4.8(c). This is attributed to the smooth surface of glass powder; however, its effect largely depends on the particle size distribution [194]. Combining glass powder with SR at 0-15% keeps the slump between 19-23 cm.

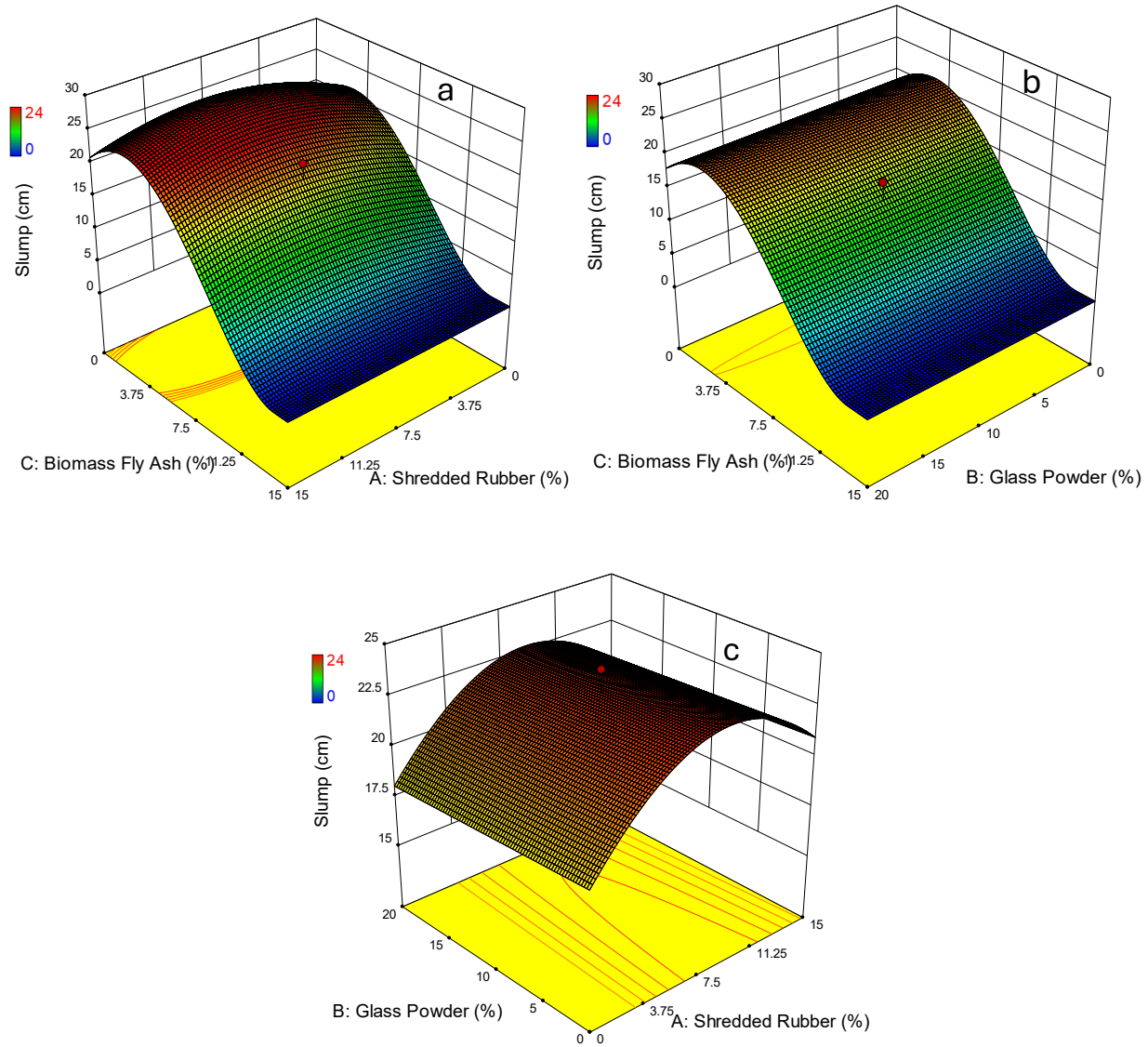


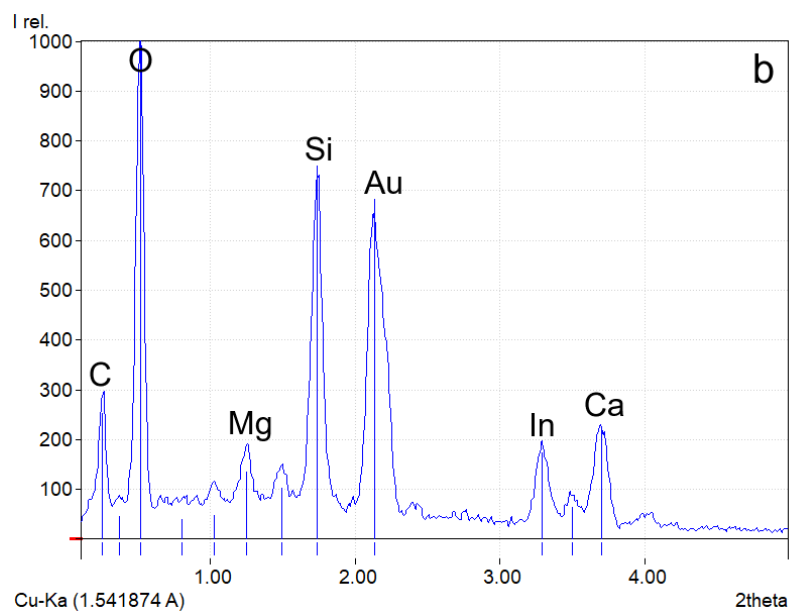
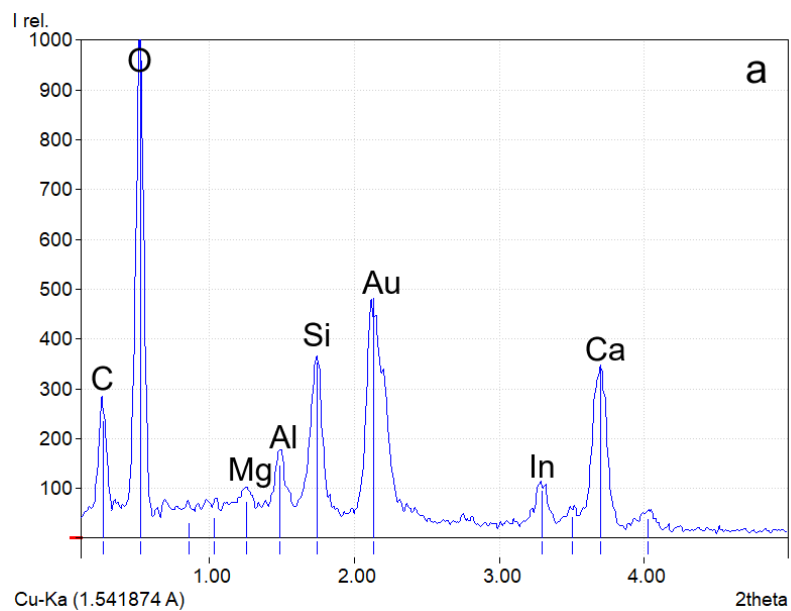
Figure 4.8: Slump (cm) a) 0% Glass powder, b) 0% Shredded rubber, c) 0% Biomass fly ash



Figure 4.9: a) Mix No.11 (7.5% SH, 10% GP, 15% BA) zero slump b) Mix No.7 (7.5% SR, 10% GP, 7.5% BFA) 192 mm slump

4.4.5 Compressive strength

The compressive strength of the specimens was evaluated at two different ages, 28 and 90 days, highlighting the effects of GP, BA, and SR and their interactions. Additionally, microstructural analysis of the mixtures was performed based on the Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDX) examinations (Figures 4.10-11) to augment the compressive strength trends (Figures 4.12–13). The increase in the GP dosage from 0% to 20% contributed to a progressive enhancement in the compressive strength at day 28, reaching a 15% (from 33 to 36 MPa) improvement compared to the reference mixture. The high SiO_2 content in glass powder (notably 70 %) along with its fine particle size (13.2 μm) played a crucial role in enhancing the compressive strength. The increased specific surface area of GP contributed to a denser concrete matrix, while the abundance of SiO_2 facilitates heightened reactivity with cement, leading to the formation of C-S-H gel. Although previous research has demonstrated C-S-H reactivity induced by GP [195,196], the compressive strength results in this study further support this behavior. To validate this, EDX analysis was conducted to assess the reactivity of GP powder in concrete. Figure 4.10 presents the chemical composition of images for the control sample, sample number 1 (10% GP), and sample number 8 (20% GP and 7.5% BA). It shows that the control sample has a Ca/Si ratio of 2.8. In comparison, mix No. 1 (with 10% GP) and mix No. 8 (with 20% GP and 7.5% BA) exhibit significantly lower Ca/Si ratios of 0.8 and 0.50, respectively. The addition of 10% GP resulted in a 71% increase in reactivity compared to the control sample. Similarly, the combination of 20% GP and 7.5% BFA resulted in an 82% increase in reactivity. This substantial reduction in the Ca/Si ratio signifies the enhanced pozzolanic reactivity, indicating a more reactive behavior compared to the control sample.



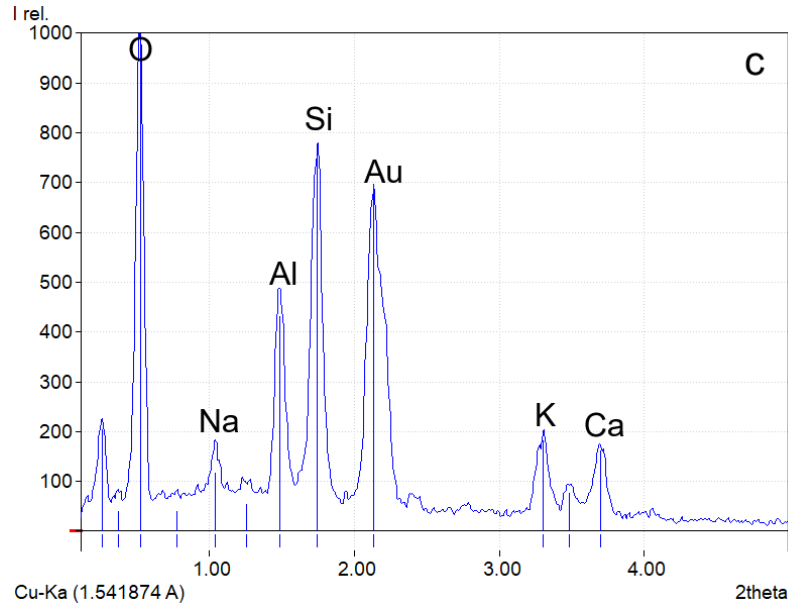


Figure 4.10: EDX results a) Control sample b) mix No. 8 (10% GP) c) mix No.1 (20% GP, 7.5% %BA)

Conversely, the incorporation of 15% shredded rubber led to a significant decrease in the compressive strength of about 55% (from 33 to 15 MPa) at 28 days in comparison to the mixture without either GP or BFA (Figure 4.12). This reduction in compressive strength can be attributed to several factors associated with the SR inclusion. SR exhibits poor bonding with the cement paste compared to traditional aggregates, creating weak interfaces within the concrete matrix, as proved in the reference [197]. Figure 4.11 compares the ITZ (Interfacial Transition Zone) between aggregate/paste and rubber/paste. As depicted, the ITZ formed between the rubber and the paste is approximately eight times greater than the ITZ found between the aggregate and the paste. A higher ITZ in concrete generally means that the zone around the aggregate is more porous and less well-bonded. The pronounced ITZ in this study can be attributed to the untreated nature of the shredded rubber, whose smooth and hydrophobic surface limits adhesion with the cement paste. This weaker bonding leads to reduced load transfer efficiency from the cement paste to the aggregates, which

are the primary load-bearing elements in concrete. As a result, the concrete structure becomes less capable of resisting compressive forces, ultimately decreasing its compressive strength [198,199].

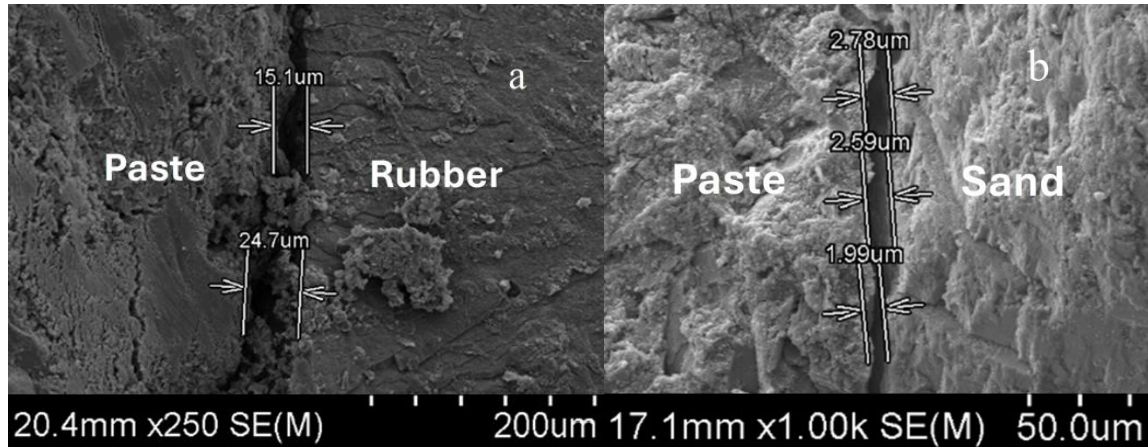


Figure 4.11: SEM photos a) mix No. 6 (12% SR, 16% GP, 3% BA) b) Control sample

However, the adverse impact of shredded rubber was mitigated by combining the mix with GP and BFA. As illustrated in Figure 4.10, in an alkaline environment such as that found in cement paste, the addition of GP and BFA increases the reactivity of the paste in comparison to the control sample. This is attributed to the amorphous structure of glass becoming reactive, allowing it to dissolve and form compounds, such as calcium silicate hydrate (C-S-H) [146]. This reactivity improvement contributes to a stronger interface between the rubber and the paste. For example, the incorporation of 15% BFA in a mix containing 15% SR increased the strength by 73% (from 15 to 26 MPa) relative to a mix with only 15% SR. For a mix containing 20% GP and 15 % SR, this improvement was 28 % (from 15 to 19.3 MPa) at day 28. Concrete with GP typically exhibits slower strength development at 28 days (Figure 4.12). Amorphous materials like glass dissolve at a slower rate compared to crystalline materials [146]. However, by 90 days, the strength of GP concrete improves as the pozzolanic reaction continues, forming additional calcium silicate hydrate (C-S-H) gel (Figure 4.13). A mix containing 20% GP and 15% SR showed a 49%

improvement (from 15.5 to 23.2 MPa) in strength compared to a mix with 15% shredded rubber but without GP at day 90. In comparison, a mix with 15% SR and 20% BFA yielded an improvement in the strength by 62.5% (from 15.5 to 25.2 MPa). Although the incorporation of GP and BFA enhanced the compressive strength of mixes containing 15% SR, the overall strength still fell short of the control sample (33 MPa). This is likely due to the significant negative impact of such a high rubber content on the compressive strength. The graphs indicated that 15% of SR with 0% GP and 0 % BFA resulted in the lowest compressive strength (blue surface) across all data points. Substituting up to 15% of cement with BFA had a minimal effect on compressive strength (Figure 4.12 b). This is because BFA primarily acts as a filler and is an inert material with a low silica (SiO_2) content. Replacing 15% cement with BFA reduces the compressive strength by 6% (33 to 31 MPa) in comparison to the control sample. Combining 15% BFA with 20% GP can mitigate this reduction and achieve a concrete gain of 33 MPa compressive strength. Compressive strength reduction of 15 % BFA turns to 2% at the age of 90 days (Figure 4.13). Low SiO_2 content of BFA limits pozzolanic reactions in early age, and contributes to long-term strength development [122].

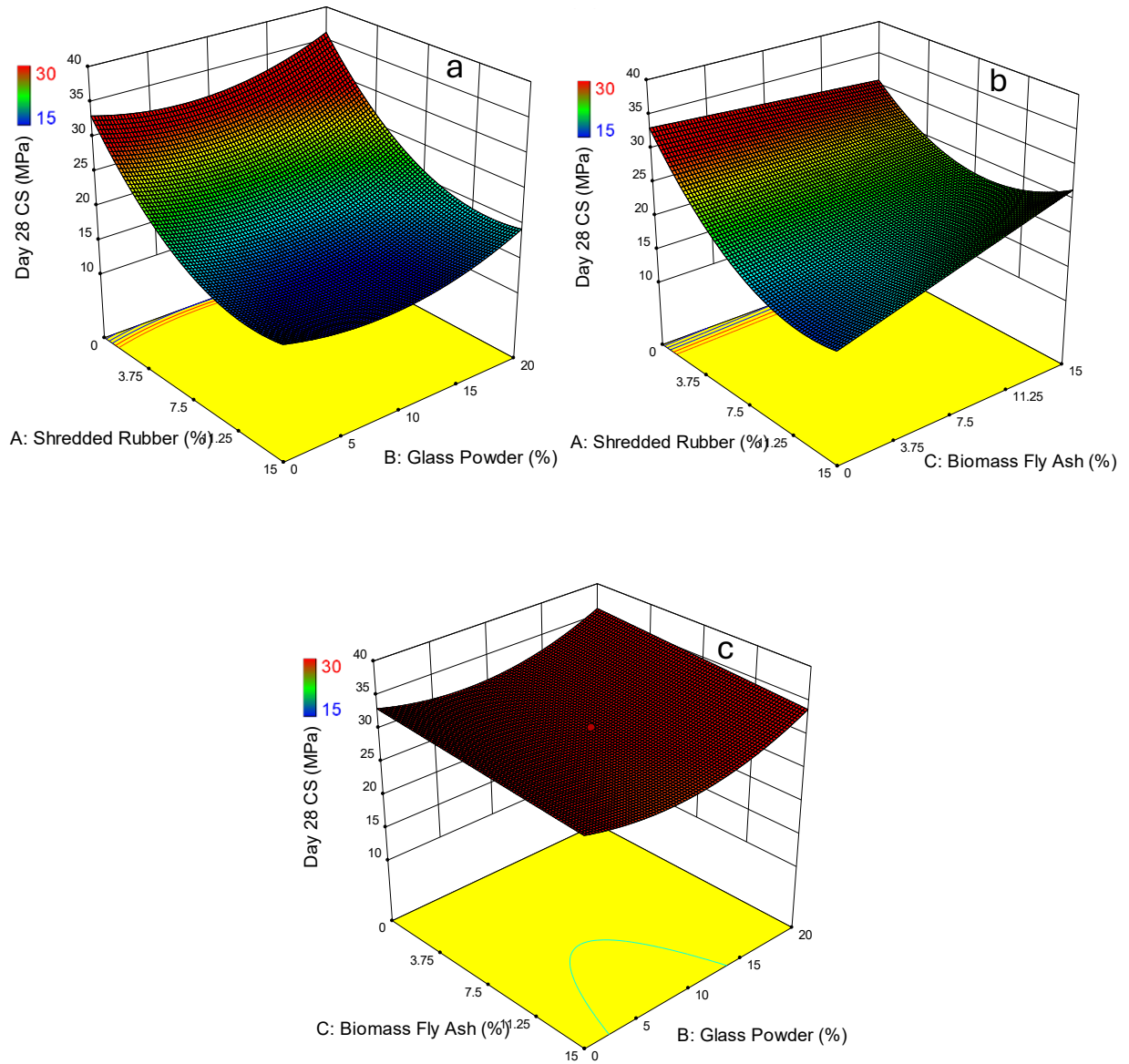


Figure 4.12: 28-Day Compressive strength at the level of a) 0% Biomass fly ash, b) 0% Glass powder, and c) 0% Shredded rubber

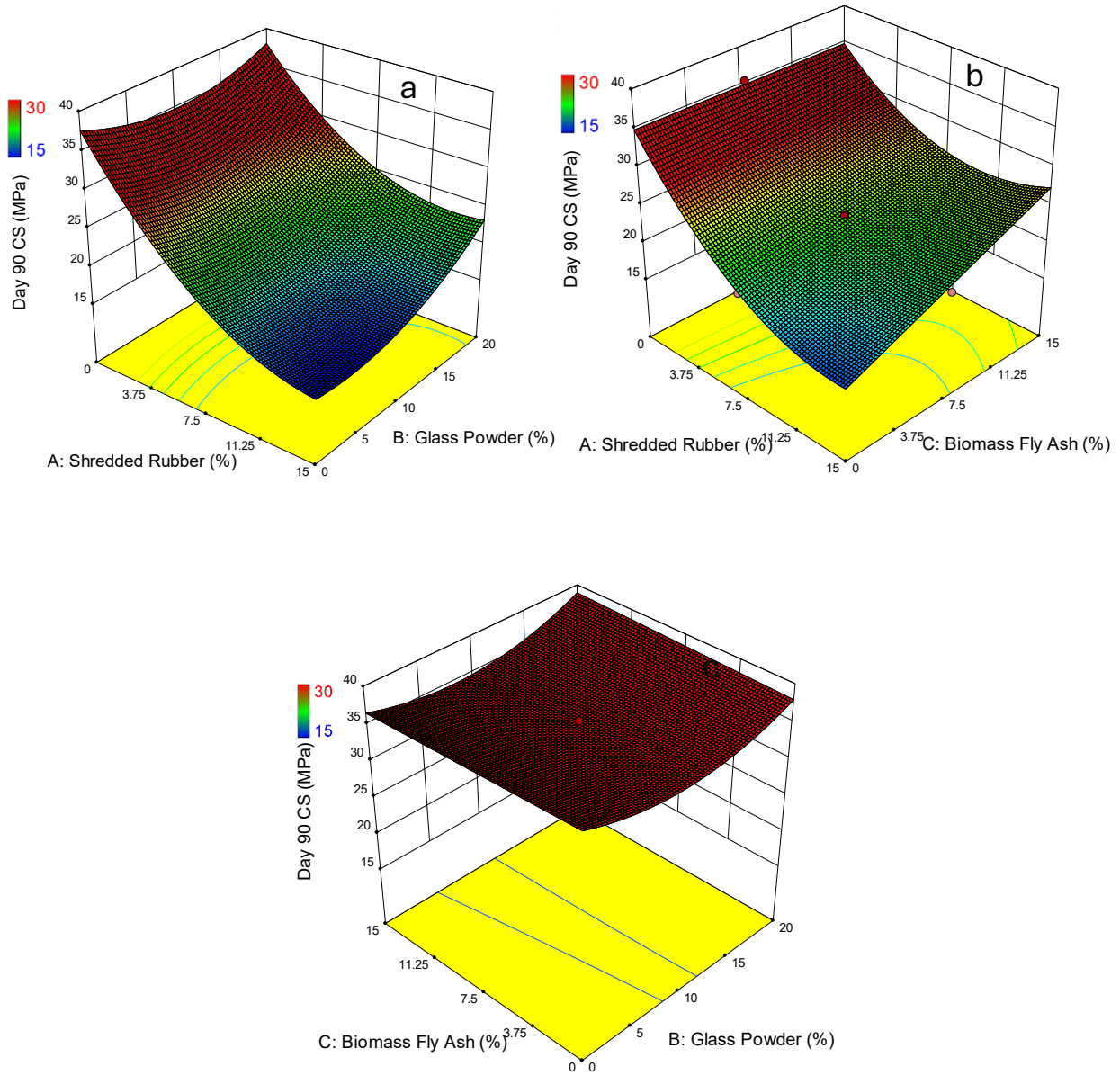


Figure 4.13: 90-Day Compressive strength at the level of a) 0% Biomass fly ash, b) 0% Glass powder, and c) 0% shredded rubber

4.4.6 RCMT

This section examines the effects of GP, BFA, and SR on chloride migration. The results emphasize the significant role of GP in reducing the migration coefficient and improving the concrete durability, particularly when GP was combined with BFA or SR. Table 4.8 indicates the

classification of resistance to chloride penetration based on the chloride diffusivity of concrete samples according to Teng et al. [200]. The addition of GP exhibited a notable reduction in the chloride diffusivity. Figure 4.14 illustrates a decrease in the migration coefficient from $14.7 \times 10^{-12} \text{m}^2/\text{s}$ for the control sample to $3.6 \times 10^{-12} \text{m}^2/\text{s}$ when 20% of GP was incorporated. Conversely, the addition of SR to the mix had an adverse effect on durability, leading to an increase in chloride penetration. Notably, the mix containing 7.5% SR exhibited the highest chloride penetration by $16.3 \times 10^{-12} \text{m}^2/\text{s}$; by adding SR to 15%, this value decreased by $14.5 \times 10^{-12} \text{m}^2/\text{s}$ similar to the control sample. This number classifies the concrete samples as moderately resistant to chloride penetration even after 90 days (Figure 4.15).

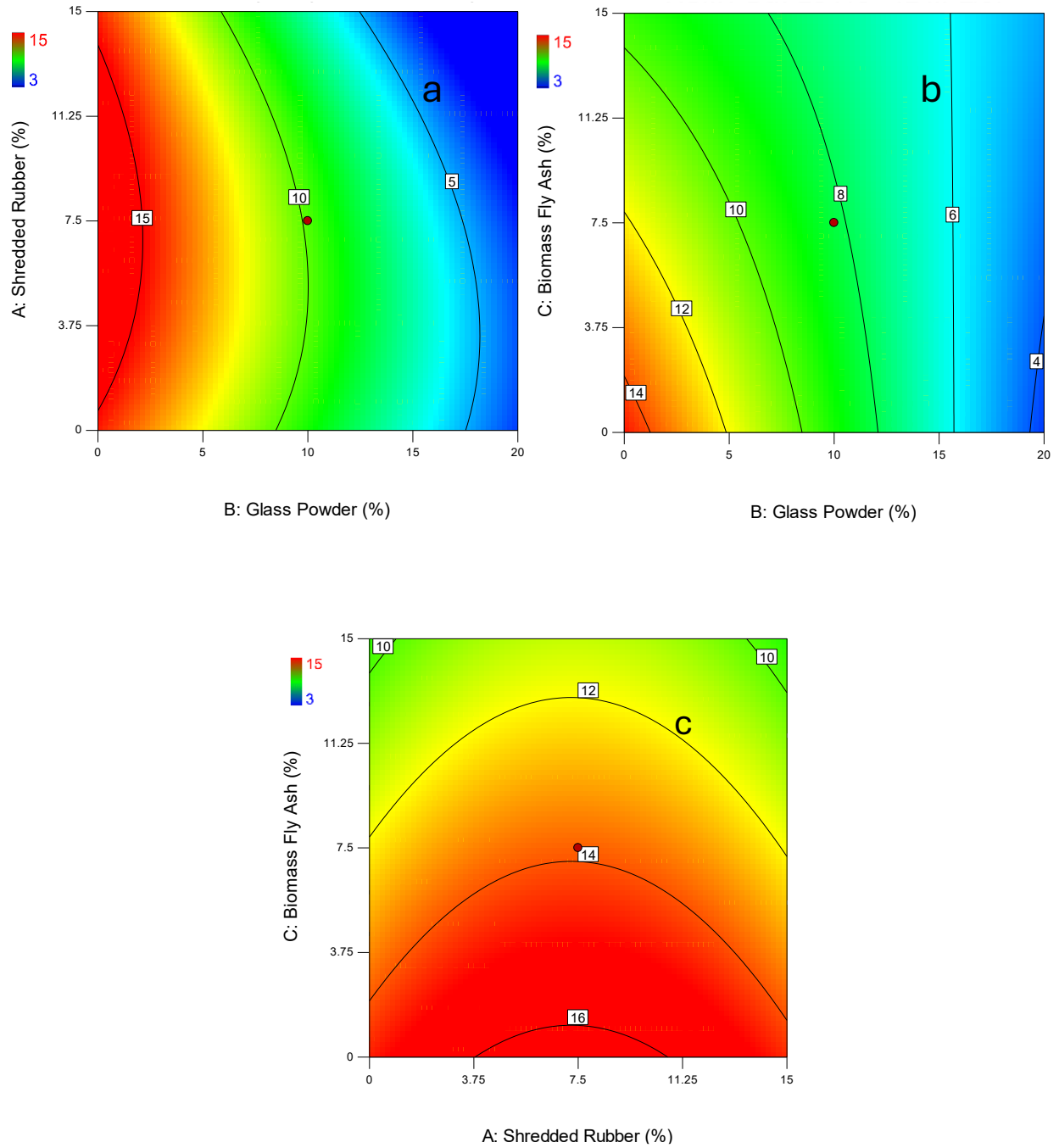


Figure 4.14: Day-28 Rapid Chloride Migration Test at a) 0% Biomass Fly Ash, b) 0% Shredded Rubber, c) 0% Glass Powder

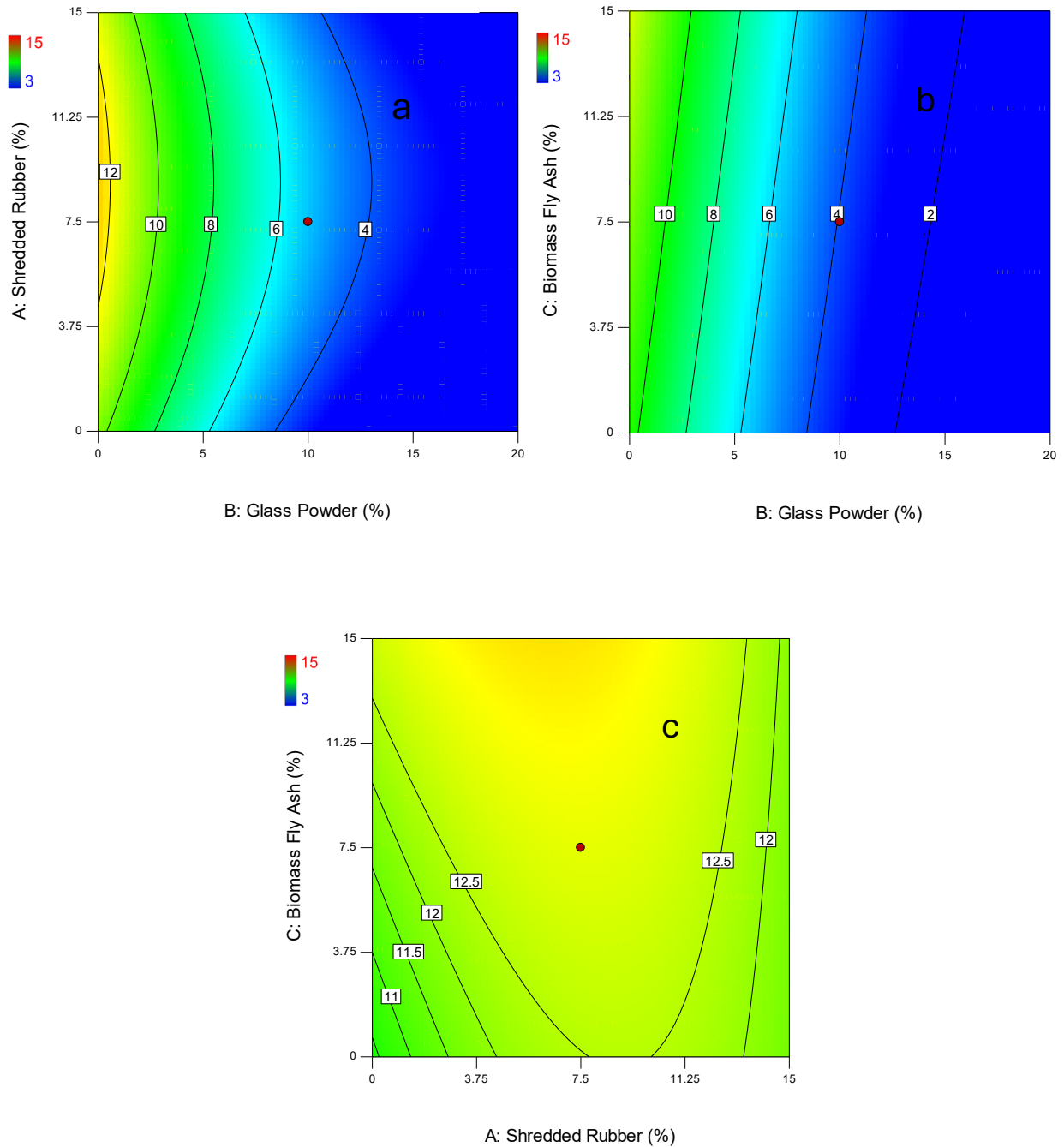


Figure 4.15: Day-90 Rapid Chloride Migration Test at a) 0% Biomass Fly Ash, b) 0% Shredded Rubber c) 0% Glass Powder

The unique characteristics of rubber particles have the potential to weaken the interfacial transition zone (ITZ) with the paste, especially when compared to the aggregate. Consequently, the creation

of pores around rubber particles forms potential zones for chloride penetration, as elucidated in the research conducted by Nadi et al. [32]. As the smaller particles of BFA and GP can improve the ITZ of SR with paste. Figure 4.16 shows the SEM images for two mixtures, mix No. 1 (7.5% SR, 20% GP, 7.5% BFA) and mix No. E3 (4.5% SR, 5% GP, 11.25% BFA). The images confirm the role of GP and BFA in decreasing the ITZ.

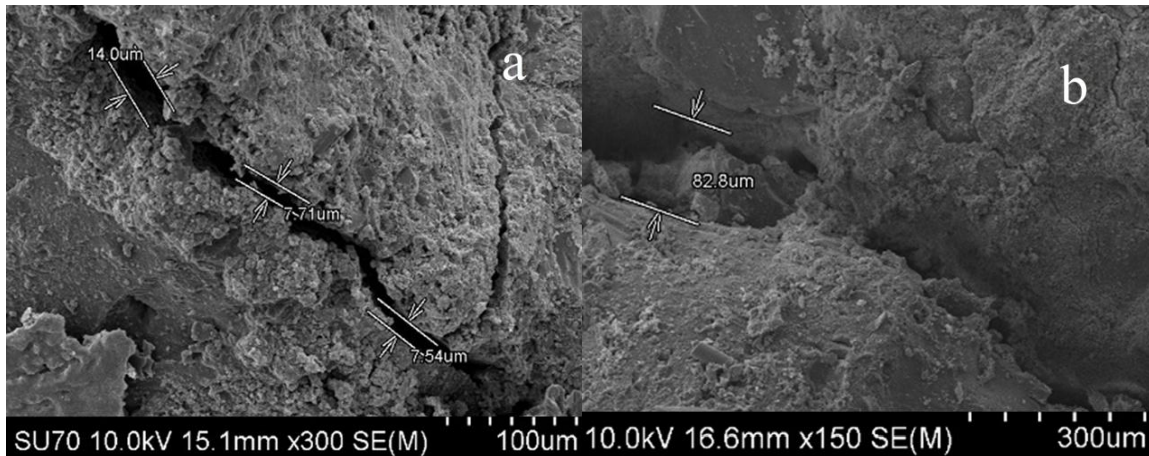


Figure 4.16: SEM photos of a) sample No. 1 (7.5% SR, 20% GP, 7.5% BFA) b) sample No. E3 (4.5% SR, 5% GP, 11.25% BFA)

A comparative analysis of the interparticle distance between the SR and the paste matrix revealed a significant difference between Mix No. 1 and Mix No. E3. Mix No. 1 exhibited a substantially smaller interparticle distance of 14 micrometres compared to 82.8 micrometres for Mix No. E3, resulting in a reduced rate of chloride ion migration. Accordingly, the migration coefficient of Mix No. E3 is 2.32 times higher than Mix No. 1, showing how using a higher amount of powders decreased the chloride penetration. At 28 days, BFA showed a 35% improvement in RCMT compared to the reference sample. However, it still fell within the moderate range of chloride penetration resistance. Adding GP to mixes containing SR enhances concrete durability. A mix containing 15% shredded rubber with a migration coefficient of $14.3 \times 10^{-12} \text{m}^2/\text{s}$ decreased to

$3.6 \times 10^{-12} \text{m}^2/\text{s}$ with the addition of 20% GP at day 28; this mixture indicates an improvement of 87% at the age of 90 days. Combining GP with BFA or SR proved effective in mitigating their negative effects on chloride penetration. The use of 20% GP with 15% BFA improved resistivity against chloride by 47% (9.5×10^{-12} to $5 \times 10^{-12} \text{m}^2/\text{s}$) relative to the reference sample on day 28 and 92% on day 90. Combining 15%_20% GP with any level of BFA or SR resulted in significantly enhanced chloride ion resistance at 90 days. These samples exhibited extremely low chloride ion diffusion coefficients, consistently below $5 \times 10^{-12} \text{m}^2/\text{s}$. For instance, mix No. 1 (7.5% SR, 20% GP, 7.5% BFA) demonstrated a diffusion coefficient of $2.46 \times 10^{-12} \text{m}^2/\text{s}$, highlighting the significant improvement in chloride ion resistance conferred by the incorporation of GP.

Table 4.8: Classification of concrete resistance to chloride penetration [200]

Chloride diffusivity, $D_{28} \times 10^{-12} \text{m}^2/\text{s}$	Classification of resistance to chloride penetration
>15	Low
10-15	Moderate
5-10	High
2.5-5	Very high
<2.5	Extremely high

4.4.7 Bulk electrical resistivity

This section evaluates the effects of BFA, SR, and GP on concrete resistivity (Figures 4.17-18). ACI 222R [142] classifies the corrosion rate based on the bulk electrical resistivity of concrete, as listed in Table 4.9. Figure 4.17 (c) shows that increasing BFA and shredded rubber to 15% has a negligible impact on bulk resistivity, which remains stable between 7-6 k Ω -cm (14% decrease) and 7-8 k Ω -cm (12.5 % increase), respectively. Even at day 90 (Figure 4.18c), the combination of BFA and SR at any level remains at a low level of electrical resistivity (less than 10 k Ω -cm). In contrast, GP consistently elevated electrical resistivity from day 28 to day 90. The addition of 20%

GP to the mix resulted in a substantial enhancement in bulk resistivity. A 167% increase (from 7 to 18.7 k Ω -cm) was observed at 28 days, followed by a further increase of 350% at 90 days, relative to the control sample (Figure 4.18) the minimum electrical resistivity, 4.5 k Ω -cm, was observed in concrete containing a mixture of 0% GP, 15% BFA, and 7.5% shredded rubber. Concrete mixtures containing 15-20% GP in combination with any level of SR or BFA may exhibit medium to low corrosion resistance at 28 days (Table 4.9), with resistivity values ranging from 10 to 20 k Ω -cm. A combination of 20% GP and 15% BFA results in the highest electrical resistivity by 25 k Ω -cm.

Table 4.9: Corrosion rate classification [142]

Resistivity, kΩ-cm	Corrosion rate
>20	Low
10-20	Low to moderate
5-10	High
<5	Very high

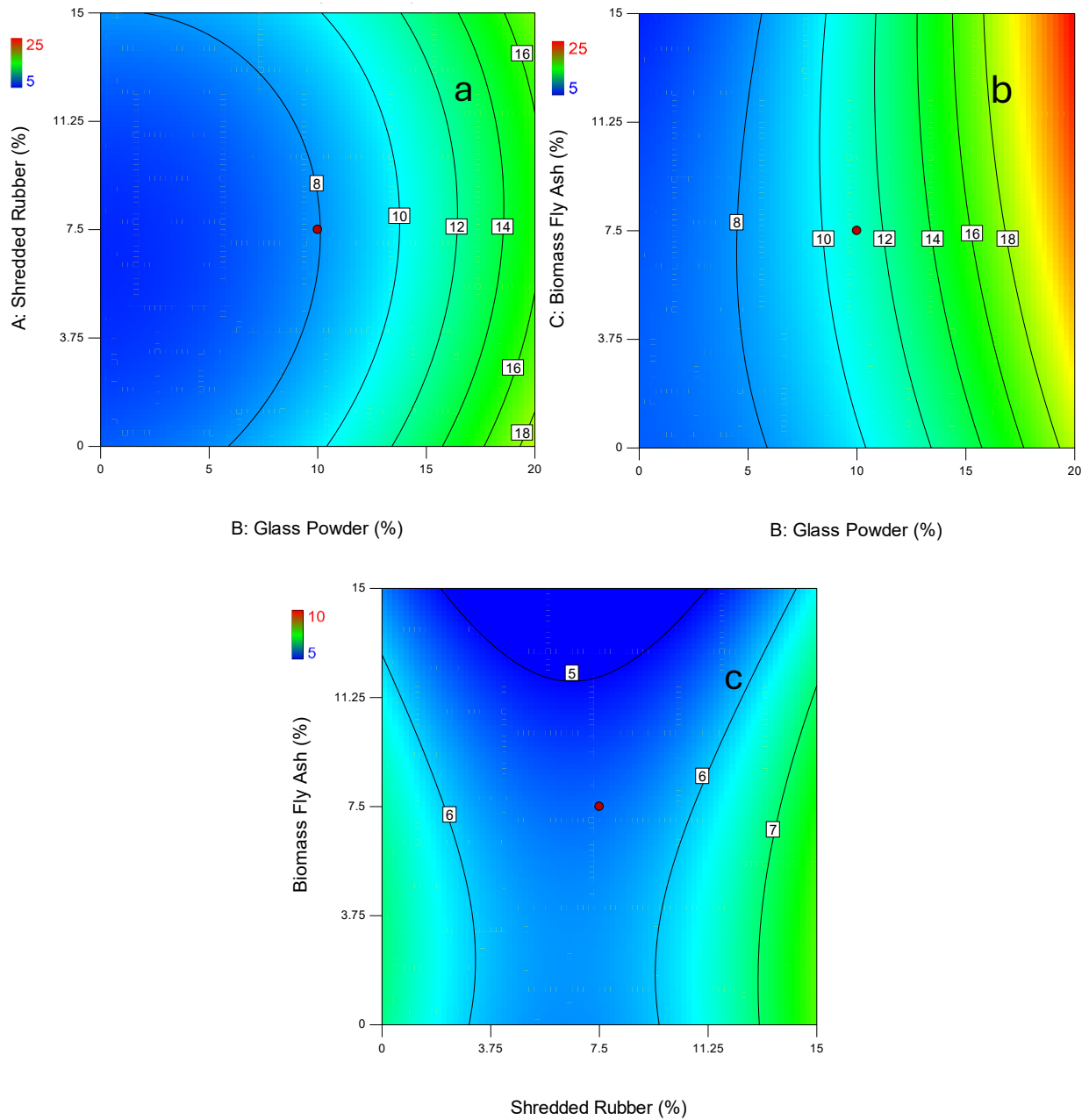


Figure 4.17. Day-28 Bulk electrical resistance test at a) 0% Biomass Fly Ash, b) 0% Shredded Rubber, c) 0% Glass powder

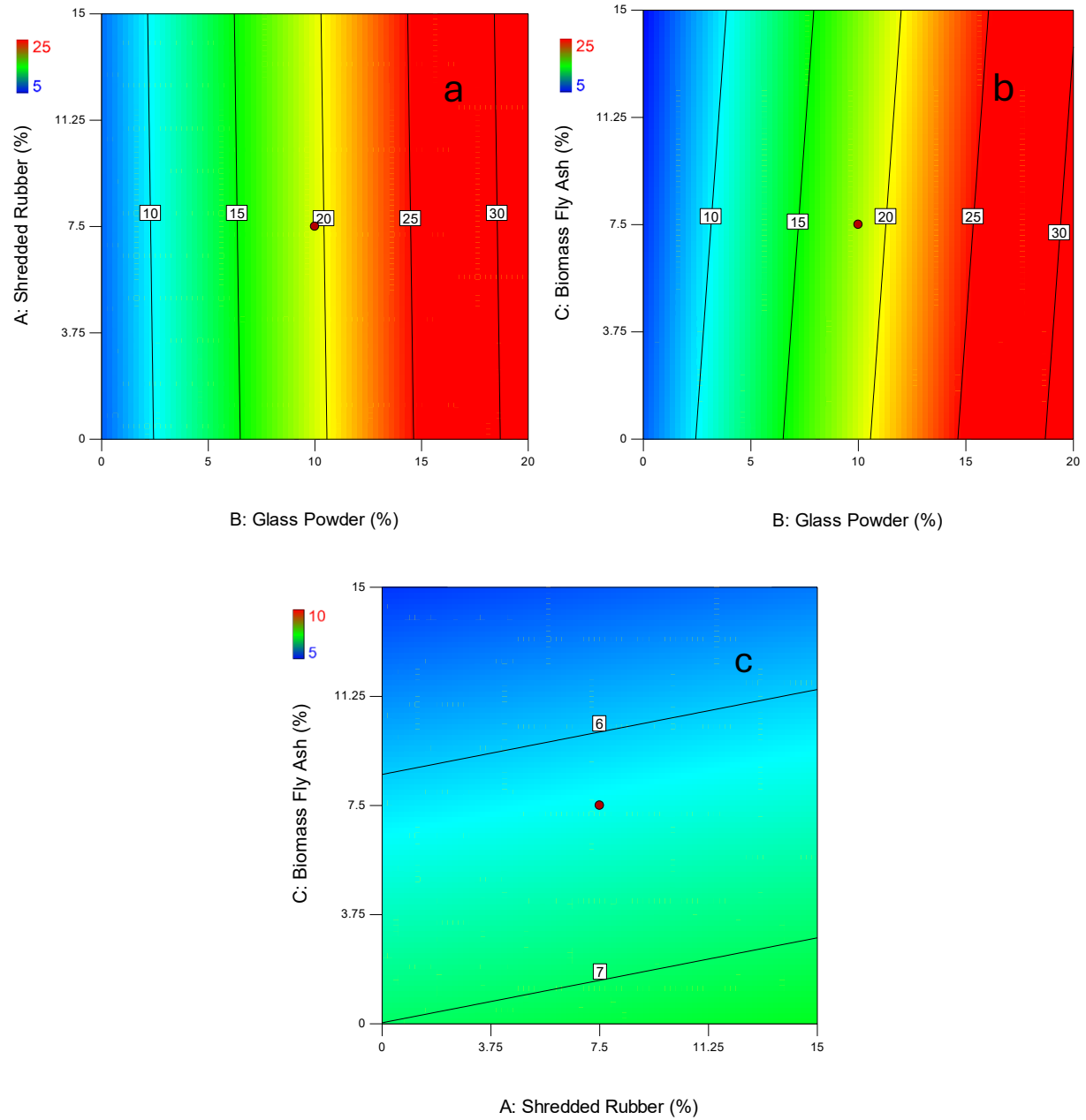


Figure 4.18: Day-90 Bulk electrical resistance test at a) 0% Biomass Fly Ash, b) 0% Shredded Rubber, c) 0% Glass Powder

4.5 Environmental Assessment

The environmental impact of a material refers to the effects of its extraction, production, use, and disposal on the environment. This includes resource depletion, energy consumption, pollution, and waste generation. The most critical phases in Life Cycle Assessment (LCA) as specified in ISO 14040 are goal and scope definition, functional unit (FU) choice, Life Cycle Inventory (LCI) analysis, Life Cycle Impact Assessment (LCIA), and interpretation of results. These phases are elaborated below.

4.5.1 Goal and scope definition

The life cycle of concrete is segmented into four main stages: the product stage, the construction process stage, the use stage, and the end-of-life stage. Our research calculates the carbon emissions generated during the examination of the extraction of aggregates, the preparation of SR, and the production of cement, superplasticizer, BFA, and GP, transportation, manufacturing and disposal. The objective of this LCA is to compare the environmental impact of concrete mixtures containing different percentages of cement, BFA, GP, and SR. The research also investigates the impact of variation in life cycle inventory (LCI) data, e.g., raw material production and transportation distance, on the overall environmental performance. These processes were evaluated in terms of their Global Warming Potential (GWP), with emissions data collected and analyzed using the SimaPro software.

4.5.2 Functional unit (FU)

The Functional Unit (FU) in environmental impact is a standardized measure used to quantify the performance of a product or system, providing a reference point for comparing different alternatives. In this study, the FU is GWP over one cubic meter of concrete multiplied by service

life, incorporating varying proportions of BFA, GP, and SR. While choosing an environmentally friendly concrete mix solely based on its absolute GWP might be misleading, instead, using a FU index would better represent the environmental impact of such a mixture. Given that a mix with a higher GWP may demonstrate greater durability, whereas a mix with a lower GWP may have reduced longevity, this study proposes an index that compares concrete mixes by evaluating the released carbon emissions per year. This index, which provides a more thorough measure for evaluating the environmental impact of concrete mixes over time, is calculated by dividing the GWP by the concrete's service life. This allows for a consistent comparison of the environmental impact across different concrete mix compositions.

$$FU = GWP / \text{Volume}_{(m^3)} \cdot SL_{(yr)} \quad (8)$$

4.5.3 Life cycle inventory (LCI)

Data for 1 m³ of concrete in Canada, encompassing materials such as cement, water, sand, gravel, superplasticizer, BFA, SR, and GP, were input for the analysis (Table 4.10). These materials were defined as markets and cut-off points within the analysis for all 19 mix designs. Carbon emissions from transportation were determined by tracking the distance each material travelled from its source to the concrete batching plant. Additionally, we accounted for the energy consumed during the mixing process: 0.00000000851024 p was considered for concrete mixing, and 0.076536313 kWh was used to calculate energy consumption on mixing 1 m³ of concrete. Cement, sand, gravel, and SR were sourced locally from markets for this project. GP was imported from Winnipeg, Manitoba, approximately 700 km from Thunder Bay. BFA was imported from the Atikokan electricity generation plant, approximately 212 km from Thunder Bay, where concrete mixing was conducted and casting was done. The distance required to supply each material is provided in Table 4.11. Since SR information was not available in the software database, its GWP was calculated

independently using the study by Farina et al. [201]. Additionally, the data for superplasticizer and biomass fly ash were sourced from the research by Simalti and Singh [202].

Table 4.10: Sources of data for concrete components

Materials and processes	Source	Region	Detail
Cement	Ecoinvent 3.0	US	Cement, Portland
GP	Ecoinvent 3.0	GLO	Glass powder
BFA	[202]	GLO	Biomass fly ash
SR	[201]	GLO	Shredded rubber
Sand	Ecoinvent 3.0	GLO	Sand
Gravel	Ecoinvent 3.0	RoW	Gravel
Superplasticizer	[202]	RoW	Water reducer
Water	Ecoinvent 3.0	CA-QC	Tap water
Mixing	Ecoinvent 3.0	GLO	Diesel, burned in the building machine
Electricity	Ecoinvent 3.0	CA-ON	Electricity medium voltage
Transport	Ecoinvent 3.0	RoW	Transport, freight, lorry >32 metric ton
Disposal	Ecoinvent 3.0	RoW	Collection for final disposal

Table 4.11: Transportation distances

Material	distance (km)
Cement	5
Sand	3
Gravel	3
SR	4
GP	700
BFA	212

4.5.4 Life cycle impact assessment (LCIA)

The global warming potential (GWP) was separately calculated for each mixture using the IPCC 2013 GWP 100a method, version 1.03 [186]. Global warming potential (GWP) is one of the most studied impact categories in concrete life cycle assessment (LCA) due to the carbon-intensive nature of cement manufacturing. In this study, the life cycle impact assessment (LCIA) was carried out to consider additional environmental impact categories beyond GWP, accounting for service

life. These categories provide a broader perspective of the environmental impact of concrete mixtures with different binders, e.g., BFA, GP and SR.

4.5.5 Global warming potential (GWP)

Figure 4.19 illustrates the released carbon emissions resulting from raw material supply, transportation, manufacturing, and end of life, summarized as the GWP for concrete containing different ranges of GP, BFA, and SR for producing 1 m³ of concrete; in Figure 4.19, the carbon emission changes between 250 and 350 kg CO₂. Figure 4.19 indicates that the control mix (mix without BFA, GP and SR) released the maximum carbon by 342 kg CO₂ per cubic meter. Replacing cement with 15% BFA, 15% shredded rubber, and 20% GP decreased the CO₂ by 32% (almost one third). Substituting cement just with GP can reduce Carbon emission to 285 kg per cubic meter (16%) compared to the control mix; this amount is 296 kg per cubic meter for 15% BFA replacement, equivalent to 13%.

There are two scenarios regarding calculating the carbon emission of shredded rubber. In the first scenario, the short-term carbon emission is considered for preparing waste tires, such as cutting, bagging, washing, diesel and electricity, etc., which led to a GWP of 245.7 kg CO₂ per ton. In the second scenario, where the whole life cycle is considered, the environmental impact is significantly reduced, and the GWP decreases by 113%. This study considered the second scenario, as tires are not manufactured specifically for recycling purposes; instead, they are shredded after their end-of-life, and other components, such as fibres, are often recycled separately. Therefore, adding shredded rubber to concrete up to 15% can reduce the GWP by 2%. Replacing cement with BFA and GP is more effective in reducing the carbon emissions of concrete, as cement production is a major source of emissions. In contrast, SR is used to replace aggregate, which has a much lower carbon footprint compared to cement.

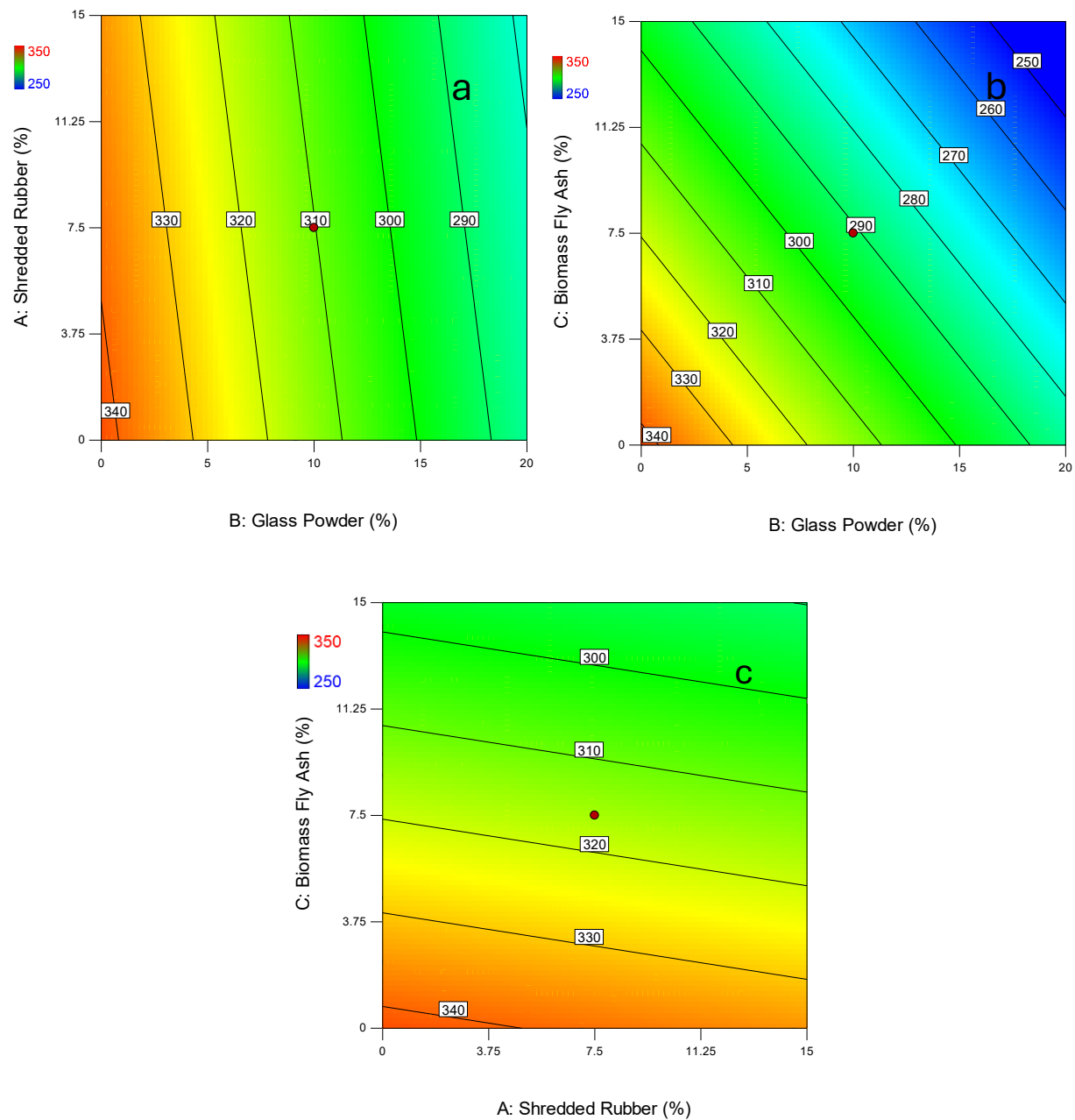


Figure 4.19: Global warming potential at (a) 0% Biomass Fly Ash, (b) 0% shredded rubber, c) 0% Glass Powder

4.5.6 Annual carbon emissions

The GWP/service life index was calculated to compare the yearly carbon emission of concrete mixes. Figure 4.20 depicts this index, where a lower ratio signifies a longer service life and reduced carbon gas emissions over the product's lifecycle. These findings indicate that a concrete mix with a lower GWP/service life index is a more sustainable and environmentally responsible choice.

The yearly carbon emission of the control sample reached a value of 7.12 kg CO₂/year on the GWP/service life index. This means that over its expected lifespan, the control sample contributes 7.12 units of carbon gas emissions per year. Irrespective of the corresponding mechanical properties, the lowest GWP/service life index, at 2.6 kg CO₂/year, belongs to a mix incorporating 20% GP, 15% BFA, and 15% shredded rubber. 20% GP and 15% BFA each could make the concrete more environmentally friendly; they could separately improve the GWP/service life index by 40% (7.12 to 4.3 kg CO₂/year) and 16.01% (7.12 to 5.98 kg CO₂/year) compared to the control sample. It means that these materials not only reduce the carbon emission of concrete but also improve the longevity of concrete. The impact of shredded rubber alone is minimal, and using 15% SR can reduce the yearly carbon emission by 8% (7.12 to 6.55 kg CO₂/year) in comparison to the control sample. However, incorporating 15% shredded rubber with 20% GP can improve the GWP/Service Life Index by 43% (6.5 to 3.7 kg CO₂/year) compared to a sample without GP. Additionally, combining BFA with 20% GP results in a 47.65% (5.98 to 3.13 kg CO₂/year) improvement. GP is the most effective among BFA and SR, as it not only reduces GWP but also increases service life by significantly enhancing the durability of concrete, as discussed earlier in the RCMT section. Comparing Mix No. 1 (7.5% SR, 20% GP, 7.5% BFA) with a GWP/service life index of 3.7 kg CO₂/year to Mix No. 14 (7.5% SR, 0% GP, 7.5% BFA) with an index of 6.31

kg CO₂/year, observed that by incorporating only 20% more GP, Mix No. 1 achieves 1.7 times lower yearly carbon emissions than Mix No. 14.

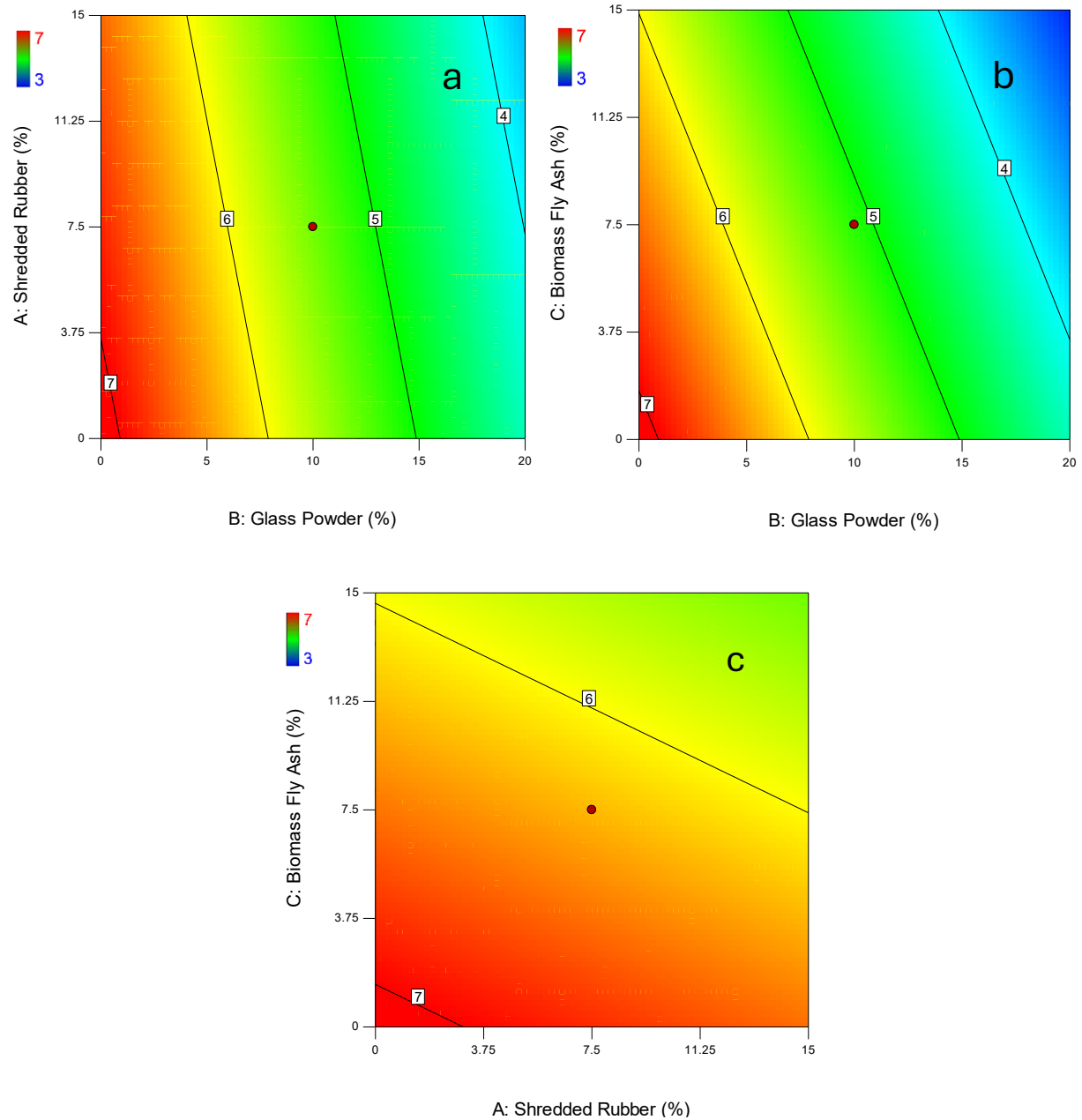


Figure 4.20: Annual carbon emissions at (a) 0% Biomass Fly Ash, (b) 0% shredded rubber, (c) 0% Glass Powder

4.6 Multi-property response and optimal design space

Following a detailed analysis of the mixture results, an optimization process was undertaken to evaluate the interactions between the variables. The objective was to identify the optimal waste material combinations in concrete that would meet the precise requirements outlined by relevant codes and standards such as ASTM or ACI. The focus was on developing a low-carbon concrete that not only adheres to environmental standards but also achieves the necessary performance benchmarks. Specifically, the concrete must exhibit sufficient compressive strength and meet durability requirements to ensure long-term service.

According to the report by Concrete Ontario [203], the baseline carbon emissions for a 30 MPa concrete mix (using GU cement and non-air entrained) should be 296.62 kg CO₂. Also, Teng et al. [200] suggest that for concrete to exhibit high resistance to chloride penetration, its migration coefficient should be between $10 \times 10^{12} \text{m}^2/\text{s}$ and $5 \times 10^{12} \text{m}^2/\text{s}$, with even greater resistance achieved at lower values. A slump of up to 20 cm can accommodate diverse applications. Additionally, adhering to ACI 222r-01 [77], a bulk electrical resistivity between 10 and 20 k Ω -cm is suggested for low to moderate corrosion rates, with values exceeding 20 k Ω -cm indicative of low corrosion rates. According to Andersen and Negendahl's study [204], the average lifespan of demolished office, trade, and warehouse buildings is 61 years, while the overall average lifespan for residential buildings is 98 years. The CSA S478 [205,206] standard defines the long life for residential, commercial, and office buildings as ranging from 50 to 99 years. In this study, service life is assessed based on chloride penetration, with a minimum critical chloride content of 0.6% (as per FIB [188]) marking the point at which rebar corrosion is expected to initiate. Corrosion significantly accelerates structural deterioration, so the service life of concrete is ideally set to cover the timeframe during which the building is expected to be in active use. Considering

Eurocode-basis of structural design [207] for building structures and other common structures, a 50-year service life for this research was determined, ensuring that concrete durability aligns with the common demolition age of buildings, allowing the concrete to withstand chloride exposure without reaching critical corrosion levels until the building itself is approaching the end of its expected lifecycle. Table 4.12 shows all the constraints applied to the concrete to obtain the optimal design space.

Table 4.12: Optimization constrains

Factors	Value
Compressive strength	>30 MPa
Slump	<20 cm
RCMT day 28	$<10 \times 10^{12} \text{m}^2/\text{s}$
RCMT day 90	$<5 \times 10^{12} \text{m}^2/\text{s}$
BER day 28	> 10 k Ω -cm
BER day 90	>20 k Ω -cm
GWP	297 kg CO ₂
Service life	>50 years
GWP/Service life	6

Figure 4.21 overlays the constraints of each test according to Table 4.12 to determine the optimal design space; the yellow region signifies concrete mixes that meet acceptable criteria. Figure 4.21 (a) exhibits the combination of SR and GP at a level of 0% BFA that offers the minimal optimal design space (yellow area). In contrast, Figure 4.21b at a level of 0% SR depict mixes containing BFA and GP that are covered by a more optimal design space. Figure 4.21c, which compares BFA and SR at a 0% GP level, shows that there is no acceptable optimal design space, making it impossible to identify a mix design incorporating these materials that meets the constraints outlined in Table 4.12. The incorporation of BFA and GP in the mixes expands the optimal design space. Noteworthy to mention that the control mixture by 33 MPa compressive strength failed to meet the environmental and durability criteria required to remain within the acceptable range.

Using more than 13% GP allowed the use of BFA 0% to 15% in concrete, while using BFA solely falls outside the optimal design space. It shows how the integration of GP with BFA can be utilized to enhance the potential of BFA as a cement alternative, enabling higher replacement ratios and lower carbon footprints, without sacrificing durability and mechanical performance standards. Additionally, only a limited number of samples containing less than 2% shredded rubber met the acceptable standards if provided by more than 16% GP in the concrete mixture. Also, samples containing 11% to 20% GP can be placed in the optimal design space.

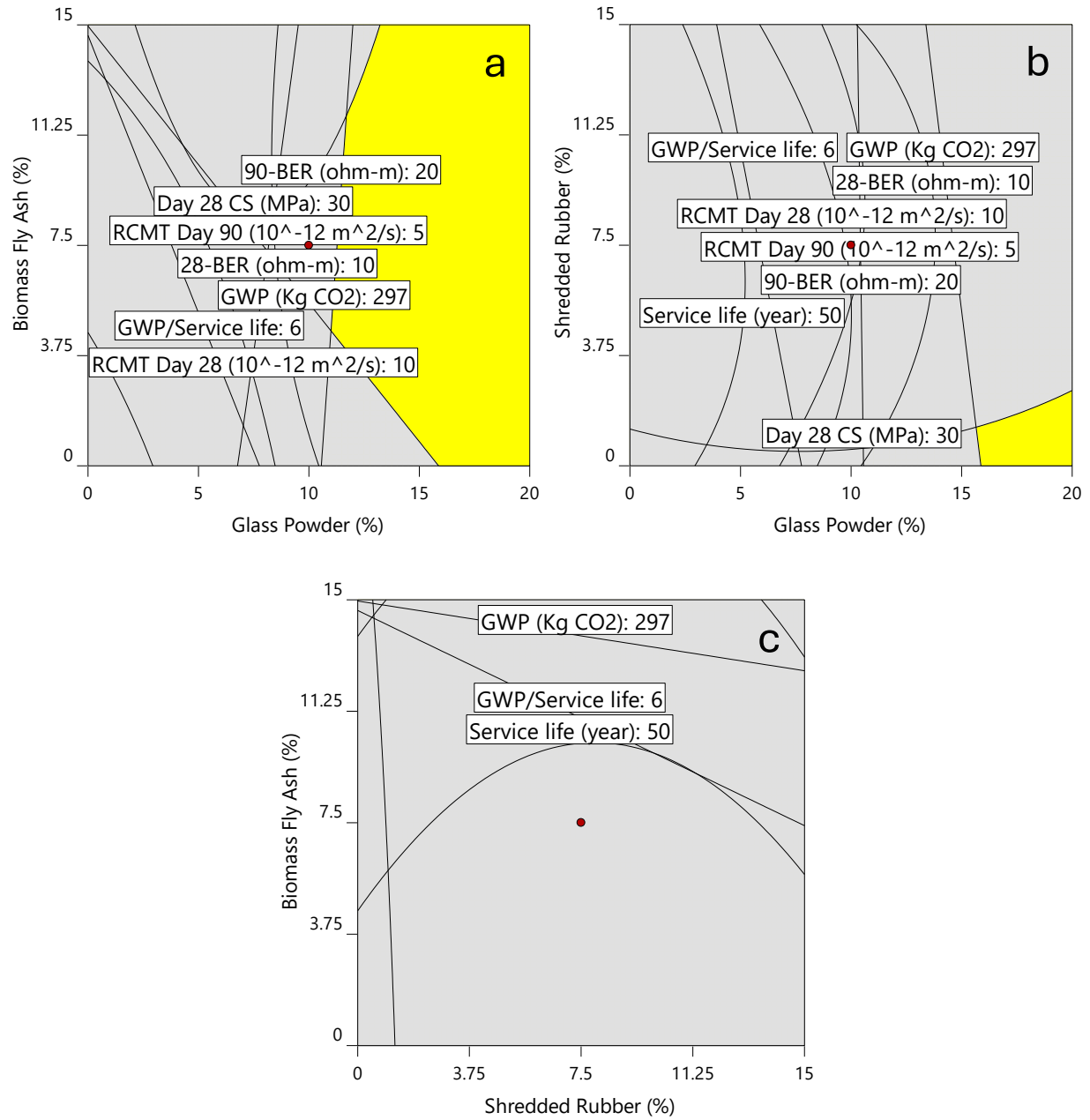


Figure 4.21: Sustainable concrete at a) 0% Biomass Fly Ash, b) 0% Shredded Rubber, c) 0% Glass Powder

4.7 Conclusion

This research demonstrated the potential of incorporating waste materials such as glass powder (GP), biomass fly ash (BFA), and shredded rubber (SR) into concrete mixtures to enhance sustainability and performance. By optimizing the combination of these materials, significant improvements were achieved in terms of environmental impact, workability, mechanical strength, and durability.

- The optimization process identified concrete mixes that met stringent performance standards, including compressive strength, slump, and chloride resistance, while minimizing environmental impact. Notably, mixes incorporating higher levels of GP, particularly 20%, demonstrated the best balance between performance and sustainability. These mixes adhered to the 30 MPa compressive strength and 50-year service life criteria while significantly reducing carbon emissions.
- A key finding of this study is the substantial reduction in Global Warming Potential (GWP) achieved through the use of alternative materials. The control mix exhibited a GWP of 342 kg CO₂, whereas the optimal design mix incorporating GP, BFA, and SR can reduce GWP to 240 kg CO₂, representing a 102 kg CO₂ decrease in carbon emissions. This highlights the significant environmental benefits of utilizing these waste materials in concrete production.
- the synergy between GP and BFA highlights its potential for promoting BFA as a viable alternative to cement, allowing for higher replacement ratios (15%) and lower carbon emissions without sacrificing durability and mechanical performance standards.
- The control mix, with a compressive strength of 33 MPa, did not meet the environmental and durability criteria, particularly for chloride resistance and GWP. This reinforces the need to incorporate alternative materials to achieve a more sustainable and durable mix.

In conclusion, this research provides valuable insights into the design of sustainable concrete. By leveraging the potential of GP, BFA, and SR, it offers a practical approach to creating concrete that is both environmentally friendly and structurally sound. Additionally, refining BFA can significantly enhance its performance, as its unburnt carbon content negatively affects concrete properties. Further research is recommended to comprehensively evaluate the long-term performance of these concrete mixes in real-world applications. This includes conducting longevity tests such as freeze-thaw cycles and shrinkage measurements to assess their durability over time. Additionally, expanding the range of alternative materials considered by AI-driven design tools can lead to even more innovative and sustainable concrete solutions. Investigating whether a combination of BFA and GP can be used as a replacement for Class F fly ash is essential to enhancing material efficiency and performance. Exploring the feasibility of applying these optimized mixes to large-scale structural elements like beams and columns is crucial to fully realize their potential in practical construction projects.

CHAPTER 5: DURABILITY PERFORMANCE OF LOW-CARBON CONCRETE INCORPORATING OPTIMIZED RATIO OF MULTIPLE WASTE MATERIALS (GLASS POWDER, BIOMASS FLY ASH, AND SHREDDED RUBBER)

Abstract

Incorporating waste materials in concrete can enhance sustainability and contribute to more environmentally friendly construction practices. However, using these materials in concrete presents challenges related to durability, mechanical, and environmental performance. This study explores the effects of incorporating glass powder (GP), biomass fly ash (BFA), and shredded rubber (SR) as partial replacements for cement and aggregates in concrete. The focus is on assessing their impact on durability, mechanical properties, and the environment. To determine the most effective combination of waste materials, Response Surface Methodology (RSM) is employed to design the experimental program and optimize the mixture proportions. The research evaluates air content, freeze-thaw resistance, compressive strength, Young's modulus of elasticity, splitting tensile strength, modulus of rupture, surface electrical resistivity, life cycle assessment (LCA), rapid chloride penetration test, and global warming potential of concrete mixtures. Results show that replacing cement with 20% GP improves durability and strength, raising electrical resistivity by 240% and achieving durability factors of more than 90%. However, SR above 7.5% reduces freeze-thaw resistance and stiffness. In addition, optimal mixes with a maximum of 16% GP or 15% BFA reach a compressive strength of 30 MPa and limit GWP to 297 kg/m³ CO₂.

Key words: *Low-carbon Concrete, Optimal mix design, Global warming potential, freezing and thawing, Waste materials, Environmental impact, Chloride penetration, Life cycle assessment*

5.1 Introduction

Concrete exterior applications are exposed to extreme weather conditions that significantly impact their performance and lifespan. In regions with harsh winters, such as in northern climates, freeze-thaw cycles pose a serious challenge, as they can lead to cracking, spalling, surface scaling and other forms of deterioration [208]. Additionally, chloride resistance becomes a key consideration for applications such as concrete pavements due to the routine application of de-icing salts during the winter months. Chloride penetration in concrete can accelerate steel reinforcement corrosion, further compromising reinforced concrete's structural integrity [209,210]. In addition to addressing durability concerns, concrete mixtures must meet the mechanical properties specified by standards, such as compressive strength, tensile strength, and flexibility. These properties are essential for ensuring the performance and reliability of the concrete in use [211–213]. However, the challenge becomes even more pronounced when sustainability goals are introduced, particularly in the design of a low-carbon concrete mixture. Concrete production accounts for approximately 8-10% of global carbon dioxide emissions [4]. Replacing traditional cement and/or aggregates with waste materials [214–217] such as waste tires [218], waste glass [9,219], and biomass fly ash [163] can reduce carbon emissions [165,212]. Furthermore, recycling these waste materials helps prevent them from being dumped in the environment [220]. Achieving a balance between performance and sustainability is particularly difficult when incorporating multiple waste materials, such as biomass fly ash, recycled glass powder, or shredded rubber, as supplementary materials. The integration of these materials in concrete, while environmentally beneficial, can complicate the design process by influencing key properties of the mixture, such as freeze and thaw cycle, air content, and mechanical properties. In addition, concrete is durable and does not require very high compressive strength. Excessive strength may lead to overdesign and extra costs [221]. Instead, durability is

enhanced by optimizing the mix design and improving material selection [221]. As a result, designing such concrete mixtures demands a precise mix design optimization process[222,223] that considers not only the mechanical and durability properties but also the environmental impact, aiming to reduce the carbon footprint while ensuring that the material performs adequately in severe environmental conditions.

According to Pino et al [224] study replacing a portion of the cement with glass powder in concrete design mainly increases the air content within the concrete mixture. However, Raydan et al. [225] reported that the particle size distribution of the ground glass filler influences the entrapped air content within the cementitious matrix. Smaller glass particles possess the capacity to occlude the pores of the matrix, leading to a reduction in porosity. Conversely, larger glass particles can contribute to an increase in entrapped air. Additionally, the duration of glass waste grinding exerts a significant impact on the entrapped air content [225]. Due to the dearth of data for specific mix designs and curing ages, the development of comprehensive equations encompassing all variables proved infeasible.

The dynamic modulus of elasticity is a pivotal indicator of the freeze-thaw resistance exhibited by concrete. According to Haque and Cook's paper [12], a reduction in dynamic modulus signifies the degradation of the cementitious matrix, terminating in a loss of elasticity. Huang et al. [226] found that rubberized concrete showed better resistance to freeze-thaw damage than plain concrete, retaining higher dynamic modulus values even after repeated freeze-thaw cycles. Grdic et al. [227] reported that waste glass concrete, characterized by its dense microstructure and high impermeability, exhibited commendable freeze-thaw resistance. He et al. [228] illustrated that combined mixtures, such as 15% rubber and 10% glass powder, demonstrated substantial improvements in freeze-thaw resistance, reducing dynamic modulus loss by over 50% relative to

plain concrete. While these studies provide valuable insights into the freeze-thaw performance of rubber or glass powder-based concretes, they primarily focus on individual or binary combinations of waste materials and assess only durability aspects. None of them incorporates BFA, nor do they evaluate a comprehensive range of properties such as fresh behavior, mechanical strength, and environmental impact. Moreover, no optimal mix design was proposed in these works. Many studies [229–232] indicated that concrete's electrical resistivity is an important indicator of its durability. Bulk resistivity measures the overall resistance of the concrete, reflecting its internal quality and durability against deterioration. Surface resistivity gauges resistance at the surface, an indicator of susceptibility to aggressive agents like chlorides and acids that can cause deterioration. Shakouri et al. [233] showed that incorporating landfilled fly ash (LFA) with a high loss on ignition (LOI) can lower electrical resistivity due to the presence of conductive, unburned carbon particles. Compressive and flexural strengths of mortars containing biomass fly ash (BFA) are increased after 28, 90, and 180 days of curing [96,234]. According to Fort et al [21], studies, mixtures with up to 30% BFA replacing cement exhibited satisfactory mechanical performance, achieving a compressive strength of 49.1 MPa and a flexural strength of 8.1 MPa after 28 days. Beyond this threshold, a noticeable decline in strength is observed, particularly for mixtures with 40% or more BFA. This reduction is attributed to changes in porosity and microstructure. Over time (90 and 180 days), the pozzolanic reaction of BFA leads to an increase in compressive strength, especially for mixtures with higher BFA content. However, flexural strength showed only a modest (~20%) improvement across all mixtures. These findings suggest that 30% BFA represents a practical limit for maintaining viable mechanical properties in mortars while utilizing the benefits of biomass fly ash [96]. Research on BFA has remained limited, particularly regarding its combination with other waste materials. Most works focus

solely on mechanical properties, overlooking durability and environmental aspects. Additionally, no optimal mix design is proposed for using BFA.

Based on the comparative analysis of glass powder (GP) concrete and conventional concrete by many studies [218,235–239], it is demonstrated that GP concrete generally exhibits lower environmental impacts across all categories. Notably, according to Jiang et al. [26] studies substantial reductions of approximately 20% are observed in global warming, carcinogenic, noncarcinogenic, ozone depletion, and ecotoxicity effects. Cement production is the primary driver of GP concrete's life-cycle impacts, particularly in global warming and health-related categories. [240].

While several studies have investigated the individual effects of waste glass powder, biomass fly ash, or shredded rubber on concrete properties, a comprehensive analysis of the combined influence of all three materials on both durability and mechanical performance, particularly about concrete's carbon footprint, remains lacking. The lack of a specialized code that focuses on durability, such as freezing and thawing, is another example of this gap in the current regulations on using multiple waste materials in concrete. Such a study is crucial for the development of sustainable concrete mixes to achieve the Net-Zero Emission Accountability Act in Canada [164]. To address these gaps, 17 concrete mixes with varying GP, BFA, and SR proportions are prepared and tested through Response Surface Methodology (RSM). This technique allows for extensive investigation of material performance and interaction effects by a range of performance tests including compressive strength, freeze-thaw durability, air content, surface electrical resistivity (SER), splitting tensile strength (STS), modulus of rupture (MOR), life cycle assessment (LCA), rapid chloride penetration test (RCPT), and dynamic Young's modulus of elasticity. Based on experimental results, performance limits, such as maximum strength, durability limits, and GWP

thresholds, are employed to identify an optimal mix design with enhanced freeze-thaw resistance. The resulting mix satisfies key performance requirements in relevant standards while incorporating maximum waste material.

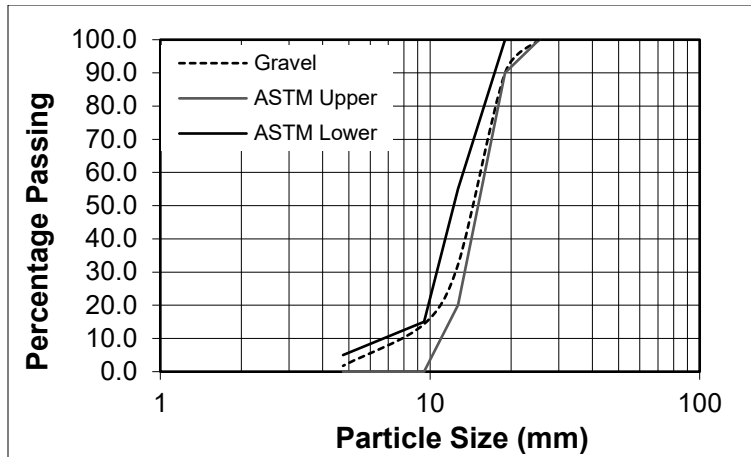
5.2 Experimental Program

5.2.1 Materials

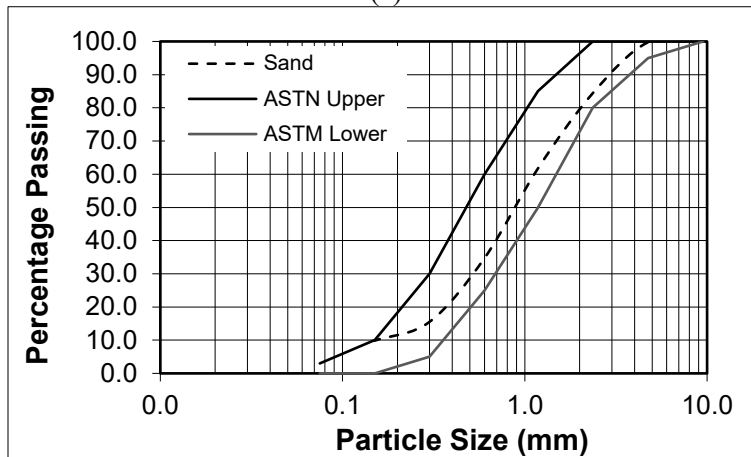
In this investigation, general-use (GU) Portland cement is selected as the primary binder, biomass fly ash is sourced from a local biomass power station, and glass powder adheres to ASTM C1866 standards [183] is obtained from a certified supplier. The chemical compositions of these materials are detailed in Table 5.1. Particle size is measured using a Mastersizer device, which yields D_{90} (where 90% of the particles are smaller than this size) values of 50 μm for cement, 13.2 μm for glass powder, and 70 μm for biomass ash. A polycarboxylate-based superplasticizer (specific gravity 1.08), MasterGlenium 7500, was used at 1% by cement weight to improve workability. This dosage is near the manufacturer’s upper limit and was confirmed through trial mixes. Similar dosages are reported in previous studies [241–243]. As shown in Figures 5.1a–b, the particle size distributions of the fine and coarse aggregates are within ASTM C33 [184]-specified bounds. The maximum particle size of the aggregate used in this study was 20 mm. The distribution curve of the shredded rubber, which is examined using sieve testing to verify that it complies with CSA A23.1 [244] grading standards, is displayed in Figure 5.1-c.

Table 5.1: Chemical composition of Portland cement, glass powder, and biomass fly ash

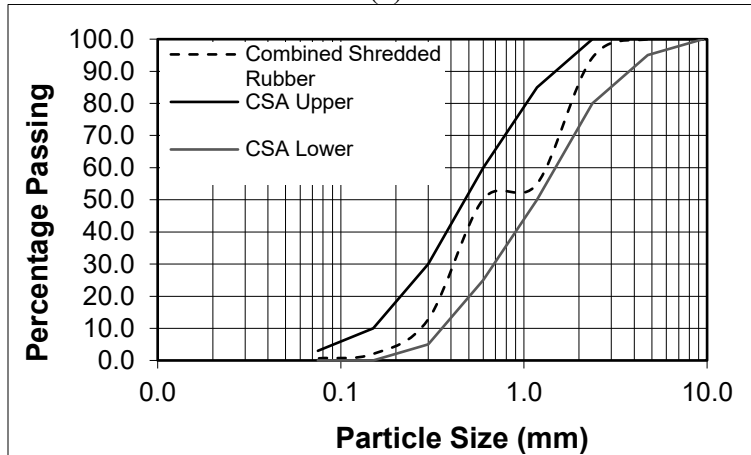
Material	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	LOI
Cement (%)	19.9	5.2	2.3	62.34	2.27	0.23	2.93
Biomass Fly Ash (BFA) (%)	2.79	0.83	1.92	42.49	5.21	0.55	29.68
Glass Powder (GP) (%)	70.07	1.57	0.34	10.46	1.47	12.85	1.11



(a)



(b)



(c)

Figure 5.1: Particle size distribution of (a) Gravel, (b) Sand, and (c) Shredded Rubber

5.2.2 Sample preparation

Each concrete mix is prepared for one minute by initially dry-mixing Portland cement, aggregates, GP, SR, and BFA. Subsequently, water and superplasticizer are gradually added to the dry mix over five minutes, ensuring homogeneous distribution. After mixing, the air content of the fresh concrete is measured according to ASTM C231 [125]. Specimens are then cast for compressive strength, freeze-thaw test, RCPT, splitting tensile strength, and flexural strength (using beam specimens). Following a 24-hour setting, all specimens are demolded and placed in a curing tank maintained at room temperature, 23 ± 2 °C.

5.2.3 Tests

The determination of air content in the fresh concrete mix is conducted in accordance with the ASTM C231 [125] standard. The procedure involved the placement of the concrete sample into the testing apparatus in three equal layers. Each layer is subjected to 25 tamping strokes using a tamping rod, followed by percussive action with a mallet to facilitate the release of entrapped air voids. After surface levelling, the air meter is filled with water, sealed to ensure an airtight environment, and pressurized to the calibrated initial pressure. The apparent air content is then recorded. The freeze-thaw durability of concrete is assessed using ASTM C666 [37], Procedure A. Concrete prisms are cast, cured for 14 days, and then saturated in a lime-saturated water bath for 48 hours before the test. Three specimens (76×102×406 mm) per mix are subjected to repeated freeze-thaw cycles, each consisting of 3 hours of freezing at -18°C and 2 hours of thawing at 4°C. The fundamental transverse frequency is determined using a Resonance Test Gauge [RTG-1] system at intervals of 30 cycles. Testing continued until 300 cycles are reached or until a specimen exhibited significant damage, defined as a mass loss greater than 10% or a relative dynamic

modulus of elasticity below 60%. The relative dynamic modulus of elasticity is calculated by equation (4.1):

$$P_c = \left(\frac{n_1^2}{n^2}\right) \times 100 \quad (4.1)$$

Where P_c is the relative dynamic modulus elasticity of a sample after c cycles, n_1 is the first fundamental transvers frequency (Hz) before starting freeze and thaw, and n is the fundamental transvers frequency (Hz) of the sample after c cycles.

To compare the freezing and thawing resistance of samples, the durability factor of each specimen is computed using equation (4.2):

$$DF = PN/M \quad (4.2)$$

Where DF is the durability factor, P is the relative dynamic modulus of elasticity at N cycles, N is the maximum number of cycles the sample undergoes before stopping the test, and M is the maximum number of cycles the sample is determined to undergo freezing and thawing, which is 300 for this test.

Compressive strength is determined at 28 days according to ASTM C39 [130] using three 100×200 mm cylindrical specimens. The flexural strength (modulus of rupture) of concrete is determined using a four-point bending test according to ASTM C78 [245]. Three concrete beam specimens (100 mm × 100 mm × 350 mm) for every mix are prepared and cured for 28 days. The beam is then placed on two supports, with loading points positioned 100 mm apart. A load is applied gradually (0.4 mm/min) at two equidistant points until failure is observed, and the maximum load is recorded. The flexural strength (MPa) (modulus of rupture) is calculated using equation (4.3):

$$R = \frac{PL}{bd^2} \quad (4.3)$$

where P is the maximum load (N), L is the support span (mm), b is the beam width (mm), and d is the beam depth (mm). The splitting tensile strength of concrete is determined using the indirect tensile test [246]. Cylindrical specimens (100 mm diameter, 200 mm length) are placed horizontally in a universal testing machine (UTM), and the compressive load is applied along the diametrical axis to induce indirect tension. The splitting tensile strength f_t (MPa) is determined by equation (4.4):

$$f_t = \frac{2P}{\pi ld} \quad (4.4)$$

Where P is the maximum load (N), l is the length (mm), and d is the diameter of the specimen (mm).

The electrical surface resistivity of concrete cylinders is measured following AASHTO T 358 [128]. A 4-point wanner Resipod resistivity meter is used to assess the electrical resistivity. To ensure consistency, three measurements are recorded around the circumference of each cylinder at equal intervals. The Global Warming Potential (GWP) of the concrete mix is calculated following the IPCC [186] guidelines, estimating the greenhouse gas emissions over a 100-year period. The GWP is measured as each mixture's equivalent carbon dioxide emissions for one cubic meter of concrete. This method evaluates long-term environmental impacts, including embodied carbon and production processes, according to equation (4.5):

$$\text{GWP}_{100\text{year}}(\text{kg CO}_2 - \text{eq}) = 1 \times \text{CO}_2 + 21 \times \text{CH}_4 + 310 \times \text{N}_2\text{O} \quad (4.5)$$

The dynamic Young's modulus of elasticity of concrete (Dynamic E) is measured using an RTG-1 device [247]. While the relative dynamic modulus of elasticity for the freeze-thaw test is determined by comparing the fundamental transverse frequency of the specimen between the initial and target cycles, the dynamic Young's modulus of elasticity is calculated using the fundamental longitudinal frequency, taking the specimen's dimensions into account. For each

mixture, three prism specimens ($76 \times 102 \times 406$ mm) are tested. An accelerometer attached to the specimen captured the resulting longitudinal frequency waves (Figure 5.2). The average of the three highest frequency peaks following each impact is recorded for each specimen. Dynamic E (Pa) is estimated by Equation (4.6) according to ASTM C 215 [247] as:

$$\text{Dynamic } E = DM(n')^2 \quad (4.6)$$

Where D is $4(L/bt)$, where l is the length of the prism (m), b is the height of the prism (m), and t is the width of the prism (m). M is the mass of the prism (kg) and n' is the fundamental longitudinal frequency (Hz).

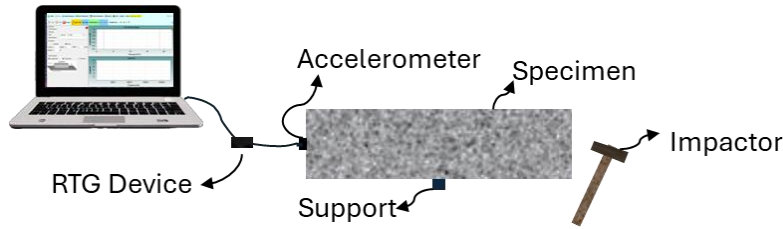


Figure 5.2: Schematic of longitudinal frequency test setup

The permeability of the pore system of the composites is assessed by the rapid chloride penetration test (RCPT) according to the ASTM C1202 standard [248]. During the test period (6 h), 60 V DC is applied to the concrete specimen. The test measures the amount of total charge passed through the concrete, and it is measured continuously to grade the penetrability resistance of the concrete to chloride ions. The tests are used to grade the penetrability of the concrete based on the total charge passed..

5.3 Mixture design

A Response Surface Methodology (RSM) experimental design is employed to investigate the effects of glass powder (GP), biomass fly ash (BFA), and shredded rubber (SR) on the properties

of concrete. The experimental design considered three concrete ingredients replacement: GP as a cement replacement (0%–20%), BFA as a cement replacement (0%–15%), and SR as a sand replacement (0%–15%). The selected factors and their coded/actual levels used in the experimental design are shown in Table 5.2. The experimental design is generated using Design-Expert, based on a Central Composite Design (CCD). The experimental matrix consisted of 17 runs, comprising 6 axial points, 8 factorial points, and 3 central points. In the CCD design, the value of α (alpha) determines the distance of axial points from the center in a central composite design. For the three-factor system used in this study, a value of $\alpha = 1.682$ is suggested by the Design-Expert software. While α can be determined theoretically or selected based on prior experience, the value recommended by the software was adopted in this study to ensure proper rotatability and uniform prediction variance. The mix design is brought in Table 5.3. All mixtures are designed with a constant binder content of 340 kg/m³, a water-binder ratio of 0.46, and a sand-to-gravel ratio of 50:50. A superplasticizer is added at a dosage of 1% by weight of the binder.

Table 5.2: Factors and their level ranges used in the experimental design

Factors		Levels				
Actual	Coded	-1.682	-1.00	0.00	1.00	1.682
SR	A	0	3.04	7.50	11.96	15.00
GP	B	0	4.05	10.00	15.94	20.00
BFA	C	0	3.04	7.50	11.96	15.00

Table 5.3: Components of the concrete mixtures for one cubic meter

Run Order	SR ¹ kg/m ³	GP ² kg/m ³	BFA ³ kg/m ³	Water kg/m ³	Cement kg/m ³	Sand kg/m ³	Gravel kg/m ³
1	26.44	68	25.5	157	246.5	867.7	938
2	26.44	34	25.5	157	280.5	867.7	938
3	0	34	25.5	157	280.5	938.0	938
4	42.17	13.77	10.33	157	315.9	825.8	938
5	42.17	13.77	40.66	157	285.6	825.8	938
6	42.17	54.23	10.33	157	275.5	825.8	938
7	26.44	34	25.5	157	280.5	867.7	938
8	26.44	34	0	157	306.0	867.7	938
9	52.89	34	25.5	157	280.5	797.3	938
10	26.44	34	25.5	157	280.5	867.7	938
11	26.44	34	51	157	255.0	867.7	938
12	10.72	13.77	40.66	157	285.6	909.5	938
13	42.17	54.23	40.66	157	245.1	825.8	938
14	26.44	0	25.5	157	314.5	867.7	938
15	10.72	54.23	40.66	157	245.1	909.5	938
16	10.72	13.77	10.33	157	315.9	909.5	938
17	10.72	54.23	10.33	157	275.5	909.5	938

¹ Shredded Rubber, ² Glass Powder, ³ Biomass Fly Ash

5.4 Results and discussion

5.4.1 Model fitting

After collecting results for 17 mixtures in each test (Table 5), the next step is to evaluate the corresponding equation for each test. In this study, the conducted tests include air content, durability factor, compressive strength, modulus of rupture, splitting tensile strength, surface electrical resistivity, global warming potential, and dynamic Young's modulus of elasticity. For each test, a second-order equation is used to fit the 17 experimental results. This equation, as shown in Equation (4.7), relates the response variable (Y) and the input factors (Xi) through linear, quadratic, and interaction terms:

$$Y = \beta_0 + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \beta_{ii} X_i^2 + \sum_{i < j}^k \beta_{ij} X_i X_j + \varepsilon \quad (4.7)$$

Y is the predicted test result, such as air content, durability factor, compressive strength, splitting tensile test, RCPT, SER, GWP, and dynamic Young's modulus of elasticity. β_0 is the intercept, β_i is the first-order (linear) coefficient, β_{ii} is the second-order (quadratic) coefficient, and β_{ij} is the coefficient of the interaction effect. On the other hand, the independent variables are X_i and X_j (GP, SR, and BFA), and the random error is ε .

Table 5.4: Summary of the results

No	Air Content (%)	Durability factor (%)	Day 28 CS ¹ (MPa)	MOR ² (MPa)	SER ³ (kΩ.cm)	STS ⁴ (MPa)	GWP (kg CO ₂)	Dynamic modulus (GPa)	RCPT ⁶ (Coulombs)
1	4.35	6.94	23.97	4	32	2.1	259.41	39.41	513.14
2	3.5	22	19.61	5.22	20.08	2.61	287.41	40.61	1397.16
3	4.95	64.12	30.8	4.47	15.44	2.49	291.14	39.22	989.21
4	5.5	95.91	15.81	4.84	17.57	2.15	315.72	38.81	2407.26
5	5.7	25.12	21.95	4.41	14.56	2.06	288.85	36.67	2555.07
6	6.9	90.20	19.69	4.07	19.16	1.85	281.72	33.13	674.07
7	3.55	24	19.32	4.82	18.77	2.41	287.41	40.74	1123.06
8	6.4	71.22	16.86	4.74	18.30	2.55	310.31	39.47	1356.22
9	4.9	22.98	17.88	3.89	17.65	1.70	284.08	25.74	965.32
10	3.4	23	19.6	4.67	20.86	2.27	287.41	41.08	1095.96
11	5	12.56	19.47	3.02	15.93	1.97	264.51	37.32	1666.81
12	7	93.23	26.22	4.28	13.86	2.35	293.09	39.76	3213.69
13	4	18.99	23.66	3.22	22.25	1.40	254.85	30.60	780.43
14	5.4	70	19.45	4.85	15.47	2.14	316.41	38.71	4031.20
15	3.7	1.87	25.55	2.83	29.83	2.29	259.09	40.21	945.34
16	5.4	85	25.40	5.06	13.83	2.41	319.97	42.61	2486.79
17	5.85	95.90	25.02	5.20	22.9	2.48	285.97	41.38	732.89

¹ Compressive Strength, ² Modulus of rupture, ³ Surface electrical resistivity, ⁴ Splitting tensile strength, ⁵ Global Warming Potential, ⁶ Rapid chloride penetration test

5.4.2 Modification of equations according to statistical criteria

After fitting the second-order equation to the results, the statistical accuracy of the equation is evaluated. The coefficient of determination (R^2), adjusted R^2 , PRESS, standard deviation, residuals, and p-values are used to assess the fit. Table 5.5 shows that the R^2 values for all tests are close to 1, indicating an excellent fit. Furthermore, the p-values for all tests are less than 0.05, demonstrating high statistical significance and confirming that the independent variables have a substantial influence on the dependent variable. In addition, Adequate Precision values greater than 4 indicate a reliable model. While there is no universally defined acceptable range for PRESS, lower values generally reflect better agreement between predicted and observed response. To assess multicollinearity among independent variables, the Variance Inflation Factor (VIF) values were calculated and are presented in Appendix 5.1. Since the experimental design is orthogonal, all VIFs are equal or very close to 1, indicating negligible multicollinearity. All VIF values were below 5, confirming that multicollinearity is not a concern and that the model coefficients are reliable. The residual analysis related to each test brought in (Appendix 5.2) demonstrates that the residuals are normally distributed and acceptable. Furthermore, the normal probability plots of residuals for all tested responses in Appendix 5.3 show that the residuals are approximately normally distributed, with points closely following the expected straight line. This indicates that the assumption of normality is reasonably satisfied and confirms the adequacy of the fitted models. After evaluating the equations, the driving equation is brought in Table 5.6.

Table 5.5: The results for full regression models

Responses	R ²	Adjusted R ²	P-Value	A _{deq} Precision	Standard deviation	PRESS
Air Content (%)	0.99	0.97	< 0.0001	22.83	0.19	2.07
Durability factor (%)	0.83	0.82	0.0462	5.73	22	278.11
Day 28 CS ¹ (MPa)	0.92	0.86	< 0.0001	15.06	1.47	79.60
MOR ² (MPa)	0.95	0.88	0.0012	10.27	0.26	3.05
SER ³ (kΩ.cm)	0.96	0.90	0.0007	14.88	1.67	137.47
STS ⁴ (MPa)	0.93	0.83	0.0033	10.98	0.13	0.62
GWP ⁵ (kg CO ₂)	0.99	0.99	< 0.0001	637.09	0.21	1.06
Dynamic Young's modulus (GPa)	0.91	0.88	< 0.0001	16.87	1.52	65.36
RCPT ⁶ (Coulombs)	0.98	0.96	0.0001 >	25.55	175	137.50

¹ Compressive strength, ² Modulus of rupture, ³ Surface electrical resistivity, ⁴ Splitting tensile strength, ⁵ Global warming potential, ⁶ Rapid chloride penetration test

Table 5.6: Equation of tests

Air Content (%)	$7.97 - 0.44 \times \text{SR} (\%) - 0.21 \times \text{GP} (\%) - 0.29 \times \text{BFA} (\%) + 0.012 \times \text{SR} (\%) \times \text{GP} (\%) - 0.013 \times \text{SR} (\%) \times \text{BFA} (\%) + -0.032 \times \text{GP} (\%) \times \text{BFA} (\%) + 0.0282806 \times \text{SR} (\%)^2 + 0.015 \times \text{GP} (\%)^2 + 0.042 \times \text{BFA} (\%)^2$	(1)
Durability factor (%)	$162.741 - 11.44 \times \text{SR} (\%) - 6.95 \times \text{GP} (\%) - 6.40 \times \text{BFA} (\%) + 0.323461 \times \text{SR} (\%) \times \text{GP} (\%) - 0.35 \times \text{SR} (\%) \times \text{BFA} (\%) - 0.48 \times \text{GP} (\%) \times \text{BFA} (\%) + 0.59 \times \text{SR} (\%)^2 + 0.28 \times \text{GP} (\%)^2 + 0.56 \times \text{BFA} (\%)^2$	(2)
Day 28 CS ¹ (MPa)	$33.18 - 2.67 \times \text{SR} (\%) - 0.49 \times \text{GP} (\%) - 0.15 \times \text{BFA} (\%) + 0.054 \times \text{SR} (\%) \times \text{BFA} (\%) + 0.10 \times \text{SR} (\%)^2 + 0.03 \times \text{GP} (\%)^2$	(3)
MOR ² (MPa)	$4.32 + 0.084 \times \text{SR} (\%) + 0.11 \times \text{GP} (\%) + 0.13 \times \text{BFA} (\%) - 0.003 \times \text{SR} (\%) \times \text{GP} (\%) + 0.011 \times \text{SR} (\%) \times \text{BFA} (\%) - 0.009 \times \text{GP} (\%) \times \text{BFA} (\%) - 0.011 \times \text{SR} (\%)^2 - 0.004 \times \text{GP} (\%)^2 - 0.016 \times \text{BFA} (\%)^2$	(4)
SER ³ (kΩ.cm)	$6.83 + 1.88 \times \text{SR} (\%) + 0.076 \times \text{GP} (\%) + 0.47 \times \text{BFA} (\%) - 0.074 \times \text{SR} (\%) \times \text{GP} (\%) - 0.043 \times \text{SR} (\%) \times \text{BFA} (\%) + 0.061 \times \text{GP} (\%) \times \text{BFA} (\%) - 0.057 \times \text{SR} (\%)^2 + 0.039 \times \text{GP} (\%)^2 - 0.047 \times \text{BFA} (\%)^2$	(5)
STS ⁴ (MPa)	$1.73 + 0.09 \times \text{SR} (\%) + 0.10 \times \text{GP} (\%) + 0.05 \times \text{BFA} (\%) - 0.004 \times \text{SR} (\%) \times \text{GP} (\%) - 0.001 \times \text{SR} (\%) \times \text{BFA} (\%) - 0.002 \times \text{GP} (\%) \times \text{BFA} (\%) - 0.006 \times \text{SR} (\%)^2 - 0.003 \times \text{GP} (\%)^2 - 0.003 \times \text{BFA} (\%)^2$	(6)
GWP ⁵ (Kg CO ₂)	$+342.32 - 0.47 \times \text{SR} (\%) - 2.85 \times \text{GP} (\%) - 3.02 \times \text{BFA} (\%)$	(7)

Dynamic Young's modulus (GPa)	$37.93 + 1.56 \times \text{SR} (\%) + 0.24 \times \text{GP} (\%) - 0.20 \times \text{BFA} (\%) - 0.051 \times \text{SR} (\%) \times \text{GP} (\%) - 0.12 \times \text{SR} (\%)^2$	(8)
RCPT ⁶ (Coulombs)	$+3869.22 + 33.29 \times \text{SR} (\%) - 391.83 \times \text{GP} (\%) - 14.09 \times \text{BFA} (\%) + 2.42 \times \text{SR} (\%) \times \text{GP} (\%) - 4.30 \times \text{SR} (\%) \times \text{BFA} (\%) - 2.62 \times \text{GP} (\%) \times \text{BFA} (\%) - 2.77 \times \text{SR} (\%)^2 + 11.38 \times \text{GP} (\%)^2 + 6.71 \times \text{BFA} (\%)^2$	(9)

¹ Compressive Strength, ² Modulus of rupture, ³ Surface electrical resistivity, ⁴ Splitting tensile strength, ⁵ Global Warming Potential, ⁶Rapid chloride penetration test

5.4.3 Verification of models

In addition to the statistical accuracy evaluation, two randomly selected mixtures are chosen to validate the equation. In this process, the test results for each mixture are compared to the predicted range derived from the equation. For this purpose, two mix designs, incorporating SR, GP, and BFA, are prepared, and the results of tests on the two mixes are presented in Table 5.7. To assess the validity of the equation, the lower and upper 95% confidence intervals for each test are calculated and compared against the experimental outcomes. For the validation to be confirmed, the results of the two mix designs must fall within these predicted ranges.

The findings revealed a tight fit within the anticipated ranges. For example, a blend with 15% GP, 0% SR, and 3.75% BFA had a compressive strength of 30.2 MPa. The respective 95% confidence interval, derived from the equation, fell between 29.3 MPa (lower) and 35.6 MPa (higher), validating that the measured value is well within the foretold range. In the same way, the same blend showed an air content of 5.5%, and the equation estimated a 95% confidence interval to be 5.32% (lower limit) to 6.37% (upper limit). After the statistical reliability and validity of the equation are established, graphical plots are created, and further tests are conducted for optimization.

Table 5.7: Validation results

Mix design			
SR (%)	0	3.75	
GP (%)	15	15	
BFA (%)	3.75	0	
Tests	Comparison	Results	
Air Content (%)	Exp	5.50	7.20
	95% CI low	5.32	7.08
	95% CI high	6.37	8.13
Durability factor (%)	Exp	73.5	79
	95% CI low	72.99	47
	95% CI high	100	100
Day 28 CS ¹ (MPa)	Exp	30.16	21.39
	95% CI low	29.26	21.87
	95% CI high	35.62	27.02
MOR ² (MPa)	Exp	4.31	4.45
	95% CI low	4.23	4.45
	95% CI high	5.63	5.86
SER ³ (kΩ.cm)	Exp	23.23	23
	95% CI low	16.91	14.42
	95% CI high	25.87	23.37
STS ⁴ (MPa)	Exp	2.71	2.25
	95% CI low	2.23	2.21
	95% CI high	2.94	2.92
GWP ⁵ (kg CO ₂)	Exp	288.13	297.70
	95% CI low	287.85	297.44
	95% CI high	288.41	298.00
Dynamic modulus (GPa)	Exp	42.50	40.81
	95% CI low	37.67	40.72
	95% CI high	44.12	45.10
RCPT ⁶ (Coulombs)	95% CI low	120.26	307.67

¹ Compressive Strength, ² Modulus of rupture, ³ Surface electrical resistivity, ⁴ Splitting tensile strength, ⁵ Global Warming Potential, ⁶ Rapid chloride penetration test

5.4.4 Air content

Figure 5.6 presents the variation in air content (ranging from 4% to 13%) in relation to GP, BFA, and SR content. The air content of the control sample is 7.9%. With the addition of 10% GP, the air content decreased to 7% Figure 5.6a. However, further increasing the GP content maintained the air content close to that of the control sample. This trend is further amplified, reaching 10% and 12% GP at SR replacement levels of 7.5% and 15%, respectively (Figure 5.3b-c).

The addition of 15% BFA also resulted in increased air content (60% relative to the control). However, the air content of 15% BFA decreased with increasing SR levels, reaching 53% and 23% at 7.5% and 15% SR replacement, respectively (Figure 5.3 a-c). The larger particles of BFA, compared to cement, along with the presence of unburned biochar particles, can trap more air on the grooved surface of the BFA, leading to an increase in air content. The influence of SR on air content is indicated by a minimum value of 6.2% at 7.5% SR replacement, subsequently increasing slightly to 7.7% at 15% SR, approaching the control value. A minimum air content of 3.2% is recorded at a composition of 11.5% BFA, 16% GP, and 7.5% SR. These results suggest that the combined presence of GP and BFA promotes a more compact particle packing arrangement, which consequently reduces air entrainment. This effect appears to be more pronounced when the combined GP and BFA content exceeds 15%.

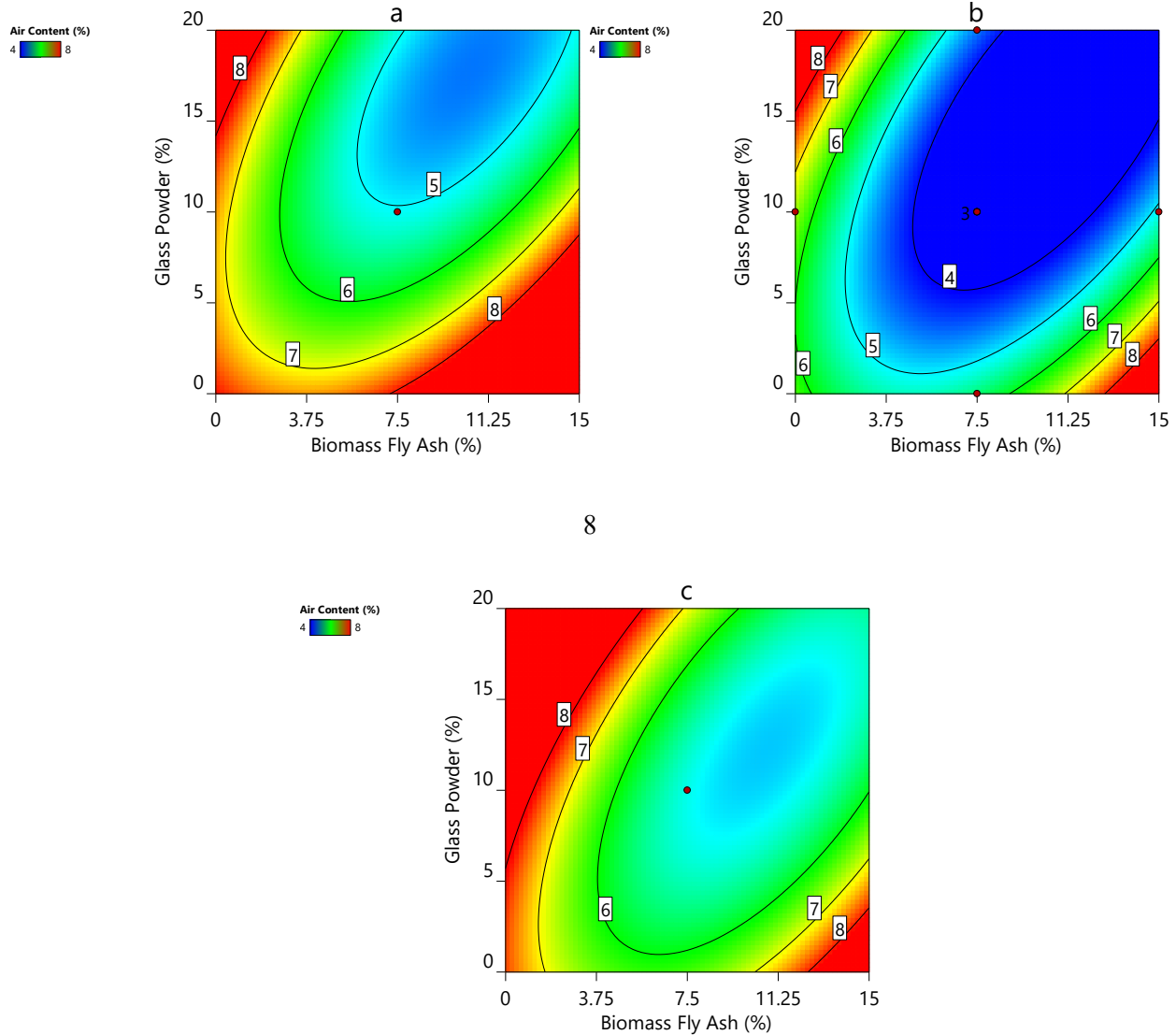


Figure 5.3: Air content at the level of a) 0% SR, b) 7.5% SR, and c) 15% SR

5.4.5 Durability factor

The durability factor results are presented in Figure 5.4, where red represents the maximum durability factor (100%) and blue indicates the minimum (1%). The incorporation of up to 20% GP and 15% BFA separately maintains the durability factor at 100% (Figure 5.4a). The durability factor stays above 70% when GP is used with less than 4% BFA, or when BFA is combined with less than 9% GP. However, using these materials above the mentioned limits reduces durability,

dropping to 25% at 20% GP, 15% BFA, and 0% SR. Notably, only the combination of 20% GP with up to 2% BFA maintains a durability factor above 70%, while exceeding 2% BFA with 20% GP causes the durability to drop below this threshold. This negative effect of combining BFA and GP is attributed to an increased compaction of the concrete, as confirmed by air content measurements in Section 4.4.4. The reduction in air content with a combination of higher GP and BFA levels suggests a denser microstructure, which may contribute to the observed durability decline. To further support the discussion of durability performance, SEM images were taken and are presented in Figure 5.5. These images show the differences in ITZ width between two mixes. Figure 5.5a shows Mix No. 7, containing 7.5% SR, 10% GP, and 7.5% BFA, with an air content of 3.5% and a low durability factor of 21.5%, indicating a dense microstructure with an average ITZ of 5 μm . In contrast, Mix No. 8, containing 7.5% SR, 10% GP, and no BFA, have a higher air content of 6.5%, a greater durability factor of 93.5%, exhibiting the ITZ width about 11 μm (Figure 5.5b). The low air content and narrower ITZ observed in Mix No. 7, compared to Mix No. 8, suggest that the concrete had a denser microstructure, which did not allow for adequate preservation of the air-void system and contributed to its poor freeze-thaw durability. Furthermore, increasing the SR content to 7.5% and 15% leads to a further reduction in durability Figure 5.4b-c, the region where the durability factor falls below 70%. The lowest durability factor (1%) is observed at 7.5% and 15% SR with 20% GP and 15% BFA. This decrease is attributed to the higher risk of surface scaling due to weaker SR/paste bond in mixtures containing SR at levels of 7.5% or more; Figure 5.6 compares how surface scaling increases as the SR content increases from 0% to 15%. Due to excessive surface scaling after freezing and thawing for these samples, the sensor is unable to be properly positioned on the concrete, and therefore, no frequency is recorded under this condition.

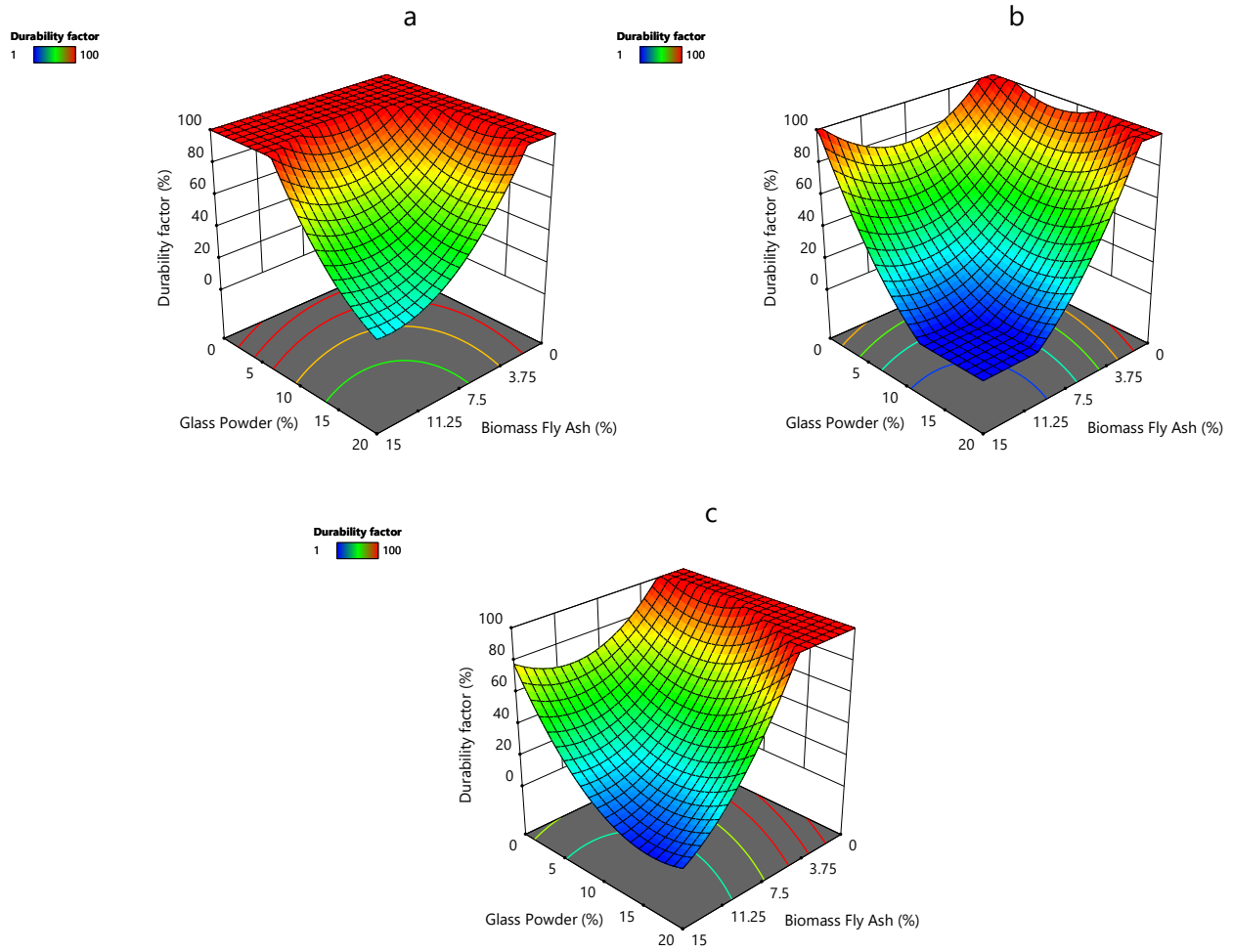


Figure 5.4: Durability Factor at the level of a) 0% SR, b) 7.5% SR, and c) 15% SR

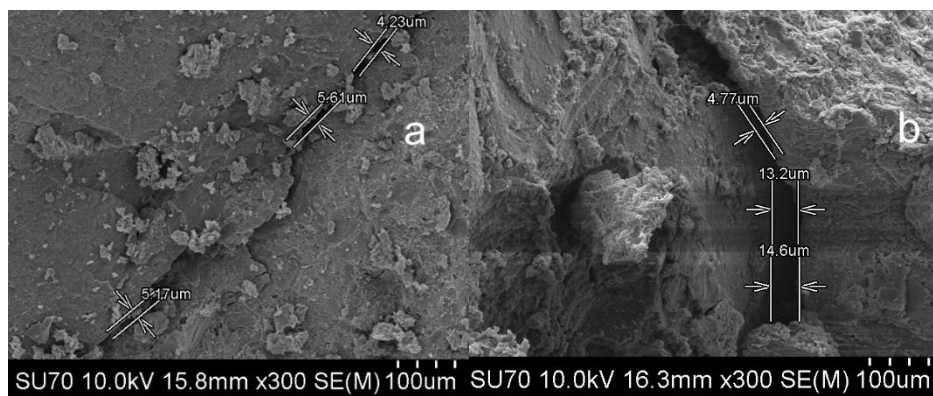


Figure 5.5: SEM images of (a) Mix No. 7 (7.5% SR, 10% GP, 7.5% BFA), and (b) Mix No. 8 (7.5% SR, 10% GP, 0% BFA)

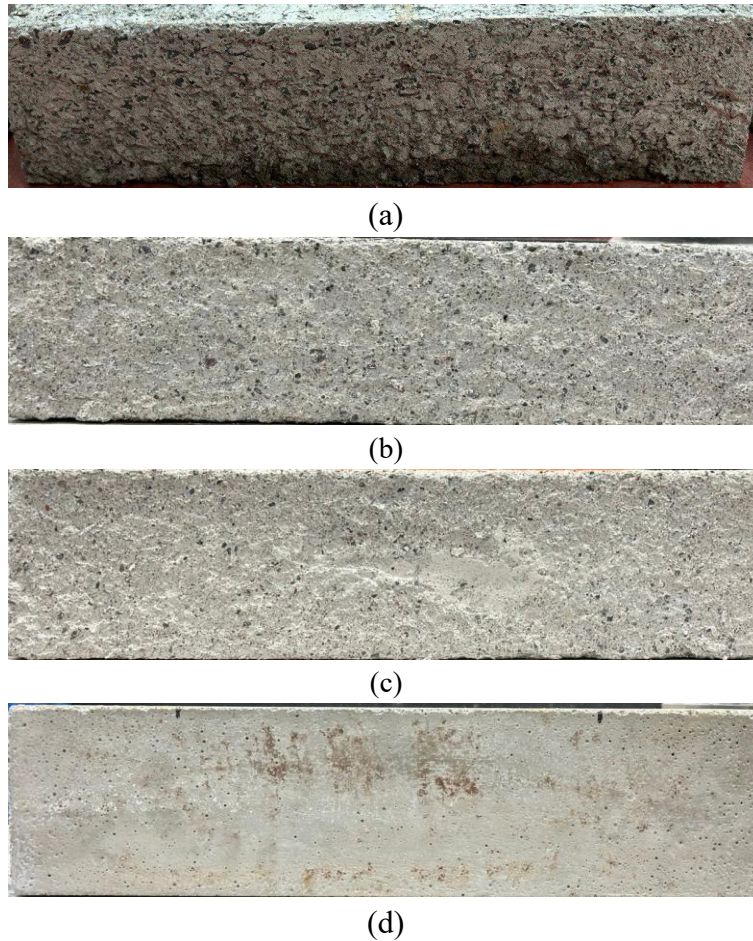


Figure 5.6: Concrete surface scaling of mix a) No.9 (15%SR, 10%GP, 7.5%BFA), b) No.1 (7.5%SR, 20%GP, 7.5%BFA), c) No.2 (7.5%SR, 10%GP, 7.5%BFA), d) No.3 (0%SR,10%GP,7.5BFA),

5.4.6 Compressive strength

Figure 5.7 illustrates the compressive strength variation of concrete incorporating different proportions of GP, BFA, and SR. The highest compressive strength, exceeding 34 MPa, is observed in mixtures with a high GP content (above 15%) and a low BFA replacement level (below 5%). This suggests that GP positively contributes to strength development due to its pozzolanic reactivity. In contrast, increasing the BFA content beyond 10% leads to a noticeable decline in compressive strength. Replacing 15% of cement with BFA results in a reduction of compressive strength to approximately 30 MPa, representing a decrease of nearly 12% compared to the highest

strength region (20% GP) (Figure 5.7a). When 7.5% SR is used, the compressive strength of mixtures that contain GP and BFA is limited to roughly 17–25 MPa (Figure 5.7b). As rubber particles introduce a weaker interfacial transition zone (ITZ) with the paste matrix [197], leading to lower compressive strength. As shown in Figure 5.8, the average ITZ thickness in the control sample (Figure 5.8a) is about 5 μm , while in the rubberized concrete, mix number 16 (Figure 5.8b), it increases to about 17.5 μm , indicating a significantly weaker and more porous interface between the paste and rubber. The rubber particles likely act as stress concentrators, reducing the efficiency of load transfer within the cementitious matrix. Compared to the 7.5% SR mixture, a further reduction in strength is observed, with values ranging from approximately 15 MPa to 25 MPa (Figure 5.7c). Particularly, by combining more than 12% BFA and 15% GP replacement, the compressive strength reaches approximately 25 MPa, indicating a significant improvement displays the effect of powders to enhance the SR/paste bond. However, the highest recorded strength of 25 MPa is lower than the 30–34 MPa range seen in the 0% SR mix, confirming the significant negative effect of rubber addition on concrete performance

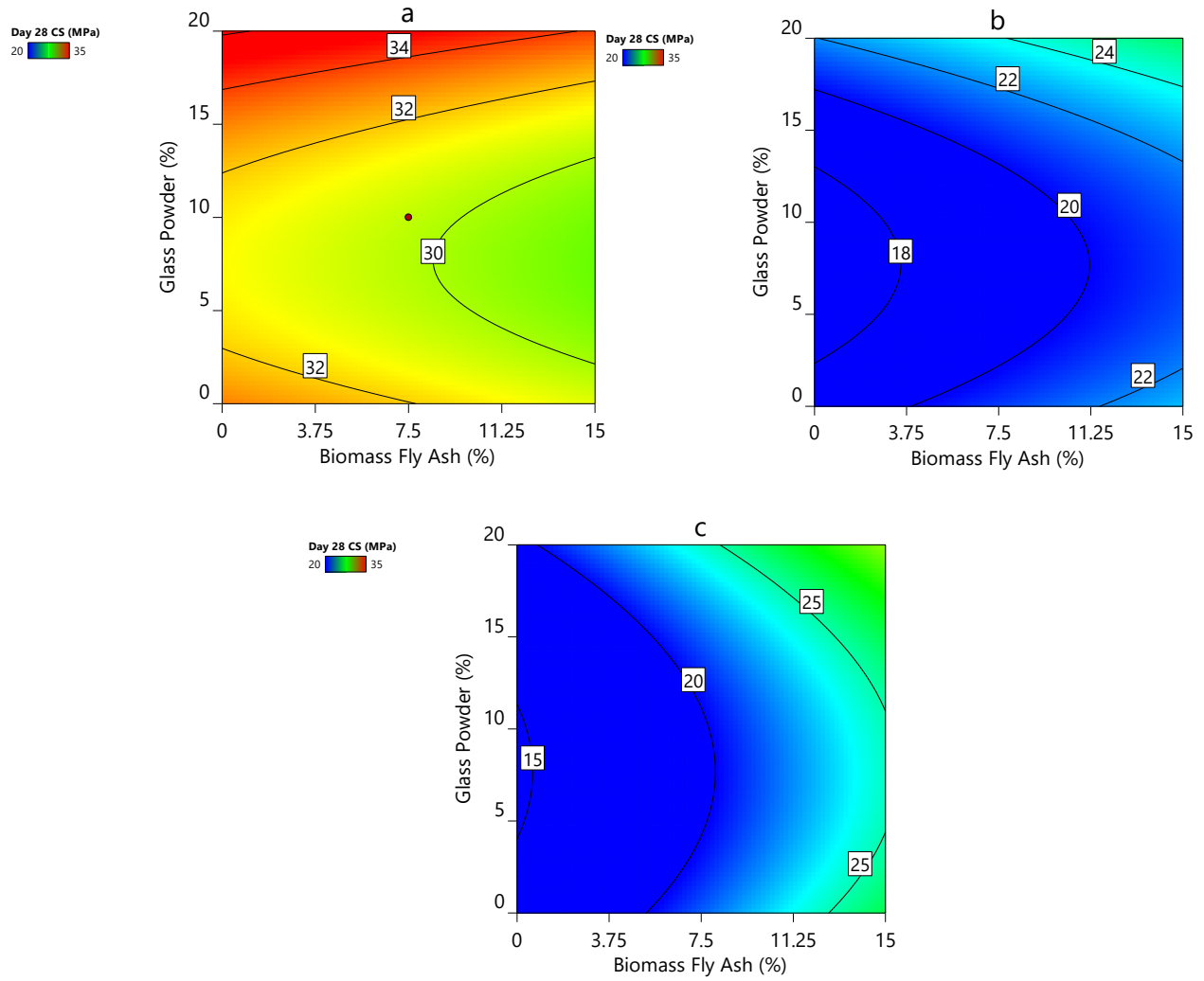


Figure 5.7: Compressive strength at the level of a) 0% SR, b) 7.5% SR, and c) 15% SR

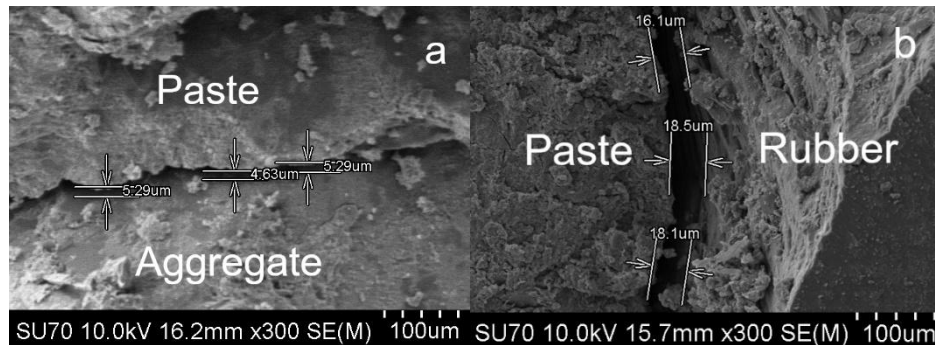


Figure 5.8: SEM images of (a) control sample showing paste–aggregate ITZ, and (b) Mix No. 16 (3% SR, 4% GP, 3% BFA) showing paste–rubber ITZ

5.4.7 Splitting tensile test (STS)

Figure 5.9 presents the STS results ranging from 1.5 to 2.5 MPa. Incorporating 20% GP significantly increased STS by 42% (Figure 5.9a), with improvements also observed at a 7.5% SR replacement level (Figure 5.9b). However, the effect of GP became insignificant at 15% SR (Figure 5.9c). BFA have a negligible impact on STS, and it rose by only 0.05 MPa when cement is replaced with 15% of BFA (Figure 5.9a). When 15% BFA is replaced at 7.5% and 15% SR levels, STS decreased by approximately 10% and 20%, respectively (Figure 5.9 b-c). This reduction is attributed to the weaker SR/paste bond.

SR does not substantially enhance STS; a 7.5% and 15% SR replacement leads to 0.25 MPa strength fluctuation compared to the control sample. The combination of 20% GP and 15% BFA resulted in the lowest STS value of 1.2 MPa, which further dropped to 0.2 MPa at 15% SR. This decline suggests that SR particles deteriorate the bond between the paste and aggregate, reducing friction and shear resistance.

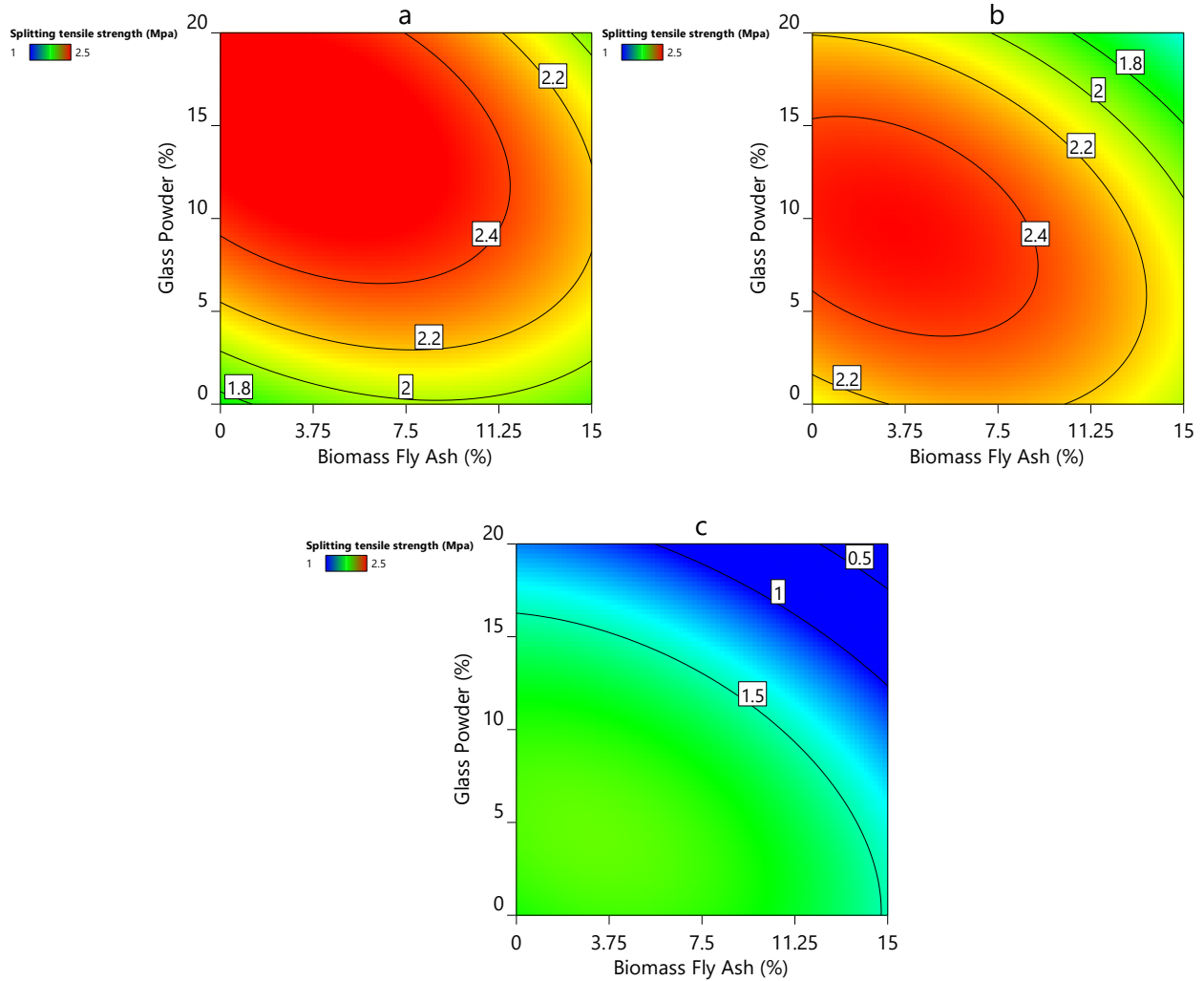


Figure 5.9: Splitting tensile test at the level of a) 0% SR, b) 7.5% SR, and c) 15% SR

5.4.8 Modulus of Rupture (MOR)

The trend of MOR approximately follows that of STS. Incorporating 20% GP in concrete mixes increased MOR by up to 16% (4.3 to 5 MPa) compared to the control sample (Figure 5.10a); however, its effect diminished at SR replacement levels of 7.5% and 15% by 4.5 MPa and 2.8 MPa, respectively (Figure 5.10b-c). Replacing cement with 15% BFA significantly reduce MOR by 42% (4.3 to 2.5 MPa) compared to the control sample, while replacing sand with 15% SR leads to a 30% (4.3 to 3 MPa) reduction in MOR. Similar to STS, the lowest MOR value (approximately 1

MPa) is observed at higher GP and BFA combinations (above 15%) at levels of 7.5 and 15% SR (Figure 5.10 b-c). Since concrete is weak in tension, a reduction in tensile properties can also adversely affect bending performance.

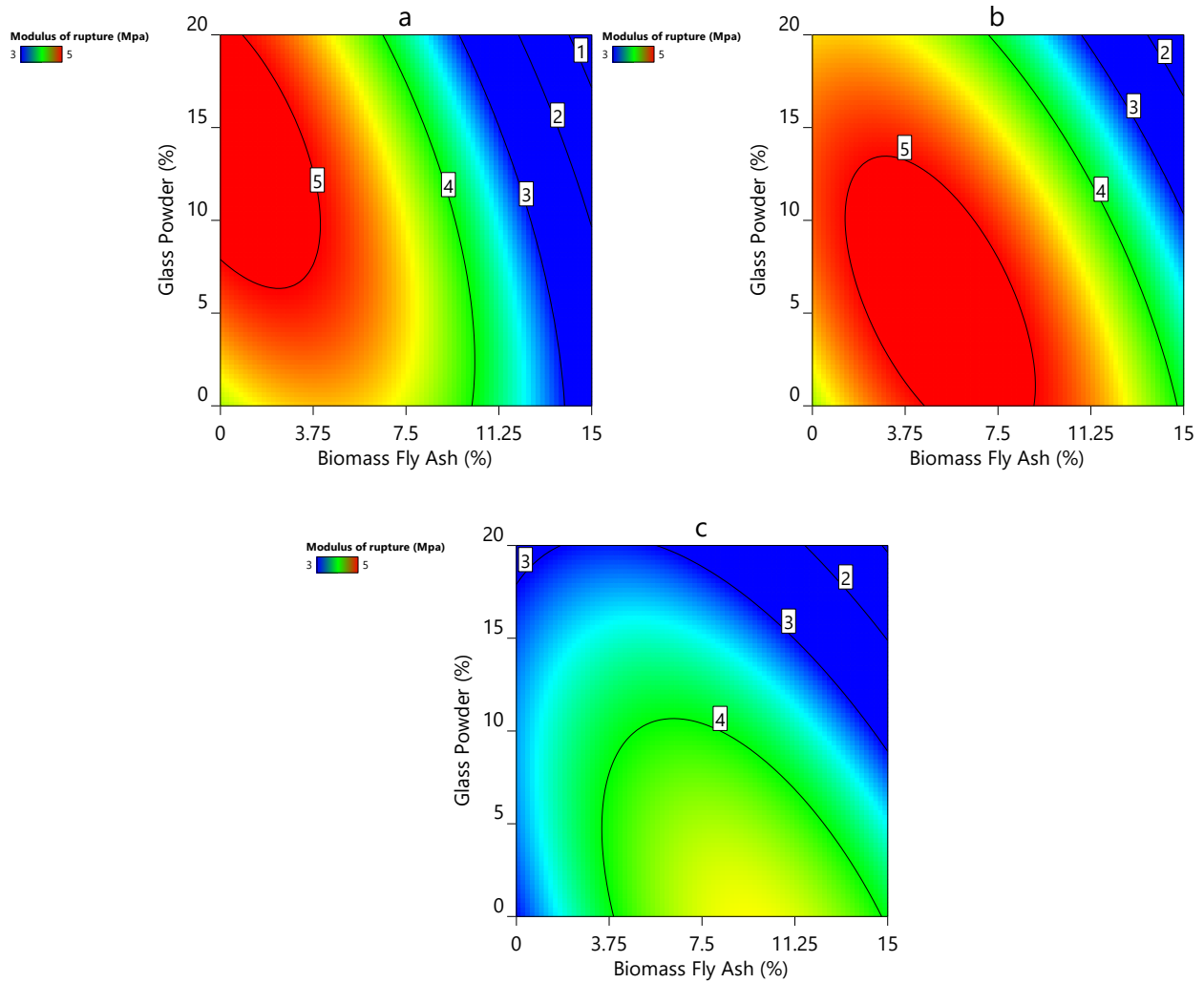


Figure 5.10: Modulus of Rupture at the level of a) 0% SR, b) 7.5% SR, and c) 15% SR

5.4.9 Surface electrical resistivity (SER)

Adding GP and BFA influences concrete's specific electrical resistivity (SER), which can indirectly indicate their impact on chemical reactivity. Replacing 20% of the cement with GP significantly increased SER by 240% (7 to 24 k Ω .cm) (Figure 5.11a). However, this increase is mitigated at higher SR replacement levels of 7.5% and 15%, resulting in only 7.5% and 15% increases in SER, respectively (Figure 5.11 b-c). Conversely, incorporating 15% BFA lead to a substantial 51% (7 to 3.4 k Ω .cm) decrease in SER compared to the control sample (0% BFA). This is attributed to the low SiO₂ content of BFA (2.79%), which results in reduced pozzolanic activity compared to GP. As seen from Table 5.1, the SiO₂ content of BFA is 67.28% less than that of GP. Furthermore, a combination of 7.5% and 15% SR with 15% BFA resulted in 46% and 59% reductions in SER compared to the mixes with 0% BFA.

SER increased by 210% at a 15% SR level alone, likely due to the SR's hindering effect on electrical conductivity. At 15% SR level, the influence of both GP and BFA on resistivity is diminished. GP showed a 22% reduction in its positive impact on SER, while BFA's negative impact is reduced by 59%. The highest SER, a 470% increase compared to the control, is observed in the mix containing 15% BFA and 20% GP without SR. This suggests the densest packing arrangement, where pores are filled by CSH gel, leading to increased resistivity and reduced electrical current flow.

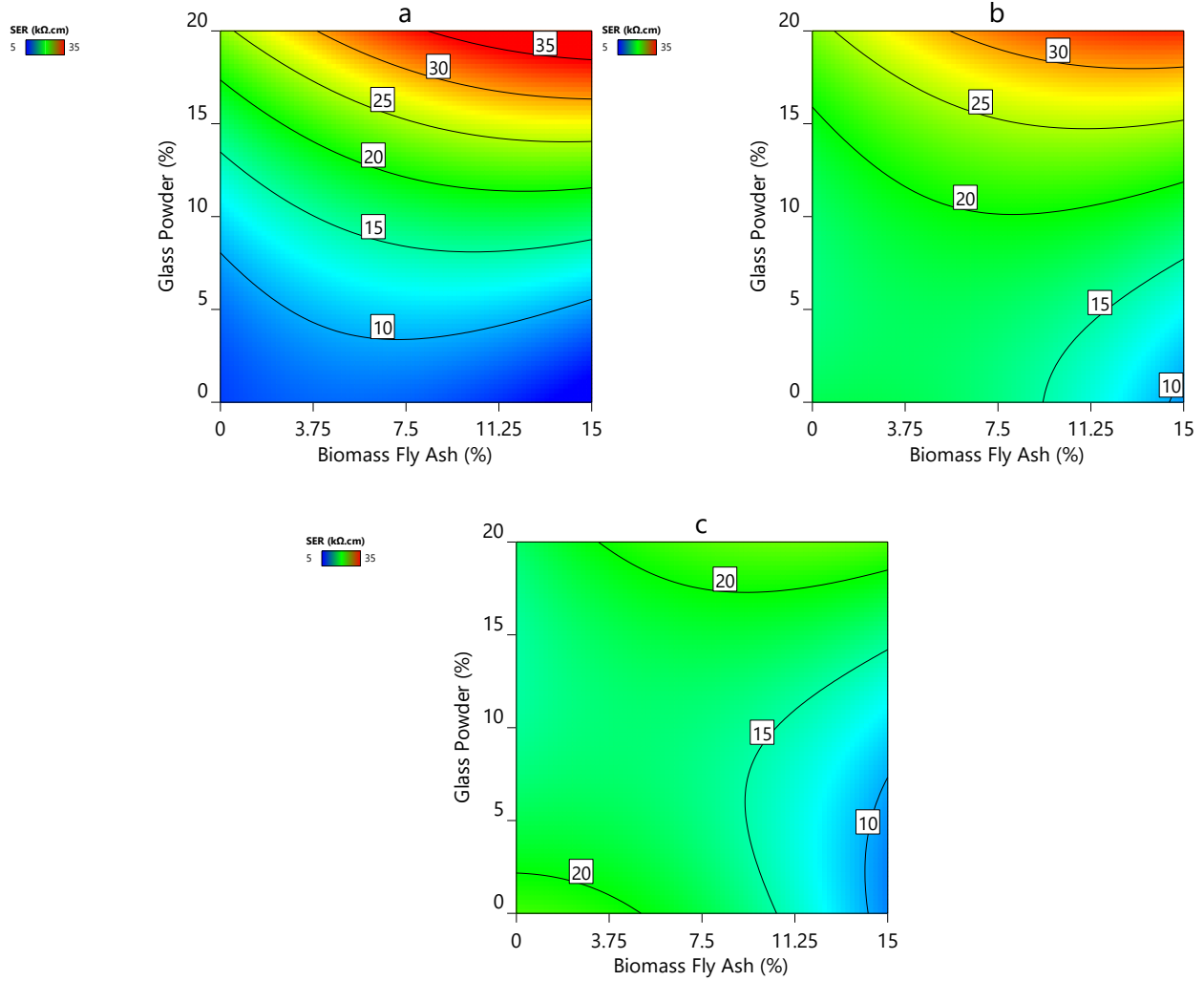


Figure 5.11: Surface Electrical Resistivity at the level of a) 0% SR, b) 7.5% SR, and c) 15% SR

5.4.10 Environmental impact

5.4.10.1 Life cycle assessment (LCA)

The life cycle assessment (LCA) in this study was conducted following the international standard ISO 14040 [249]. These standards define a structured framework comprising four main steps: Goal and scope definition, Life cycle inventory (LCI), Life cycle impact assessment (LCIA), and Interpretation. The life cycle of concrete includes production, use, and end-of-life stages. Calculating the Global Warming Potential (GWP) across these stages is crucial to determine the overall carbon footprint of concrete. This enables a better understanding of where emissions occur

and informs strategies to reduce environmental impacts. The emissions are calculated using the IPCC 2013 GWP 100a method [186], which is widely used for assessing long-term climate effects.

5.4.10.2 Goal and scope definition

The present study aims to calculate the GWP for the product stage, including raw material supply, transportation, manufacturing processes and end-of-life stages. Therefore, the system boundaries are set as cradle-to-grave. The functional unit (FU) is defined as 1 m³ of concrete to compare 17 single mix designs with varying proportions of BFA, GP, and SR.

5.4.10.3 Life cycle inventory (LCI)

The life cycle inventory (LCI) data for all materials and processes were collected using SimaPro software and primarily sourced from the Ecoinvent v3.0 database. This database was selected due to its comprehensive, high-quality global coverage and its compatibility with SimaPro. Based on standard batching procedures, the energy consumed during mixing was fixed at 0.076 kWh per m³. Since SR data are unavailable in the SimaPro database, its GWP was separately calculated based on Farina et al. [201]. Similarly, data for superplasticizer and BFA were sourced from [202]. The life cycle inventory of materials and processes is summarized in Table 5.8. Transportation emissions were calculated based on actual distances travelled for each material, as detailed in Table 5.9, reflecting realistic supply chain conditions. Except for GP and BFA collected from Winnipeg and Atikokan, respectively, other materials were supplied in Thunder Bay, where concrete was mixed and cast.

Table 5.8: Sources of data for concrete components

Materials or processes	Data source	Location
Cement, Portland	Ecoinvent 3.0	US
Glass powder	Ecoinvent 3.0	GLO
Biomass fly ash	[202]	GLO
Shredded rubber	[201]	GLO
Sand	Ecoinvent 3.0	GLO
Gravel, crushed	Ecoinvent 3.0	RoW
Superplasticizer	[202]	RoW
Tap Water	Ecoinvent 3.0	CA-QC
Mixing	Ecoinvent 3.0	GLO
Electricity, medium voltage	Ecoinvent 3.0	CA-ON
Transport, freight, lorry >32 metric ton	Ecoinvent 3.0	RoW
Final disposal	Ecoinvent 3.0	RoW

Table 5.9: Distances for material transportation

Material	distance (km)
Cement	5
Aggregate	3
Shredded rubber	4
Glass powder	700
Biomass fly ash	212

5.4.10.4 Life cycle impact assessment (LCIA)

The LCIA phase was conducted using the IPCC 2013 GWP 100a method in SimaPro to convert inventory flows into impact indicators (i.e. GWP). The emissions from each life cycle stage were characterized to estimate their contributions to overall CO₂-equivalent emissions.

5.4.11 Global warming potential (GWP)

Figure 5.12 presents the GWP, or released carbon emissions, of concrete samples incorporating varying proportions of GP, BFA, and SR. GP and BFA significantly contribute to GWP reduction (Figure 5.12a), as cement production is a significant source of carbon emissions. Compared to the control sample, replacing 15% of the cement with GP reduces GWP by 16% (342 to 285 kg CO₂). This reduction remains consistent at approximately 16% for SR levels of 7.5% and 15%, likely due to the minimal impact of SR and the relatively linear effect of GP (Figure 5.12b-c). BFA also reduce GWP by approximately 13% (342 to 296 kg CO₂) compared to the control, with a similar consistent reduction observed at 7.5% and 15% SR levels. The most considerable GWP reduction, 109 kg CO₂, is achieved with a combination of 20% GP, 15% BFA, and 15% SR, as all three materials contribute to lowering carbon emissions.

Replacing 15% of the sand with SR only reduces GWP by approximately 2% (Figure 5.12c). While sand doesn't contribute significantly to carbon emissions, its extraction depletes natural resources. Therefore, replacing part of the sand with SR offers a valuable recycling method for waste tires, mitigating environmental accumulation.

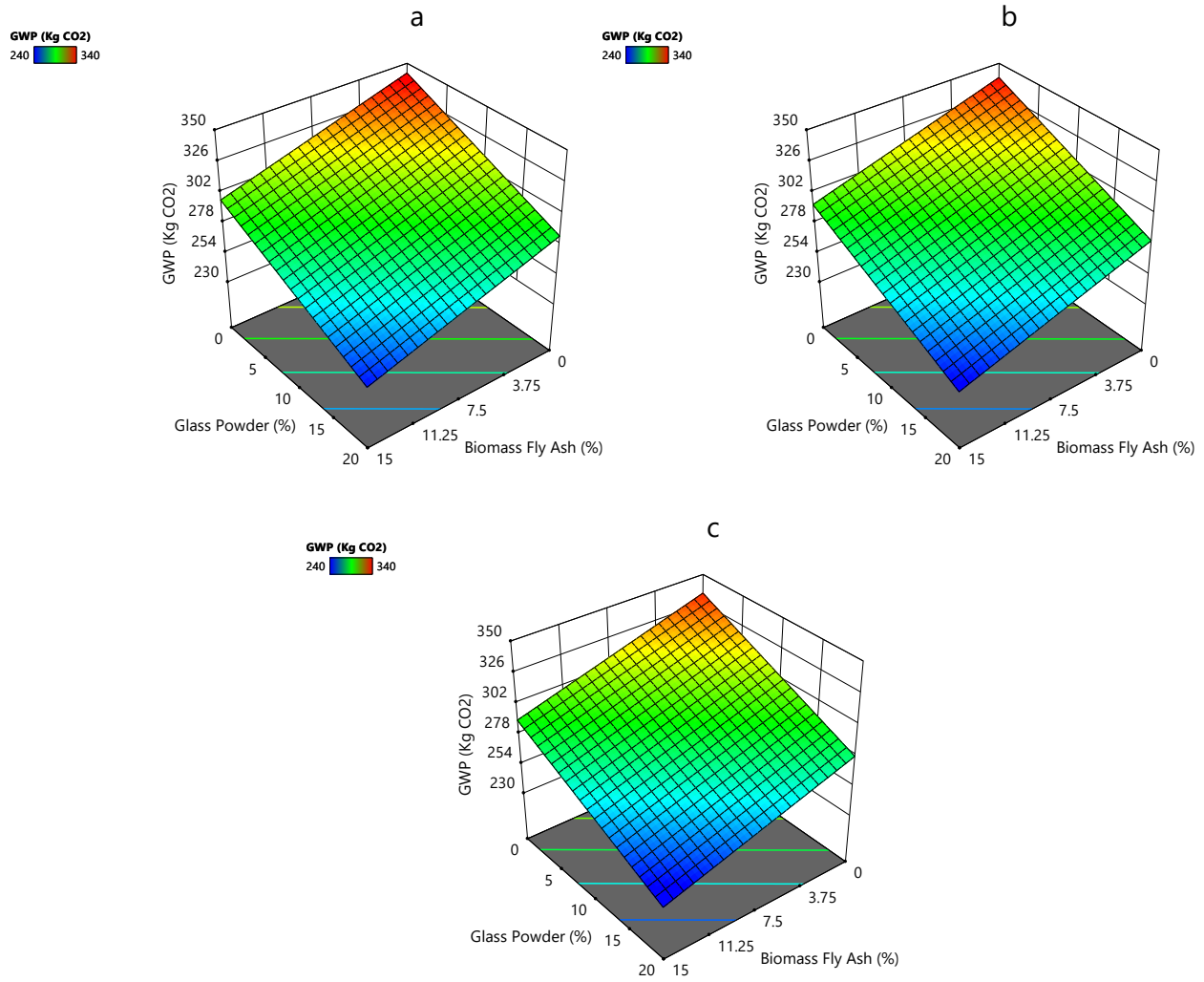


Figure 5.12: GWP at the level of a) 0% SR, b) 7.5% SR, and c) 15% SR

5.4.12 Dynamic Young's modulus of elasticity

The relationship between the dynamic Young's modulus of elasticity and GP and SR contents is shown in Figure 5.13, at BFA levels of 0, 7.5%, and 15% of the cementing binder. As shown in Figure 5.13a, incorporating 20% GP increases the dynamic Young's modulus of elasticity by 13% (38 to 43 GPa), likely due to the densification of the concrete matrix, which facilitates the

transmission of impact waves. Conversely, 15% SR decreases the dynamic Young's modulus of elasticity by approximately 11% compared to the control sample across all three BFA levels (Figure 5.13c). This reduction is attributed to the elastic resilience and energy absorption capacity of the SR aggregates, which dampen impacts within the concrete structure. Incorporating 15% BFA also resulted in an 8% (38 to 35 GPa) reduction in the dynamic Young's modulus of elasticity. Consistent with the findings of Zheng et al. [26], which determine an inverse relationship between Young's modulus of elasticity and damping ratio in rubberized concrete, the minimum Young's modulus of elasticity by 20.5 GPa is observed at 20% GP, 15% BFA, and 15% SR, suggesting the highest damping potential for this combination. However, the maximum dynamic Young's modulus of elasticity occurs with a combination of 0% SR, 0% BFA and 20% GP by 43 GPa.

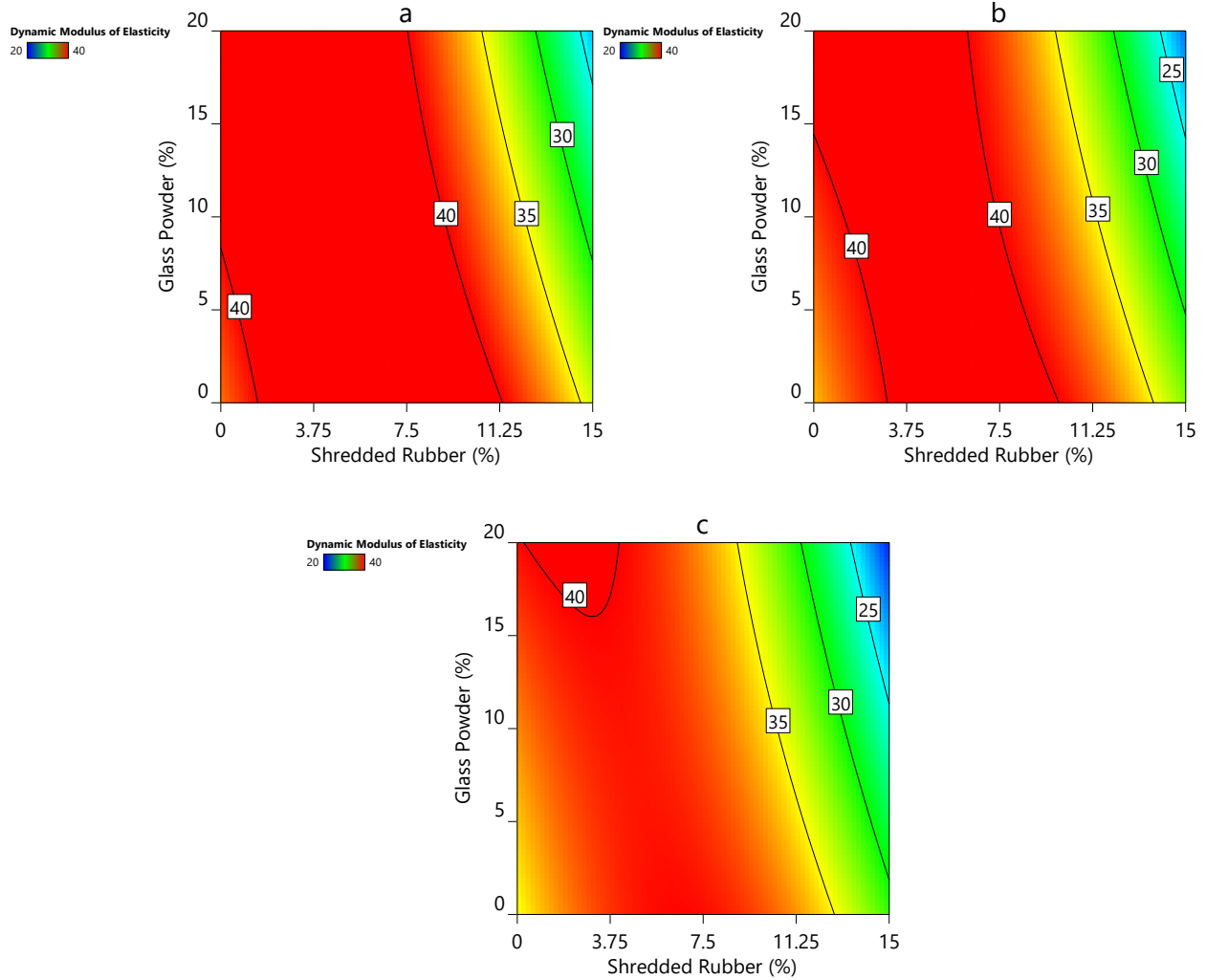


Figure 5.13: Dynamic Young's modulus of elasticity at the level of a) 0% BFA, b) 7.5% BFA, and c) 15% BFA

5.4.13 RCPT

The RCPT assesses the penetrability of all the concrete mixtures at day 90, and the results of the passing charges are shown in Figure 5.14. Figure 5.14-a illustrates a positive relationship correlating the increase in the GP dosage and a corresponding reduction in the passing charges values, reaching an 85% reduction (3855 to 582 coulombs) when 20% of GP is added, compared to the control sample. GP reacts pozzolanically with calcium hydroxide in the concrete, forming additional calcium silicate hydrate (C-S-H) [59]; therefore, the fine particles of glass powder

expand into larger pores and further limit the movement of chloride [250]. Figure 5.15 shows the RCPT sample for mix No. 16 (3% SR, 4% GP, 3% BFA) with high chloride penetrability, where the chloride penetration depth reaches 21.7 mm. On comparison, in Mix No. 6 (12% SH, 16% GP, 3% BFA), the chloride penetrability depth is only 5 mm. The transformation of a high chloride penetrable concrete (i.e., mix No. 16) into a low chloride penetrable concrete is attributed to filling of the pores by C-S-H gel when the glass powder (GP) is added. Samples containing more than 15% GP exhibit significantly reduced chloride ion penetration due to the enhanced formation of a dense C-S-H gel layer. This reduction in chloride ion permeability is observed even in combinations of 15%-20% GP with SR or BFA, as evidenced by chloride tests showing less than 1100 coulombs of charge passed for these mixes. For instance, Mix No. 6 (12% SH, 16% GP, 3% BFA) records only 674.07 coulombs of charge passed.

the SR effect is negligible, since the Coulomb values varied only by about 3% across the 15% SR range (Figure 5.14b-c), placing the concrete in the moderate classification of chloride ion penetrability. The incorporation of 15% BFA adversely affects the passing charges relative to the reference sample, with an increase of 33% (3856 to 5143 coulombs). Consequently, adding BFA places the concrete in the 'high chloride penetrability' category according to ASTM standards. However, both SR and GP demonstrate the capability to reduce the adverse effects of BFA on coulomb penetration, improving the penetrability class of the tested specimen. Incorporating 20% GP in a mix containing 15% BFA can decrease the passing charges by 78% (from 5143 to 1100 coulombs) compared to a mix without GP.

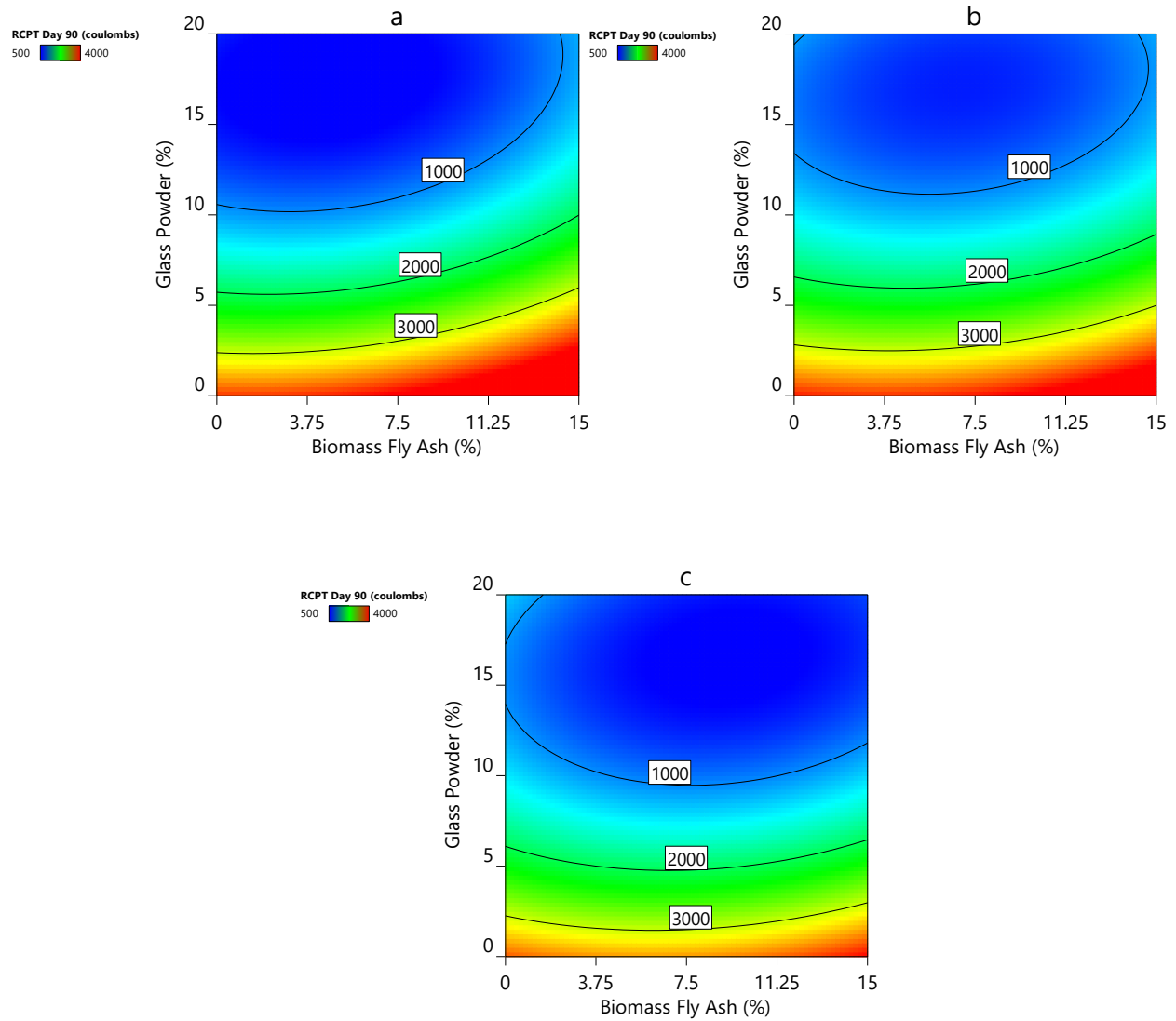


Figure 5.14: Day-90 Rapid Chloride Penetration Test (Coulombs) at a) 0% Biomass Fly Ash, b) 0% Shredded Rubber, c) 0% Glass Powder

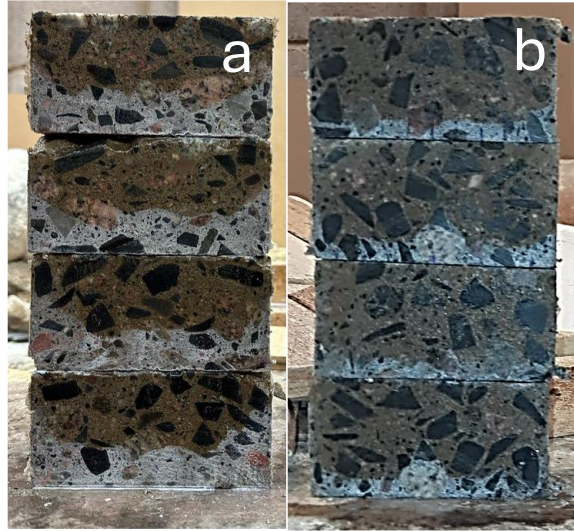


Figure 5.15: RCPT section photos for depth of penetration a) Mix No. 16 (3% SR, 4% GP, 3% BFA), b) Mix No. 6 (12% SR, 16% GP, 3% BFA)

5.5 Optimal space design

Due to the long duration of the freeze-thaw test (approximately two months, considering 5 hours per cycle), the resistance of concrete to freeze-thaw cycles is often assessed based on its air content, which provides a more practical and efficient alternative. [251]. According to the Federal Highway Administration (FHWA), the durability factor for grade three high-performance concrete should exceed 90% [252]. Meanwhile, the Canadian Standards Association (CSA) recommends an air content of 5% to 8% for concrete exposed to severe freeze-thaw conditions [244]. As shown in Figure 5.16, the hatched area represents concrete with an air content exceeding 5%, yet its durability factor remains below 90%. This suggests that a higher air content is necessary to ensure adequate durability, particularly when the concrete contains glass powder (GP) and biomass fly ash (BFA). Additionally, incorporating shredded rubber (SR) further reduces the mix acceptable durability range, with no suitable area observed at 15% SR content. However, designing concrete with optimal resistance to freezing and thawing requires considering multiple factors. An optimal range should be identified by balancing compressive strength, durability factor, global warming

potential (GWP), and air content. According to Concrete Ontario [203], a 30 MPa concrete mix should have a maximum CO₂ emission of 297 kg. Additionally, for medium freeze-thaw exposure, an air content of 5% [244] and a durability factor of 70% [252] are recommended (Table 5.10). As shown in Figure 5.17, the yellow area represents the optimal design space. Up to 15% biomass fly ash (BFA) and 16% glass powder (GP) can individually be used to meet the specified criteria. Additionally, a suitable combination of GP and BFA can fall within the optimal design space. However, incorporating shredded rubber (SR) significantly reduces this space, with no acceptable range observed at 7.5% SR content.

Table 5.10: Optimization constrains

Factors	Value
Air content	> 5%
Durability factor	> 70%
Compressive strength	> 30 MPa
GWP	< 297 kg CO ₂

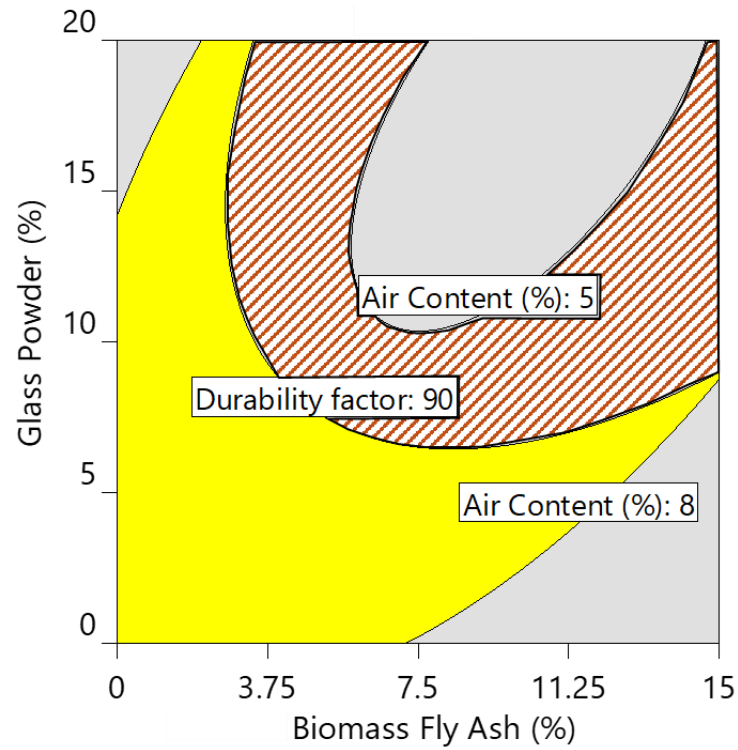


Figure 5.16: The relationship between air content and durability factor

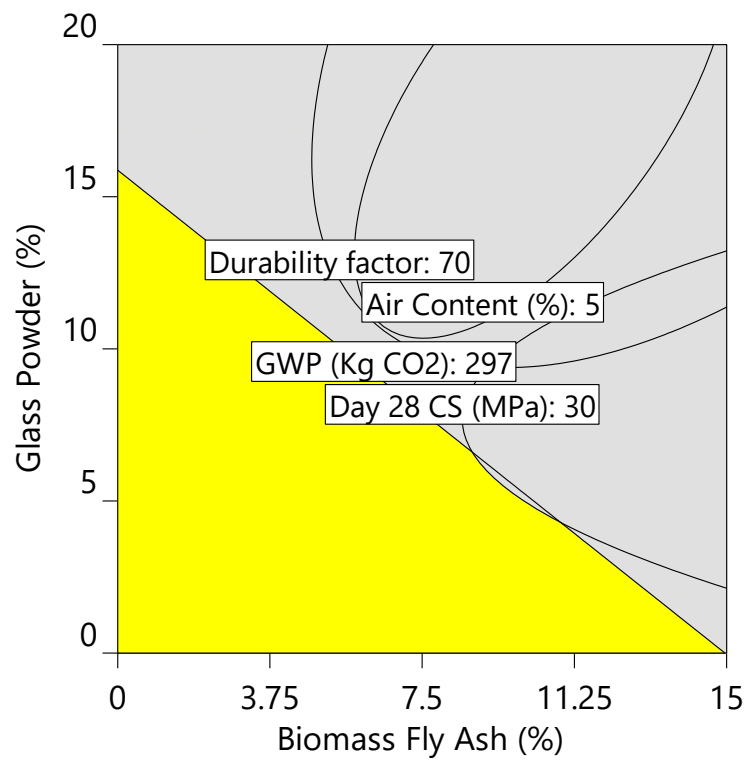


Figure 5.17: Optimal design space based on the constraints

5.6 Conclusions

This study evaluates the incorporation of glass powder (GP), biomass fly ash (BFA), and shredded rubber (SR) into concrete, focusing on their effects on durability, mechanical properties, and environmental impact.

- The addition of GP significantly enhances concrete durability, improving air content and freeze-thaw resistance. The air content increases by up to 20% GP, enhancing the freeze-thaw durability factor. However, combining GP with SR reduces the freeze-thaw durability when SR content exceeds 7.5%. The freeze-thaw durability factor drops at higher BFA levels (15%), especially in mixtures with 15% SR. The SER also improved with GP, demonstrating better resistance to electrical conductivity. However, the beneficial effects of GP are reduced when SR and high BFA content are combined. Overall, GP improves durability, while SR negatively impacts it, especially when combined with higher BFA levels.
- GP significantly improves compressive strength and STS, particularly at 20% replacement. Compressive strength increases with GP and is optimal at 20% GP and low BFA content. However, BFA negatively impacts both compressive strength and STS, with a more pronounced effect when combined with SR. SR reduce the mechanical properties, particularly in tensile strength and MOR, due to the weakened ITZ. Additionally, SR negatively impact the dynamic Young's modulus of elasticity, with reductions in stiffness observed at higher SR contents. The combination of 20% GP with low BFA produced the best mechanical performance, while SR resulted in a noticeable decline in strength.
- The environmental benefits of incorporating GP and BFA are substantial, reducing the GWP by 16% and 13%, respectively. The combination of 20% GP, 15% BFA, and 15% SR leads to the most significant reduction in GWP, highlighting the potential of these materials to lower the

carbon footprint of concrete. However, while SR contributes to environmental sustainability by recycling waste tires, it minimally reduces GWP.

- While CSA recommends 5%–8 % air content for severe freeze-thaw conditions, some mixtures in this study exceeded 5% yet fail to achieve the FHWA durability factor threshold of 90%, suggesting that higher air content is needed, especially with GP and BFA. Balancing durability, strength, and environmental impact, the optimal design space included up to 15% BFA and 16% GP. Combining these materials (up to 16%) could comply with restrictions while achieving a concrete strength exceeding 30 MPa, with a maximum GWP of 297 kg CO₂.

Despite promising results, this study has limitations. Conducted at the laboratory scale using small specimens, the results may not represent structural concrete members' behavior in real construction projects. The absence of microstructural analysis also limits understanding of material behavior. Furthermore, the economic implications of replacing cement with waste materials were not evaluated, leaving questions about cost-effectiveness unanswered. Therefore, future work should include large-scale testing, a comprehensive environmental assessment, microstructural studies, and an economic analysis to determine the financial viability of this approach. The integration of RSM-generated data with existing literature through artificial intelligence (AI) techniques can substantially improve the robustness and accuracy of predictive models.

CHAPTER 6: AI-BASED META MODEL FOR PREDICTING THE PERFORMANCE OF LOW-CARBON CONCRETE, CONSIDERING THE EFFECTS OF MULTIPLE WASTE MATERIALS

Note:

The manuscript had been slightly altered from the original paper by renumbering the tables and figures to include the chapter number. In addition, the reference list and list of notations have been moved to the appropriate sections in the thesis as indicated in the table of contents.

Abstract

Low-carbon concrete incorporating waste materials offers significant environmental benefits while maintaining structural performance. However, designing an optimal mix of these waste materials is challenging due to their potential impact on concrete properties. This paper presents a meta model based on a Multilayer Perceptron (MLP) neural network integrated with a Monte Carlo-based back analysis framework to capture the effects of waste materials, including shredded rubber (SR), glass powder (GP), and biomass fly ash (BFA), on concrete performance and identify the optimal mix design. The proposed mix design is validated through laboratory tests across four performance metrics: environmental (global warming potential), durability (rapid chloride permeability and bulk electrical resistivity), mechanical (compressive strength and splitting tensile strength), and workability (air content and slump). The results demonstrate the AI model's accuracy in predicting concrete performance using statistical accuracy measures, including root mean square error (RMSE), mean absolute error (MAE), and Coefficient of determination (R^2). Additionally,

the back analysis provides optimized mix designs tailored to specific performance constraints. According to the specified target for designing low-carbon, chloride-resistant, and normal strength (45–55 MPa) concrete, a mixture of waste materials with SR = 3.4026%, GP = 25.6%, and BFA = 6.92% is proposed by the developed meta model. To assess the accuracy, the proposed mix design was cast in a laboratory environment and subjected to the same experimental tests. The results show that the optimized mixed design achieves high accuracy, with predicted values falling within one-unit standard deviation of the mean values.

Keywords: *Waste materials, shredded rubber, biomass fly ash, glass powder, low-carbon concrete, artificial intelligence meta model, ANN*

6.1 Introduction

Incorporating waste materials in concrete has gained significant attention in recent years due to its potential to reduce environmental impacts, lower production costs, and improve concrete properties [253–256]. However, conducting precise experiments on the properties of concrete containing multiple waste materials remains a complex challenge. This complexity is particularly pronounced when evaluating the concurrent effects of various waste materials, each uniquely interacting with the concrete matrix. Isolating the individual contribution of each component to specific concrete properties becomes inherently challenging, while assessing their combined or synergistic impact on the overall performance of concrete adds a layer of difficulty due to potential interactions and nonlinear behaviors [257–260]. For example, the simultaneous use of glass powder and shredded rubber in concrete has captured the attention of some researchers in recent years [261–263]. Ramdani et al. [262] illustrated that the combined use of waste rubber aggregates and glass powder in concrete significantly improves its performance compared to waste rubber

alone. Although rubber aggregates reduced compressive and tensile strengths, adding 15% finely ground glass powder mitigated this adverse effect by strengthening the bond within the cement matrix through its pozzolanic activity. The optimal mix containing 10% waste rubber and 15% glass powder achieves a compressive strength exceeding 36 MPa at 28 days and 41.5 MPa at 90 days, demonstrating the synergistic benefits of combining these waste materials to produce durable and eco-friendly concrete [262]. In another study, the investigation of the simultaneous use of waste rubber particles (RPs) and glass powder (GP) in concrete revealed that their combination reduces workability and leads to a general decrease in compressive and tensile strengths compared to the reference mix. Slump tests showed a notable reduction in flowability, especially with higher RP content and larger particle sizes. Despite these effects, the mix with 5% RPs (3–5 mm) and 10% GP demonstrate the best balance of strength and workability among all tested combinations [261]. On the other hand, recent studies have shown the potential of wood ash as a partial substitution for cement in concrete, offering both environmental and economic advantages. Owing to its pozzolanic components, such as calcium oxide and silica, wood ash can potentially participate in the hydration process, thereby enhancing specific mechanical properties of concrete. Research indicates that optimal replacement levels around 10–15% improve compressive and tensile strengths, although higher dosages may negatively affect workability and durability. Given the variability in composition based on the source and combustion method, proper pre-treatment and characterization of wood ash are essential to ensure its suitability as a sustainable cementitious material [16,264–266].

Noticeably, most existing studies focus on just one or two types of waste materials and examine only a limited range of concrete properties, most commonly compressive strength or slump tests, thereby lacking a comprehensive evaluation of their broader impact on concrete performance [68–

71]. This is because evaluating concrete containing one or more types of waste material by considering all perspectives of strengths, durability, workability, and environmental impact is a lengthy, time-consuming and costly process that requires extensive experimental testing and analysis. Therefore, most studies only focus on a few parameters [73–75]. This highlights the need for more efficient and comprehensive predictive models that collectively address all four critical aspects of concrete performance.

In response to these limitations, researchers propose the development of an advanced AI-based meta model [267,268] to assess the above-mentioned concrete performance. Numerous studies have applied artificial intelligence (AI) techniques to predict the properties of concrete by incorporating waste materials [269–271]. Although these studies have contributed valuable insights, their scope remains limited; many have focused on a single type of waste material and primarily on optimizing the amount of waste based on the mechanical properties of the concrete [270]. Moreover, they overlook critical aspects such as durability (e.g., chloride permeability [272], bulk electrical resistivity [273], or environmental impacts such as carbon emissions [271]). For instance, Huang et al. [274] developed a neural network model to predict the compressive strength of rubberized concrete using 353 experimental data sets. While the model achieved high accuracy, it was limited to shredded rubber. It did not account for the combined effects of multiple waste materials and just predicted compressive strength, flexural strength, tensile strength, and elastic modulus [274]. Similarly, in the paper by Tvakoli et al. [275], waste glass powder as supplementary cementitious material is used to evaluate concrete compressive strength via AI prediction. A dataset of 1045 samples is collected from studies, and some machine learning models are tested. Among them, the Sparrow Search Algorithm–Extreme Gradient Boosting (SSA–XGB) model achieved the highest accuracy with an R^2 value of 0.9645 to predict actual compressive

strength values. However, the study lacked integration of other critical concrete properties, such as air content [275], splitting tensile strength (STS) [269], or other parameters for analyzing the effectiveness of fly ash in concrete. Researchers observed the effectiveness of glass powder in concrete from the perspective of compressive strength [276–278]. However, experimental works have proven that it can resist water and chloride ingress in concrete due to the reduction in pore size and connectivity of concrete and the increase in tensile strength and 28-day flexural strength [50,149,279]. Studies have demonstrated the application of various artificial intelligence (AI) models for predicting concrete properties include basic approaches such as Generalized Linear Models (GLM) as well as more advanced algorithms like Artificial Neural Networks (ANN), Deep Learning (DL), Decision Trees (DT), Random Forests (RF), Support Vector Machines (SVM), and Gradient Boosted Trees (GBT). Among these, ensemble methods like GBT and RF have shown superior accuracy due to their ability to model complex nonlinear relationships, while deep learning models have performed especially well with large datasets [280]. However, the present study adopts a novel approach by employing Back Analysis as a reverse-design method for optimizing concrete mix compositions. Unlike purely data-driven models that predict outcomes from inputs, Back Analysis starts from the desired mechanical performance and works backward to determine the optimal mix proportions by utilizing both numerical and experimental data.

The novelty of this study lies in the application of back analysis for designing concrete mix designs using waste materials. While most previous research has focused on predicting the behavior of concrete, this study reverses that approach, determining the optimal rate of waste material based on the desired mechanical properties of the concrete. Another significant innovation is the model's flexibility in handling multiple performance objectives. However, seven performance criteria are defined in this research; the model and algorithm are designed to accommodate any number of

additional objectives without causing a significant increase in computational complexity or convergence time. A further key innovation is introducing and implementing a non-deterministic mix design approach. Instead of assigning fixed values to mix components, statistical distributions are used, and the mean of each distribution is considered the representative value. In other words, this research is the first to incorporate the concept of uncertainty in concrete mix design in a practical and computationally measurable way.

This paper adopts a meta modeling approach that integrates a Multilayer Perceptron (MLP) neural network with a Monte Carlo-based back analysis to incorporate uncertainty in concrete mix design. The proposed model is trained on a hybrid dataset comprising both experimental data collected from literature and synthetically generated samples using statistical sampling techniques. The MLP is architected to learn nonlinear interactions among multiple input features, including waste materials proportions and mixture parameters, enabling accurate prediction of key concrete performance metrics including compressive strength (CS), slump (S), Global Warming Potential (GWP), Rapid Chloride Permeability Test (RCPT), Splitting Tensile Test (STS), Bulk Electrical Resistivity (EBR), and air content (AC). Beyond forward prediction, the model employed back analysis to identify optimal mix designs aligned with user-defined performance criteria. This dual capability defines the scope of the present work, which is to develop a predictive and optimization model for proposing low-carbon concrete mix designs.

6.1.1 Research Significance

Based on the reviewed articles, it is found that most of the research conducted in investigating the strength of concrete with waste materials involves only one waste material at the AI scale or, at most, two waste materials within the concrete. Moreover, the parameters under investigation are typically limited to compressive strength and slump. However, adding waste materials to concrete

requires evaluating other strengths, workability, and durability parameters. On the other hand, it is noteworthy that researchers in their AI projects have used data from previous studies for training purposes. In contrast, this research aims to comprehensively cover the topic and ensure practical data training by utilizing data from previous studies and data generated through RSM software. Therefore, the combined effects of multiple waste materials have been insufficiently explored, leaving a gap in understanding their complex interactions.

6.2.1 Data Generation from Experiments and Existing Statistical Relationships

The authors' previous studies have extensively investigated the performance of concrete samples containing multiple waste materials [281]. These experiments covered a wide range of tests, including S, CS, RCPT, GWP, BER, AC, and STS. The results of these experiments, statistical analyses, and corresponding empirical equations have been published in other articles [282]. The equations used in this study are based on the mentioned paper and are brought to Appendix 6.1.

For each parameter involved in the problem, a precise range of variation is defined, as present in Columns 5 and 6 of Table 6.1. For instance, the SR content, used as a partial replacement for sand, ranged from 0% to 15%, the GP and BFA, both serving as partial replacements for cement, varied from 0% to 30% and 0% to 15%, respectively. Subsequently, a set of synthetic samples is generated, ensuring that these samples not only fall within the defined ranges for each parameter but also follow a uniform distribution. On the other hand, the density of distribution is the same throughout the range. Uniform sample generation ensures that the synthetic samples comprehensively cover the entire range of variations and provide diverse and reliable data.

6.2.2 Data Collection from the Literature

This study seeks experimental studies that incorporate at least one of the waste materials, including X(Shredded rubber), Y(Glass powder), and Z(Biomass fly ash). Initially, a relatively large number of studies involving these waste materials were compiled from the literature. Subsequently, studies are organized based on the similarity of chemical and physical properties of their materials to those used in this research, ensuring practical comparability with respect to material characteristics. Specifically, a range of variations is defined for the properties of the waste materials. If the waste materials in the literature studies fall within this range, they are included as samples in the dataset. The selected papers must have conducted and reported at least one of the experimental tests referenced in this study. In cases where the reported data from the studies use different units (e.g., imperial and SI units), all units are standardized to ensure proper comparison and facilitate their use in the neural network training process.

As a result, this technical literature review collected 64 papers, each containing several tested samples. The data is carefully gathered and compiled. A summary of the selected studies, the waste materials used in them, and the types of laboratory tests conducted are provided in Appendix 6.2 in the appendix section of the paper. Based on the entire dataset collected from the literature, the input parameter variations are reported in columns 3 and 4 of Table 6.1.

Table 6.1: Range of variation for the parameters involved in the problem

Num.	Parameter	Derived from the Literature		Assumptions for Generating Synthetic Data	
		Min	Max	Min	Max
1	Shredded Rubber (X) (% of sand)	0	100	0	15
2	Glass Powder (Y) (% of cement)	0	60	0	30
3	Biomass Fly Ash (Z) (% of cement)	0	70	0	15
4	Cement (kg/m ³)	98	600	340	340
5	Water to Binder (%)	30	68	46	46
6	Super Plasticizer (% of cement)	0	2.4	1	1

The data generated by the formula is highly accurate within a specific range, for example, 0 to 15% for shredded rubber, and numerous values can be produced within this range. In contrast, the data collected from the literature review consists of a few discrete points, not distributed values like formulas, typically providing results at fixed percentages such as 0%, 25%, 50%, and 100%. We combined these two datasets to expand the range and improve the overall accuracy of our analysis. Combining these synthetic data with the literature-based data ensured two key objectives: (1) the full expected range of parameters is covered, and (2) both direct experimental results and previously established statistical studies are incorporated into the dataset. This approach enhances the coverage and inclusivity of the dataset, ultimately improving the accuracy and reliability of the predictive models.

6.3 Meta Modeling

The dataset collected from the literature and previous statistical studies is a resource for training a meta model. To this end, the data package was first organized into a matrix, where the inputs (cement, W/B, shredded rubber (SR), glass powder (GP), biomass fly ash (BF), and

superplasticizer (SP)) and outputs (slump (S), compressive strength (CS), global warming potential (GWP), rapid chloride penetration test (RCPT), splitting tensile strength (STS), air content (AC), and bulk electrical resistivity (BER)) are systematically arranged. The dataset is split into training and testing subsets with an 80/20 ratio. Specifically, approximately 80% of the data is used to train the meta model, while the remaining 20%, which the model had not seen before, is used to evaluate its predictive accuracy.

This data management structure is schematically illustrated in Figure 6.1.

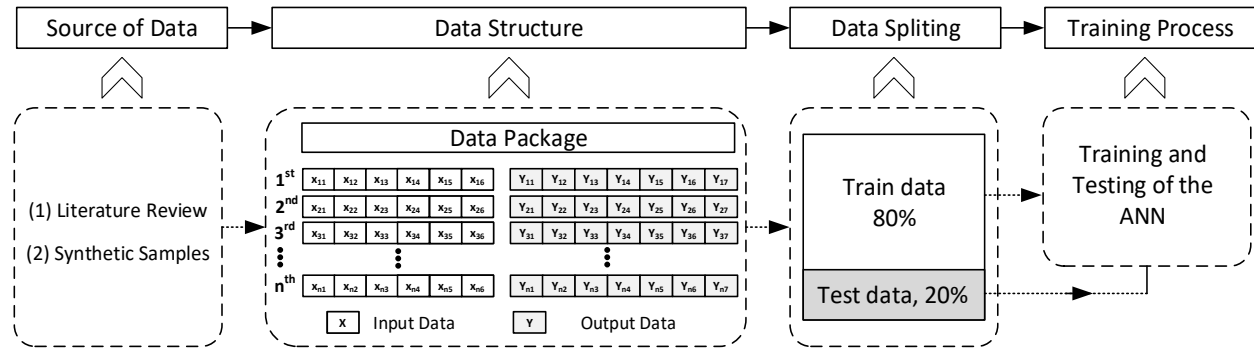


Figure 6.1: Data structure for meta model training

The architecture of the neural network employed in the meta model consists of an input layer with seven neurons (one neuron for each variable), three hidden layers with 7, 5, and 3 neurons, respectively, and an output layer with seven neurons (one neuron for each output variable). This configuration is determined after experimenting with a wide range of neuron combinations in each layer, and was found to be the most effective in terms of model accuracy and generalization. A schematic representation of this neural network is shown in Figure 6.2. The Levenberg-Marquardt (LM) optimization method was used to optimize the network weights and train the model.

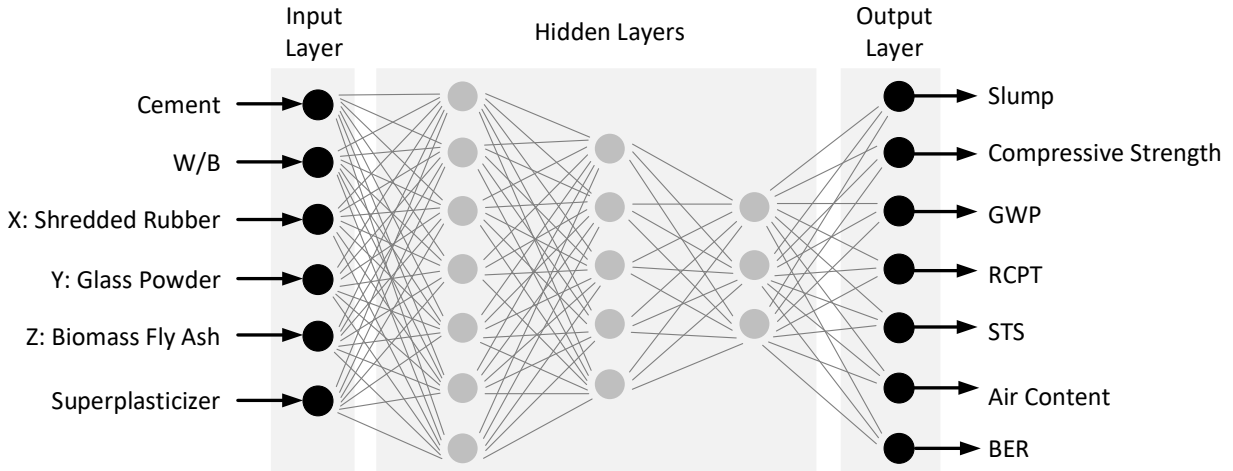


Figure 6.2: Schematic representation of the trained neural network

To evaluate the accuracy of the proposed neural network, the predicted values for each test data sample are plotted alongside their actual values, providing a visual criterion for assessing the network's accuracy. These plots, which encompass the prediction results for all neural network outputs, are presented in Figure 6.3. These plots show that the neural network accurately predicts the outputs for almost all test data, which were not seen during the training process. This demonstrates the network's strong capability to learn the patterns within the data and generalize them to new, unseen data.

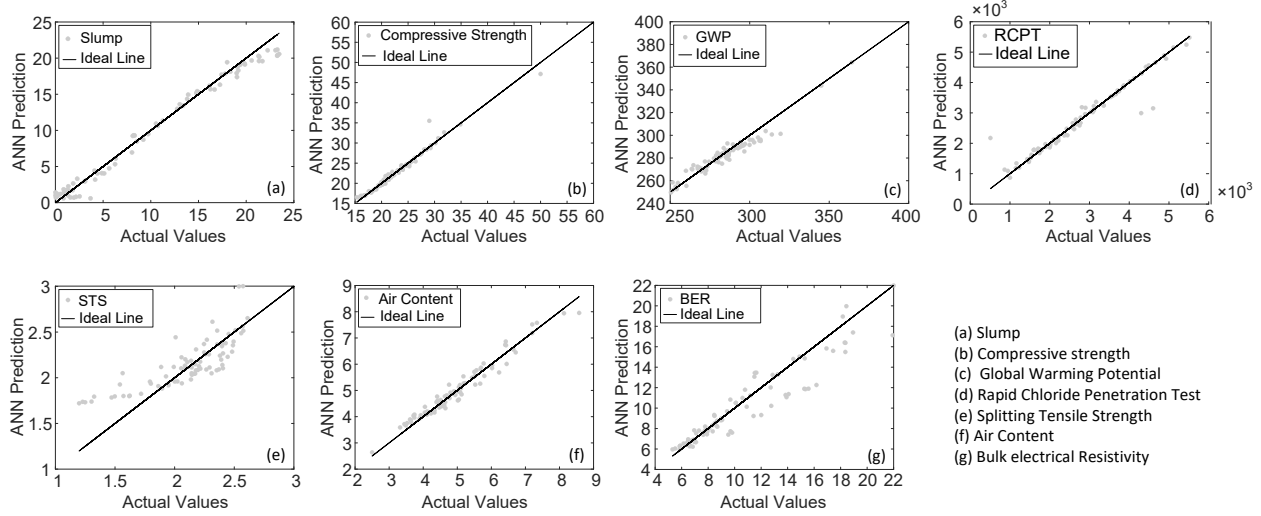


Figure 6.3: Actual Values vs ANN prediction for all output variables

To further examine this, three evaluation metrics, RMSE (Root Mean Square Error), MAE (Mean Absolute Error), and Coefficient of Determination (R^2), are calculated for each output of the model on test datasets. These values are presented in Table 6.2. As seen, the R_2 values exceed 0.9 for all tests, indicating a strong correlation between the predicted and actual values.

Table 6.2: Evaluation metrics for ANN outputs based on the test datasets.

Evaluation metrics	S^1	CS^2	GWP^3	$RCPT^4$	STS^5	AC^6	BER^7
RMSE	2.06	0.44	13.62	6.98	0.02	0.09	3.53
MAE	0.83	0.45	4.57	102.23	0.15	0.19	0.84
R^2	0.98	0.99	0.94	0.97	0.94	0.96	0.91

Slump¹, Compressive strength², Global warming potential³, Rapid chloride penetration⁴, splitting tensile strength⁵, Air content⁶, Bulk electrical resistivity⁷.

6.4 Discussion on ANN results

The slump test results corresponding to three different SR levels are illustrated in Figures 6.4 (a1-a3). As observed, at the zero SR level, increasing the BFA content by 15% resulted in a reduction of approximately 70% in slump. This behavior is attributed to BFA's physical and chemical

characteristics [107]. The elevated water absorption associated with BFA is mainly due to its high unburned carbon content, which contributes to a pronounced decrease in slump. In contrast, incorporating GP at levels up to 30% resulted in minimal changes in slump, less than 7%, demonstrating its limited effect on workability. This stable performance is attributed to the inherent characteristics of GP, which, as a predominantly pozzolanic material, does not significantly affect the fluidity of the mix when used in moderate replacement ratios [283]. At SR replacement levels of 7.5% and 15%, incorporating BFA consistently lead to a slump reduction of around 65%, indicating a substantial adverse effect on workability. In contrast, adding GP under the same SR levels (i.e., 7.5% and 15%) significantly improves slump, with increases of approximately 26% and 55%, respectively. Nevertheless, when the BFA content exceeds 10%, the combined presence of GP and SR is still insufficient to maintain adequate workability, with slump values dropping below 6 cm. SR plays a significant role in this reduction, especially at replacement levels above 7.5%. This is mainly due to the coarse surface texture of rubber particles, which hinders flow and reduces the overall fluidity of the concrete mix.

According to the data, the control concrete mix (without supplementary materials) achieved a compressive strength of 31.5 MPa. As shown in Figure 6.4 (b1), replacing 30% of cement with GP resulted in a 23.1% increase in compressive strength compared to the control. This improvement is primarily due to the pozzolanic activity of GP, which enables it to react with calcium hydroxide in the cement paste, forming additional calcium silicate hydrate (C-S-H). The formation of C-S-H enhances the binding within the cement matrix and contributes to a more refined and compact microstructure. In addition to its chemical reactivity, GP is an effective micro-filler, reducing porosity by occupying voids within the mix. The combined effects of matrix densification and C-S-H formation result in a notable compressive strength enhancement [146]. The impact of GP on

compressive strength is reduced when SR is added to the mix. At SR levels of 7.5% and 15%, the strength gain associated with GP drops to 15% and 6%, respectively Figure 6.4 (b2-3). This reduction is likely due to the disruptive effect of rubber particles on the cement matrix. However, the high silica content of GP continues to form the C-S-H gel, which remains beneficial to strength development. In contrast, adding 15% BFA has a negligible influence on compressive strength, offering only a modest improvement of around 4%. Mechanical performance of BFA typically falls short compared to Class F fly ash. This is primarily due to its inconsistent chemical composition, suboptimal particle size distribution, slower hydration kinetics, and lower pozzolanic reactivity [234]. A notable synergistic effect is observed when BFA and GP are combined. Incorporating 15% BFA and 30% GP leads to a compressive strength of 47.6 MPa, representing a 51% increase compared to the control mix. However, at higher SR levels, such as 15%, this strength decreases to 42.7 MPa. This reduction is attributed to the adverse influence of SR on compressive strength. Two main factors contribute to this decline: first, the elastic nature of rubber makes it significantly less stiff than conventional aggregates, leading to deformation under load and a consequent reduction in concrete stiffness and internal cohesion. Second, the presence of rubber increases drying shrinkage, which promotes microcracking and further weakens the mechanical performance of the concrete [284].

In this study, the GWP of concrete mixtures incorporating GP, BFA, and SR ranged between 190 and 325 kg CO₂ Figure 6.4(c1-3). The control mix, containing only ordinary Portland cement, exhibited the highest GWP at 325 kg CO₂. When 30% of the cement is replaced with GP, the GWP drops by approximately 19%, reaching 263 kg CO₂ Figure 6.4 (c1). This significant reduction is primarily due to the substantially lower GWP associated with GP production than cement [285]. In contrast, replacing 15% of cement with BFA resulted in a negligible GWP reduction of less than

1%. Although BFA emits less CO₂ during its production than cement, the difference is insufficient to lower the overall GWP meaningfully. As a result, the environmental benefit of BFA in terms of carbon footprint reduction is minimal in this context [286]. Notably, the release of carbon from burning biomass is considered in the GWP assessment by some references. However, in another scenario, it could be excluded, as the primary purpose of burning biomass is often electricity generation, not the production of BFA. The released carbon in the second scenario is much lower. The combination of 30% GP and 15% BFA results in a 28% reduction in GWP compared to the control mix. Incorporating SR in concrete also reduces the GWP. Concrete mixtures containing 7.5% and 15% SR reduce GWP to 291 kg and 289 kg CO₂, respectively Figure 6.4 (c2-3). The most significant reduction is observed when 30% GP, 15% BFA, and 15% SR are used together, bringing the GWP down to 135 kg CO₂, representing a 41% decrease relative to the reference mix. As illustrated in Figure 6.4 (d1-3), the RCPT values across the tested mixtures range from 580 to 4200 coulombs. For the control sample, the RCPT is recorded at 3584 coulombs. However, replacing 30% of cement with GP results in a dramatic 83% reduction in chloride ion permeability, lowering the RCPT to 583 coulombs Figure 6.4 (d1). The resulting C-S-H gel enhances the microstructural density of the concrete, effectively filling pore spaces and limiting pathways for ion penetration [50]. Consequently, the permeability of the concrete is significantly reduced, as reflected by the substantial decrease in RCPT. In contrast, a 15% increase in BFA leads to a 17% increase in chloride ion penetration compared to the control sample. This is due to the lower reactivity of BFA with cement.

The combination of waste materials results in various outcomes. At medium and high levels of SR (i.e., 7.5% and 15%), a 30% replacement of GP still results in an 80% reduction in chloride ion penetration Figure 6.4 (d2-3). However, a 15% increase in BFA at the 7.5% SR level leads to a 16%

increase in RCPT, while at the 15% SR level, the same amount of BFA replacement causes an 8% reduction in chloride ion penetration. BFA alone increases porosity and water absorption in concrete, which results in higher chloride ion penetration [143]. Furthermore, combining any level of BFA and SR with high amounts of GP (25%) consistently reduces RCPT, such that RCPT values for these combinations always remain below 1000 coulombs. However, a 7.5% and 15% increase in SR leads to a 13% and 21% reduction in chloride ion penetration, respectively, Figure 6.4 (d2-3). Using SR in concrete reduces chloride ion penetration, as it increases electrical resistivity, alters pore structure, and improves the hydrophobic properties of concrete. These characteristics prevent chloride ion movement; however, the amount and method of incorporating rubber into concrete are essential, as excessive replacement increases porosity and negatively affects concrete durability [287].

When 30% GP and 15% SR are used, the STS value is approximately 2 MPa lower than when 30% GP and no SR are used, as shown in Figure 6.4 (e1-3). On the other hand, a 15% increase in BFA leads to a 34% reduction in STS compared to the control mix. This reduction reaches 28% and 20% at SR levels of 7.5% and 15%, respectively. Due to the lower reactivity of BFA compared to cement, the mechanical properties of concrete weaken. Similarly, using 15% SR in concrete also results in a 34% decrease in STS relative to the control mix. The addition of rubber particles to concrete reduces its tensile strength, as rubber has lower hardness than cement, leading to weak spots within the concrete that are prone to cracking and stress concentration. These weak zones cause the concrete to fail under lower stress levels. Moreover, as the rubber content increases, the non-homogeneous structure of the concrete becomes more pronounced, leading to less consistent tensile strength results. In other words, the presence of rubber particles creates weak regions in the concrete, which reduces tensile strength and consistency [288]. The lowest STS value, equal to 2

MPa, occurs when 15% BFA and 15% SR are combined without GP Figure 6.4 (e3). In contrast, the highest STS value is achieved when 30% GP is incorporated into the concrete mix.

As shown in Figure 6.4 (f1), the results show that AC in the control sample is 5.25%. With a 15% increase in BFA, the AC value increases by 49% as shown in Figure 6.4 (f3). Adding BFA increases porosity and water absorption, resulting in higher AC in the mortars. This increase in AC is attributed to the presence of BFA [280]. The high amount of unburned carbon present in BFA, which includes porous biochar with a large surface area, is the main factor contributing to the increase in AC [163]. In addition, a 30% increase in GP has no significant effect on AC, with only a 2.7% reduction observed. Similarly, a 15% increase in SR shows little impact on AC, causing only a 1.5% decrease compared to the control sample. This is because SR replaces some fine aggregates in the mix. Moreover, although rubber particles increase porosity and thus air content due to the formation of large voids within the cement paste, this issue may not arise if the rubber is well-dispersed within the matrix [52]. The lowest AC value is obtained in the mix containing 7.5% BFA and 15% GP, which increases concrete density and reduces the AC to a minimum of approximately 3% Figure 6.4 (f1-3).

As shown by the results of the BER in Figure 6.4 (g1-3), a 30% increase in GP leads to a 72% increase in BER, compared to the control sample. This is attributed to the pozzolanic reaction of GP, which improves the pore structure by reducing porosity [145]. This increase is due to the greater reactivity of GP and the formation of C–S–H gel, which has a pore-filling effect and consequently enhances electrical resistivity [50]. A 15% increase in BFA also raises the electrical resistivity from 8 k Ω ·cm to 10 k Ω ·cm, Figure 6.4 (g1). At early stages, mortars containing BFA exhibit lower electrical resistivity than the reference mortars, since the pozzolanic reactions between BFA and calcium hydroxide produced by cement hydration proceed more slowly. This

reaction delay initially results in a less dense mortar structure, leading to lower resistivity. Over time, as the pozzolanic reactions progress, the mortar structure becomes thicker, and its electrical resistivity increases accordingly [143]. In addition, replacing 15% of the aggregates with SR leads to a 1.5 k Ω ·cm decrease in electrical resistivity Figure 6.4 (g3). The SR specimens showed lower electrical resistivity compared to the control sample. This reduction is attributed to the prolonged moisture retention within the concrete structure, as concrete containing SR remains wet for longer [289]. Combining 15% GP with any range of BFA and SR maintains the BER value above 15 k Ω ·cm. The highest measured BER value, equal to 23.5 k Ω ·cm, is obtained when a combination of 15% BFA, 30% GP, and 15% SR is used [290].

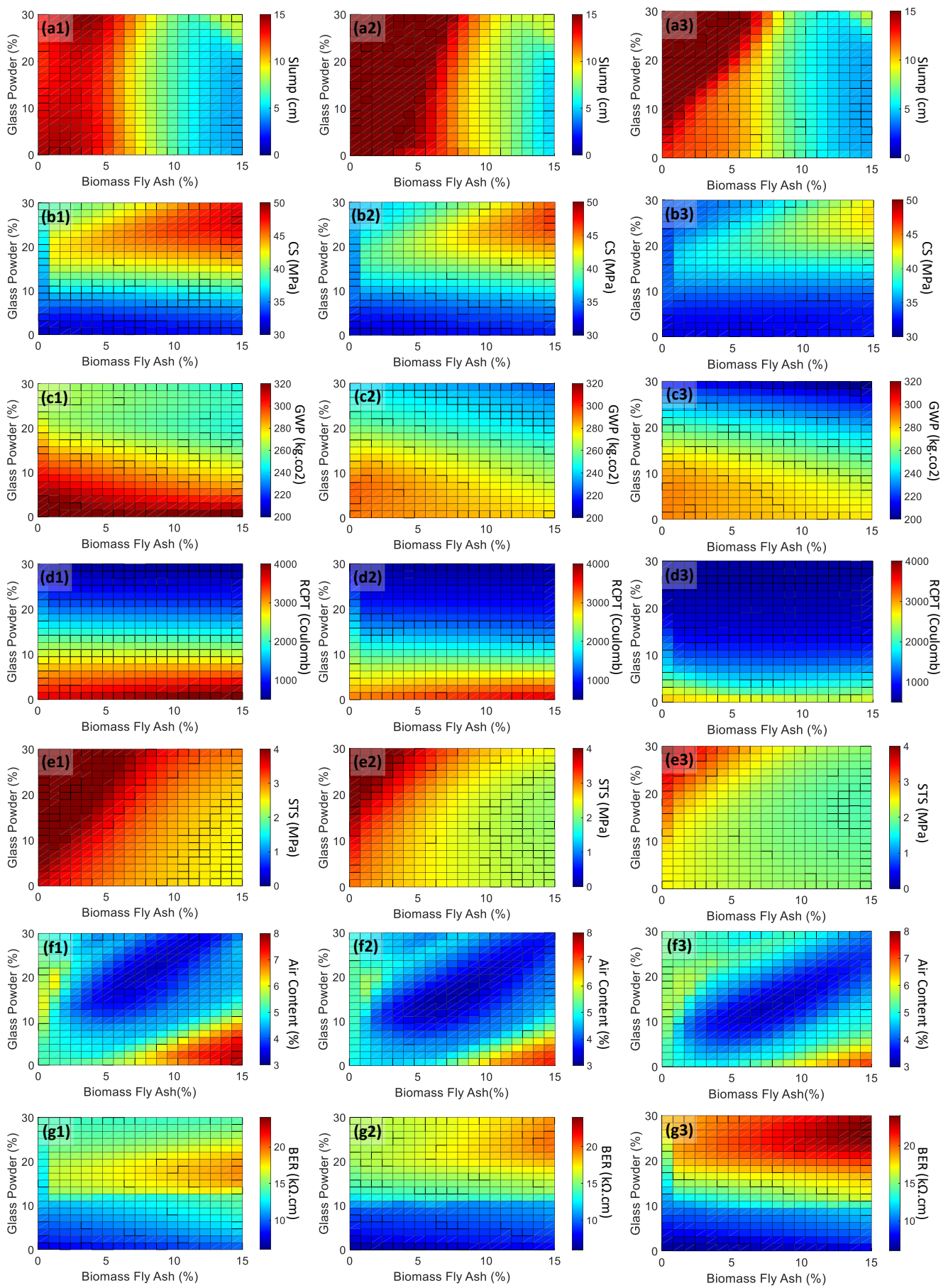


Figure 6.4: Results of seven tests conducted on mixtures at three SR replacement levels. Each group of subfigures corresponds to a specific test, and subfigures 1, 2, and 3 represent SR

contents of 0%, 7.5%, and 15%, respectively. S (a1-a3), CS (b1-b3), GWP (c1- c3), RCPT (d1-d3), STS (e1-e3), AC (f1-f3), BER (g1-g3).

6.5 Optimal mix design algorithm

6.5.1 Target concrete behavior

Incorporating waste materials into concrete offers an approach to sustainable construction but poses challenges, particularly in relation to their impact on the mechanical properties and durability of the concrete. Thus, optimizing their content is essential to ensure consistent and reliable performance.

In this context, a neural network trained on the experimental data collected in the previous section predicts key concrete behavior parameters, including CS, S, RCPT, GWP, BER, AC, and STS. The model inputs include water content, cement, superplasticizer, and waste materials (i.e., GP, BFA, and SR). This analytical tool enables a precise assessment of the effects of varying the proportions of waste materials on concrete behavior, providing reliable results. In other words, optimal percentages of waste materials are identified using the trained neural network to achieve the desired concrete performance. This study assesses concrete resistance to chloride ion penetration, a key criterion for evaluating durability in corrosive environments. Chloride penetration is controlled by restricting specific concrete parameters, as presented in the second row of Table 6.5. These limits have been established based on regulatory guidelines for controlling chloride-induced corrosion.

According to the Canadian Standards Association (CSA), concrete in the C-XL exposure class, which is intended for severe chloride-exposed environments, should have a minimum compressive strength of 50 MPa at 56 days [244]. Additionally, the permissible chloride penetration for this concrete class is set at a maximum of 1000 coulombs at 91 days. Further, the ASTM standard categorizes concrete samples with chloride penetration below 1000 coulombs as "Very Low." This study considers a compressive strength range of 45 to 55 MPa to cover a broader spectrum of

concrete strengths. Moreover, a chloride ion penetration value of less than 1000 coulombs at 28 days has been set as a stricter criterion for assessing concrete permeability. These limits are designed to ensure optimal concrete performance in corrosive environments. In the environmental impact assessment section, the GWP is determined based on the guidelines provided by the Concrete Ontario Council [291]. The maximum allowable GWP for concrete with a specified compressive strength is 394.05 kg of CO₂ equivalent. However, to achieve more environmentally friendly concrete, it is recommended to reduce GWP by approximately 30% below this limit, targeting around 300 kg of CO₂ equivalent. In respect to BER, according to ACI guidelines, concrete samples with electrical resistivity greater than 10 kΩ·cm are classified as having "High Electrical Resistivity." This study has also adopted this range as the evaluation criterion for concrete electrical resistance. Additionally, ACI recommends a minimum air content of 4%, which has been followed in this research [189]. Finally, the STS value has been considered without specific restrictions, allowing for a comprehensive assessment of the influence of other parameters on this property.

6.5.2 Optimization Process

Achieving the predefined target ranges for concrete behavior parameters is the primary objective of the mix design process. In other words, an optimal combination of water, cement, waste materials, and superplasticizer must be identified to ensure that the behavior of concrete mixes falls within the target limits. This study has achieved this goal through an optimization process based on a back analysis. To implement this back analysis, 10,000 uniform random samples are first generated for each input variable, including waste materials. These random samples are fed into the previously trained neural network to estimate the corresponding concrete behavior parameters. Subsequently, each sample is evaluated to determine whether the predicted outputs

fall within the predefined target range. Samples not meeting the criteria are excluded from further consideration, while those that satisfy the conditions are retained. This process generated a set of random input samples, approximately 133 samples, as shown in Figure 6.5, which ensured the desired concrete behavior.

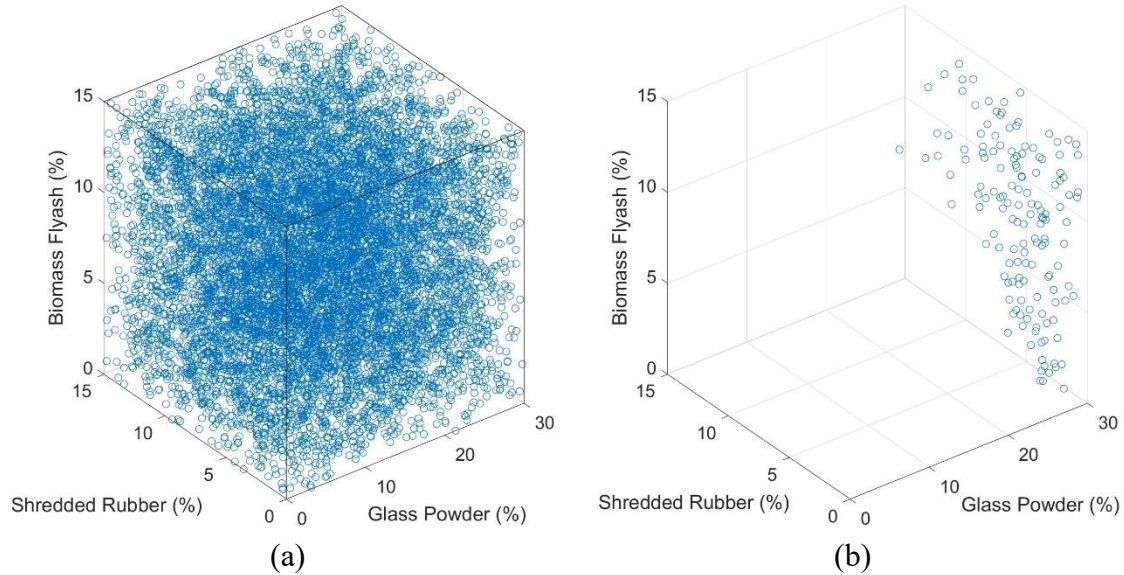


Figure 6.5: (a) Random samples generated and (b) the accepted samples

Subsequently, the probability density function for each input variable is plotted using the accepted samples and their respective means and standard deviations. Based on these first distributions, new random samples are generated, and the optimal samples are updated. This process is iteratively repeated within a computational loop to refine the governing distribution of input variables as accurately as possible, thereby reducing uncertainty regarding the statistical characteristics of the optimal mix design. After 10 iterations of this process, the final governing distribution of input variables is obtained, as illustrated in Figure 6.6.

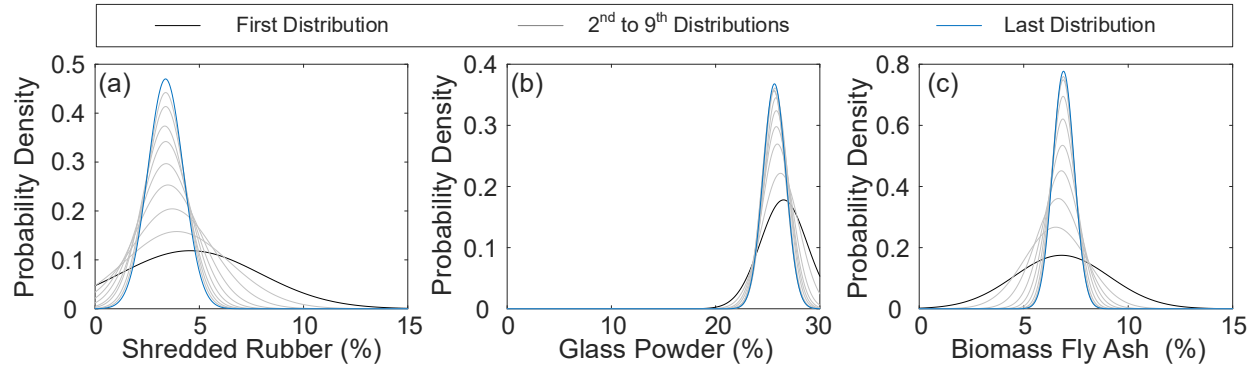


Figure 6.6: Probability distribution governing the proportion of waste materials in concrete after 10 iterations.

As illustrated, the distribution characterizing the optimal proportions of waste materials follows a normal probability density function. To determine an optimal value for the percentage of waste materials, using the mean of the distribution function is the most appropriate. The estimated mean proportions for SR, GP, and BFA are 3.2%, 25.8 %, and 7.4 %, respectively. These values are accompanied by their corresponding standard deviations, as detailed in Table 6.3.

Table 6.3: Optimized values of waste materials

Waste materials	Mean (%)	Standard deviation
SR	3.2	0.82
GP	25.2	1.03
BFA	7.4	0.47

Subsequently, the mean values reported in Table 6.3 are considered the optimal mix design and validated through a laboratory-based experimental model.

6.5.3 Evaluation of Optimal Mixed Design

The outcomes derived from the optimization process, specifically the optimal proportions of waste materials, are utilized as input parameters for designing a concrete mix subsequently produced under controlled laboratory conditions. This experimental implementation validates the accuracy of the proposed mix design methodology. In preparing the laboratory specimen, the water-to-

binder ratio, cement content, and superplasticizer dosage are all kept constant with the values used during the optimization phase. These parameters are detailed in Table 6.4.

Table 6.4: Mixed design parameters are used to prepare the laboratory concrete specimen.

Parameters	Values	Unit
SR	3.2	%
GP	25.8	%
BFA	7.4	%
W/B	45	%
Water	153	kg/m ³
Cement	340	kg/m ³
Sand	910	kg/m ³
Gravel	940	kg/m ³
Superplasticizer	1	%

To evaluate the fresh concrete, slump and AC tests are conducted based on ASTM C143 [126] and ASTM C231 [125]. Following casting, the specimens are retained within their molds for 24 hours to undergo initial curing. Subsequently, they are demolded and placed in a water-curing tank maintained at a controlled temperature of $23 \pm 2^\circ\text{C}$, where they remain for 28 days. After the 28-day curing period, the CS is evaluated following ASTM C39 [130] using three cylindrical specimens. Each specimen is subjected to uniaxial compressive loading, and the maximum applied load is recorded to determine the compressive strength.

Chloride ion penetration resistance is assessed via the RCPT, following the procedures outlined in ASTM C1202 [248]. For this purpose, two discs with a diameter of 100 mm and a thickness of 50 mm are cut from the cured cylindrical specimens. These concrete disks are placed in RCPT cells, containing 3% NaCl and 0.3 M NaOH solutions on opposing sides of the specimen. A constant electrical potential of 60 V is applied across the specimens for six hours, and the total electrical charge passed through the concrete is measured as an indicator of chloride permeability.

BER is measured using an RCON electrical resistivity apparatus. In this procedure, the concrete specimen is positioned between two stainless steel electrodes, and an alternating current with a frequency of 1000 Hz is applied.

STS is determined following standard test procedures [128]. Cylindrical specimens with 200 mm in length and 100 mm in diameter are placed horizontally under a Universal Testing Machine (UTM) to undergo a compressive loading, and the corresponding split tensile strength is calculated in megapascals.

The GWP is calculated based on a life cycle assessment (LCA) model developed in a prior study using the SimaPro software to evaluate the environmental implications of the optimized concrete mix. This estimation provided insight into the carbon footprint associated with the material composition and mix design.

The assumed constraints, as outlined previously, are presented in Table 6.5. In addition, the parameters associated with the optimal mix design derived from the meta model are also included in this table. Furthermore, the corresponding values obtained from the laboratory experiments are provided for comparison. As demonstrated, the experimental values exhibit a high degree of agreement with those predicted by the meta model. This suggests that the meta model effectively forecasts the concrete properties and determines the optimal design of waste concrete.

Table 6.5: Concrete performance parameters are based on the defined model, laboratory experiment, and artificial intelligence (AI) model.

	CS (MPa)	S (cm)	RCPT (coulombs)	GWP (kg/m ³)	BER (k Ω .cm)	AC (%)	STS (MPa)
Constrain	45-55	10-15	<1000	300<	>10	4>	-
Experimental	46.74	15	797.1	243.9	16	5	2.1
AI	46.28	12.83	781.6	252	21.7	4.86	2.63

To further assess the proposed meta model's accuracy in predicting waste concrete behavior, a set of samples generated based on the optimal distribution is input into the ANN to predict the corresponding concrete properties. The outcomes are illustrated in the scatter plot presented in Figure 6.7. The average data values are shown in these plots using a blue solid line and upper and lower bounds corresponding to one-unit standard deviation from the mean. The values obtained from the laboratory experiments for all concrete properties fall within one-standard-deviation range and are very close to the mean values. This indicates the high accuracy of the proposed meta model, as it has successfully predicted the target concrete properties.

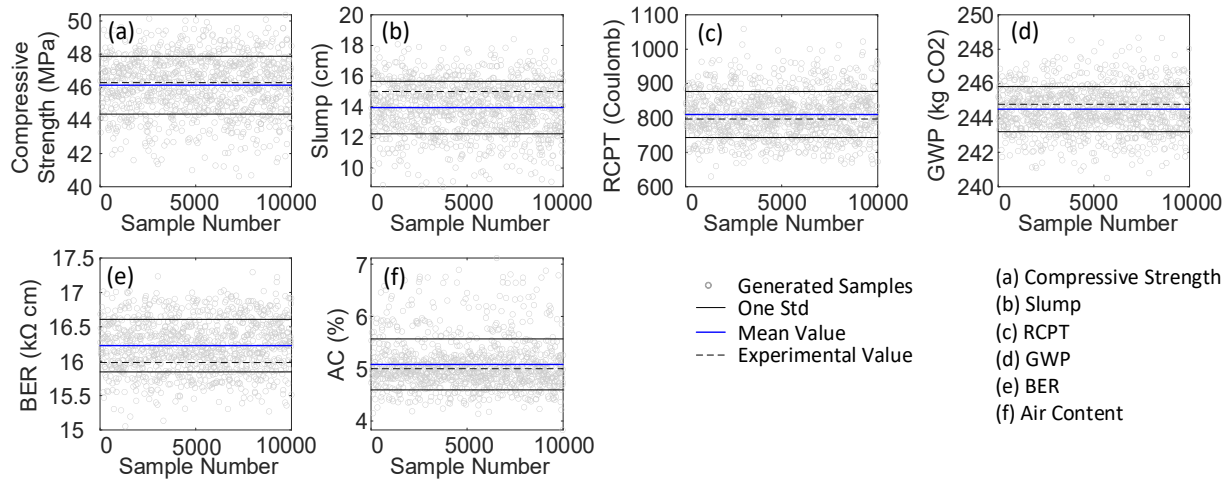


Figure 6.7: Estimating accuracy by comparing generated samples with experimental values.

6.6 Sensitivity analysis

A critical factor in assessing the performance of low-carbon concrete is measuring the impact of waste materials on its properties. To achieve this, a sensitivity analysis is conducted, where the impact of changes in each type of waste material on the concrete properties is evaluated separately. For example, to assess the impact of SR on the compressive strength, considered as the target variable, the SR value is varied within the predefined range presented in Table 6.3. From this range, n random samples are generated using uniform distribution. In this process, all other input

parameters, including GP, BFA, W/B, cement, and superplasticizer, are held constant, ensuring that only SR is varied. These random values are then fed into the ANN, resulting in n corresponding predictions for compressive strength. Since all other input parameters remained constant, the resulting variations in CS are solely attributed to changes in SR. To assess the extent of these variations, the standard deviation of the CS values is used as a measure of sensitivity. The process of conducting this analysis is schematically illustrated in Figure 6.8.

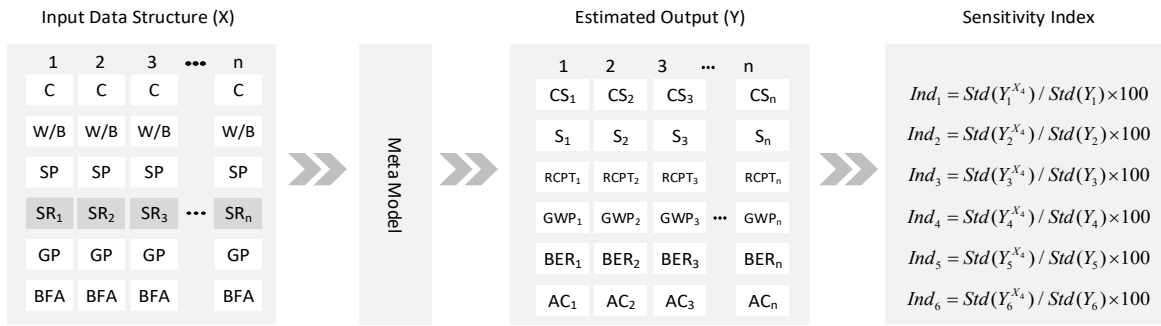


Figure 6.8: Schematic of the sensitivity analysis process, considering SR as the input and CS as the target output.

This approach has also been extended to other concrete properties. By holding all other parameters constant and varying only one input variable (i.e., SR, GP, or BFA), the influence of the selected variable on the various output properties is quantified by calculating the standard deviation of the corresponding outputs. Subsequently, using the obtained data, the sensitivity index (Ind) is calculated using Eq. (5.1):

$$Ind_i = \frac{Std(Y_i^{X_j})}{Std(Y_i)} \times 100 \quad (5.1)$$

where Ind denotes the sensitivity index, $Std(Y_i^{X_j})$ represents the standard deviation of the output Y_i (such as CS, S, RCPT, GWP, BER, or AC) under conditions in which only the input parameter X_j (such as SR, GP, or BFA) is varied, and $Std(Y_i)$ indicates the standard deviation of the same

output when all input parameters are simultaneously altered. This analysis yields the sensitivity index for all input variables and their corresponding outputs using Eq. (1). The results of this analysis are presented in Figure 6.9.

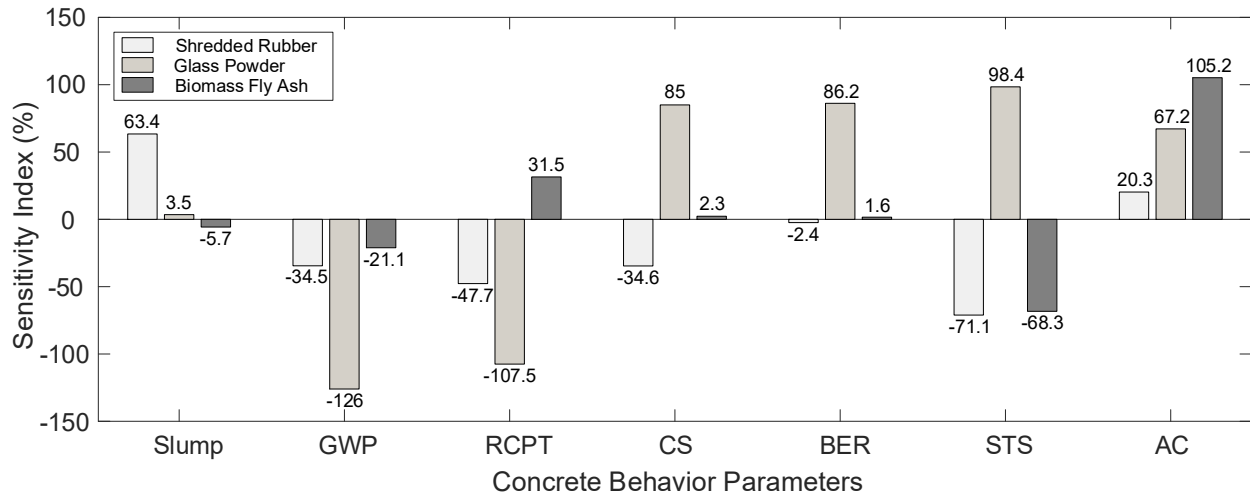


Figure 6.9: Sensitivity index for each of the three input parameters (X, Y, and Z) corresponding to concrete properties

According to the sensitivity analysis results, incorporating the waste material SR significantly raises the concrete slump, resulting in a 63.4% increase in this parameter. Moreover, this material effectively reduces the standard deviation of GWP by up to 34.5%. In terms of durability, SR at maximum capacity has improved the concrete's resistance to corrosive elements by reducing the standard deviation of chloride ion penetration by 47.7% when used at maximum capacity.

However, the influence of SR on the mechanical properties of concrete is detrimental, with the standard deviations of CS and STS decreasing by 34.6% and 71.1%, respectively. Only negligible changes are observed regarding the BER, and no significant impact is detected. While the standard deviation of the AC for SR is lower than that of the other two waste materials, SR still has a positive impact on the AC value, improving it by 20.3%.

Although GP has a negligible effect on the concrete slump, it significantly impacts on the concrete's strength, durability, and environmental performance properties. Specifically, in the best case, GP has led to a 126% reduction in the standard deviation of GWP. Regarding durability, the use of GP resulted in a substantial decrease in chloride ion penetration, with the related standard deviation reduced by 107.5%. Furthermore, the BER increased by 86.2%, indicating enhanced compaction and improved microscopic structure of the concrete due to the inclusion of GP.

In terms of the mechanical properties, GP demonstrates remarkable performance of the concrete, improving CS and STS by 58% and 98.4%, respectively. In the best measured case, the standard deviation of AC reaches 67.2% when using GP. In contrast, BFA deteriorates the overall properties of the concrete, particularly in STS, which experienced a significant decrease of 68.3%. Additionally, BFA leads to a 31.5% increase in chloride ion penetration, reducing the concrete durability. However, BFA demonstrates a positive effect in only two indices: a 21.1% reduction in GWP and a significant increase in AC by 105.2%. The impact of this material on CS and BER is relatively insignificant, with no substantial changes observed in these parameters.

Among the three types of waste materials examined, GP demonstrates a more pronounced positive impact on concrete's strength, durability, and environmental performance than the other materials.

6.7 Large-scale beam

6.7.1 Experimental setup for beam

After creating the metamodel and evaluating its accuracy, large-scale samples such as beams were tested. The beams were full-scale, each measuring 2440 mm in total length with a cross-section of 250 mm $\times$ 250 mm (Figure 6.10). To reinforce the beams, two 25 mm diameter steel bars were placed in the tension zone, and two 10 mm diameter steel bars were placed in the compression

zone. Stirrups with a diameter of 10 mm were placed closely along the beam at a constant spacing of 150 mm. A uniform concrete cover of 30 mm was maintained on all sides of the beams during casting. These beams were cast according to the studies by Mohamed K. Ismail et al. [292] on the flexural behavior and cracking of reinforced concrete beams. Figure 6.11 shows the test setup for the four-point flexural test. To ensure beam rotatability, two roller supports were used at the top (Figure 6.12a). Additionally, one roller support (Figure 6.12b) and one pinned support (Figure 6.12c) were employed to ensure that the beam's performance under load closely matched the design assumptions. To prevent local cracking or failure at the connection between the concrete beam and its support, a steel bar with a width of 5 cm was used to effectively transfer/distribute the load (Figure 6.13).

linear variable displacement transducers (LVDTs) and strain gauges were used to record the deformation and yielding of the rebars in concrete containing shredded rubber (SR), glass powder, and biomass fly ash (BFA). Three LVDTs were installed at one-third intervals along the length of the beam. Four strain gauges were installed on the rebars and the concrete: two were placed at mid-span on each of the bottom rebars, one additional strain gauge was installed next to one of them as a backup, and one was placed on top of the concrete to measure the compressive strain (Figure 6.13). To measure the strain at the effective depth d (the distance from the top surface of the concrete to the centroid of the bottom rebars), the strain gauges were attached to the sides of the rebars.

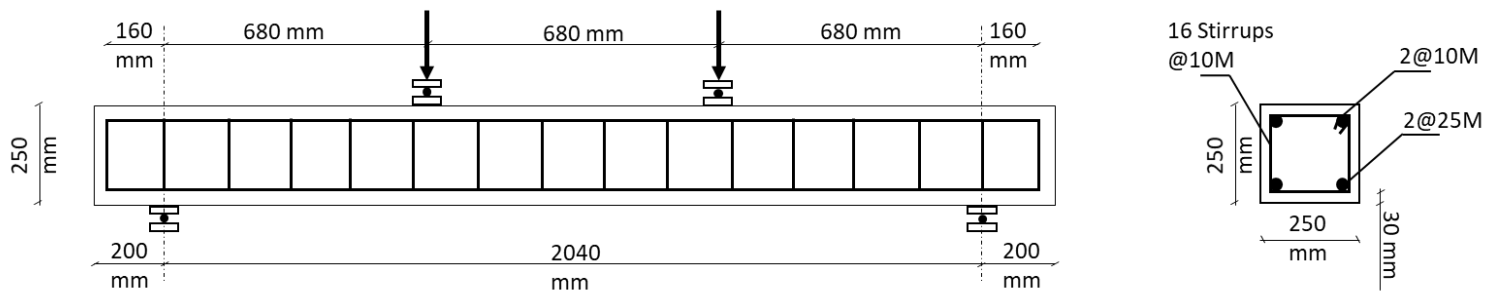


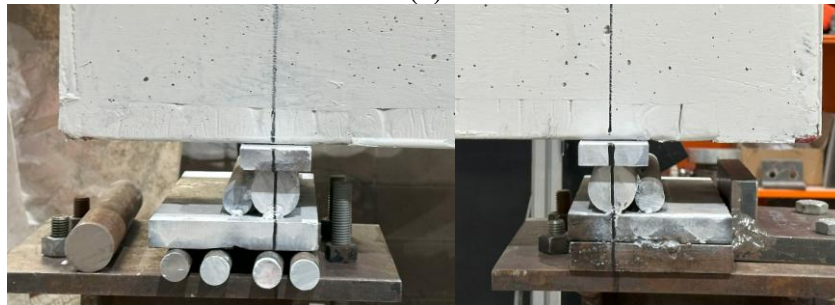
Figure 6.10: Schematic detail of the large-scale beam (2440 mm×250 mm×250 mm)



Figure 6.11: Four-point flexural beam setup



(a)



(b)

(c)

Figure 6.12: Illustration of different beam support configurations: a) roller support at top, b) roller support at bottom, and c) pin support at bottom.



Figure 6.13: Strain gauge installation

6.7.2 Performance-based mix design for large beams

To conduct this investigation, four beams were prepared, each with a specific mix design to meet a specific performance (Performance-based mix design): a control sample, a beam with improved chloride resistance, a beam with resistance to freeze-thaw cycles, and a beam designed to resist both chloride penetration and freeze-thaw damage. This approach was adopted to reflect real-world industrial practice, where large-scale testing is necessary to ensure that incorporating waste materials does not negatively affect the structural behavior of concrete. Specifically, the fracture properties and load-carrying capacity were maintained within acceptable limits, while the mixes still achieved the targeted durability enhancements. Because structures are exposed to a variety of service conditions, the beams were designed with different durability objectives to confirm that the optimized mixes could satisfy both mechanical and durability requirements in practical applications. For each beam, specific performance constraints were applied to achieve optimized mix designs incorporating waste materials. These constraints are summarized in Table 6.6. Constraints were applied to compressive strength, slump, bulk electrical resistivity (BER), global warming potential (GWP), and air content to reflect mechanical properties, durability, workability, and environmental performance. The compressive strength of all four mixes was kept similar to enable a fair comparison of the structural behavior of beams incorporating different waste materials. To study the behavior of waste materials in large-scale beams, the water-to-cement (W/C) ratio, total binder content, and superplasticizer dosage were kept constant across all mixes. The metamodel was used to derive the mix design for each beam, as detailed in Table 6.7. The control sample contained no waste material, while all beams shared the same binder content and water-to-binder ratio. After conducting the laboratory tests, the experimental results were compared with the predictions from the metamodel for each performance criterion (Table 6.8).

Table 6.6 Performance constraints

No	Constrain	Compressive strength	Slump	RCPT	GWP	BER	Air content
B1	Control sample	45-55	10-15	-	-	-	-
B2	FT resistance	45-55	10-15	-	300<	-	-
B3	Chloride resistance	45-55	10-15	<1000	300<	>10	>5
B4	FT/Chloride resistance	45-55	10-15	<1000	300<	>10	>5

Table 6.7 Derived Mix design of beams for each category

Parameters	Control	FT resistance	Chloride resistance	FT/Chloride resistance
SR (%)	0	1.15	3.20	2.76
GP (%)	0	18.00	25.80	24.36
BFA (%)	0	1.22	7.40	0.42
W/B	0.45	0.45	0.45	0.45
Water (kg/m ³)	153	153	153	153
Binder (kg/m ³)	340	340	340	340
Sand (kg/m ³)	940	929.13	898.95	914.04
Gravel (kg/m ³)	940	940	940	940
Superplasticizer (%)	1	1	1	1

Table 6.8: Evaluation of four concrete beams' performance using meta model and lab testing

No	Constrain		CS	Slump	RCPT	GWP	BER	AC
B1	Control	AI	49.6	14.4	3434	323.7	8.32	5.08
		Exp	48.31	15	4275.47	342	9.73	3.9
B2	FT resistance	AI	51.85	12.88	1487	273.5	16.8	6.53
		Exp	52.74	15	1769.71	286.68	13.54	6
B3	Chloride resistance	AI	49	13.73	744.67	248.38	16.13	4.56
		Exp	46.74	15	797.05	244.84	16	5
B4	FT/Chloride resistance	AI	50	14.34	965.78	258.87	15.73	7.9
		Exp	57.02	14.5	717.89	270.19	17.40	7

6.7.3 Large-scale beam performance

Once the mechanical properties, durability, workability, and environmental criteria for each beam were evaluated and confirmed during the mix design stage, the next phase involved testing the large-scale beams. All beams were subjected to a loading rate of 0.4 mm/min, and the test was discontinued upon reaching 80% of the peak load. All reinforcement details were kept identical across the four beams to allow for a comparison of concrete performance (Figure 6.14). In this study, Grade 400 reinforcing bars were used, with a yield strength f_y of 400 MPa and a standard

Young's Modulus (E) of 200,000 MPa, resulting in a yield strain of 0.002 (or 2000 $\mu\epsilon$). As shown in Figure 6.15, the strain in each bottom rebar exceeded the yielding threshold. As expected, yielding began once the strain approached approximately 2000 $\mu\epsilon$. According to the strain gauge results, all bottom reinforcement in the beams reached their yielding strain but did not reach their ultimate strain (as concrete failed earlier).



Figure 6.14 Concrete beam specimens after test, showing compression failure

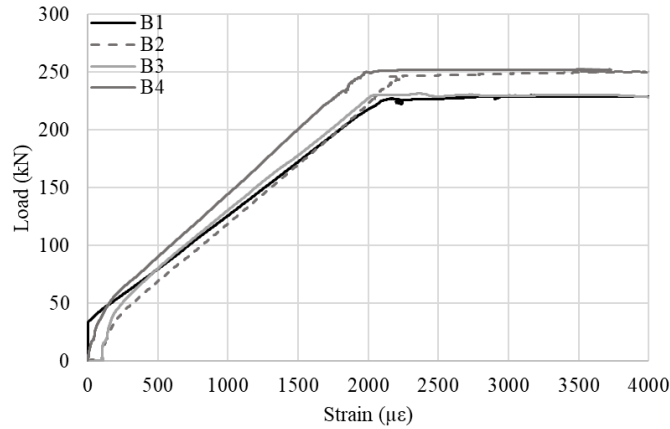


Figure 6.15 Load-strain curve for the beam under applied loads.

The load–deflection graphs of the beams are presented in Figure 6.16, and the corresponding fracture properties are reported in Table 6.9. The energy absorption capacity of all the beams, with the exception of Beam 3 (B3), was close, measured by the area under the load–deflection graphs, of about 9000 N·mm. B3 showed a weaker performance compared to the other beams. This reduction in performance is mainly attributed to its higher shredded rubber content (3.2%) and biomass fly ash content (7.4%), as compared to the other mixtures. The low compressive strength is another factor for its lower performance, which is attributed to the increased BFA content that slows down the hydration and delays strength development. B4 gained the lowest ductility (2.10), max load capacity (256.34 kN), and max deflection at load (29.12 mm), as can be seen from Table 6.9.

To evaluate the experimental moment resistance of the beams, the theoretical moment resistance (M_r) was calculated in accordance with CSA A23.3 [244] using equation (5.2):

$$M_r = (K_r + \dot{K}_r) b d^2 10^{-6} \quad (5.2)$$

Where M_r is the moment resistance, K_r is the resistance factor for the bottom reinforcement, K_r' is the resistance factor for the top reinforcement, b is the beam width, and d is the distance from the top of the concrete section to the centroid of the bottom longitudinal reinforcement. Figure 6.17 plots the experimental and theoretical values of M_r . As can be seen, the values are in close agreement, with no difference being more than 5 kN·m. Although Beam 4 (B4) was less ductile than the control sample, it was more resistant to moment and peak load.

Overall, considering moment resistance, all beams showed comparable performance, with a standard deviation of 3.16 kN·m. It can be concluded that large-scale beams can meet structural requirements while being designed for freeze–thaw and chloride resistance, with a lower carbon emission. For instance, Beam B4, which was designed for enhanced durability (FT/ chloride resistance), exhibited a global warming potential (GWP) of 270.19 kg CO₂/m³, which is significantly lower than the control sample, while achieving a moment resistance of 3.6 kN·m, higher than the control beam.

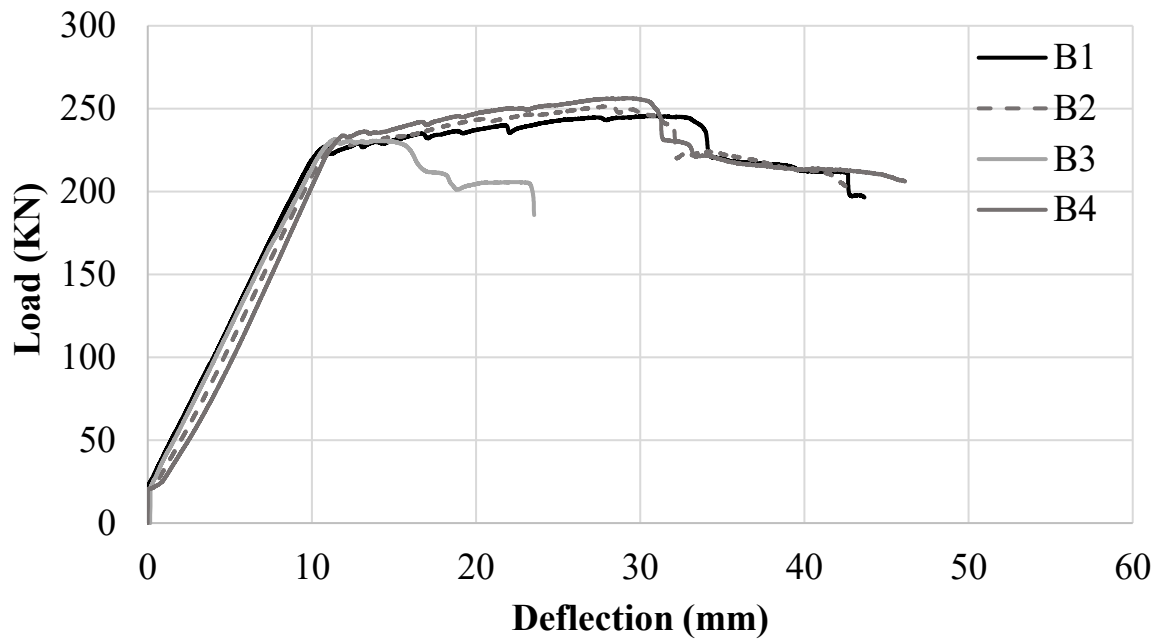


Figure 6.16 Load vs deflection graph for B1) control beam, B2) FT resistance beam B3) chloride resistance beam, and B4) FT/chloride resistance beam

Table 6.9: Fracture parameters of beams

No	Area (kN·mm)	Ductility	Max load (kN)	Deflection at max load (mm)	Compressive strength (MPa)
B1	8974	4.40	245.5127	30.93	48.31
B2	8726	4.00	251.3954	28.1128	52.74
B3	4100	2.17	231.4246	11.3995	46.74
B4	9427	2.10	256.3096	29.1262	57.02

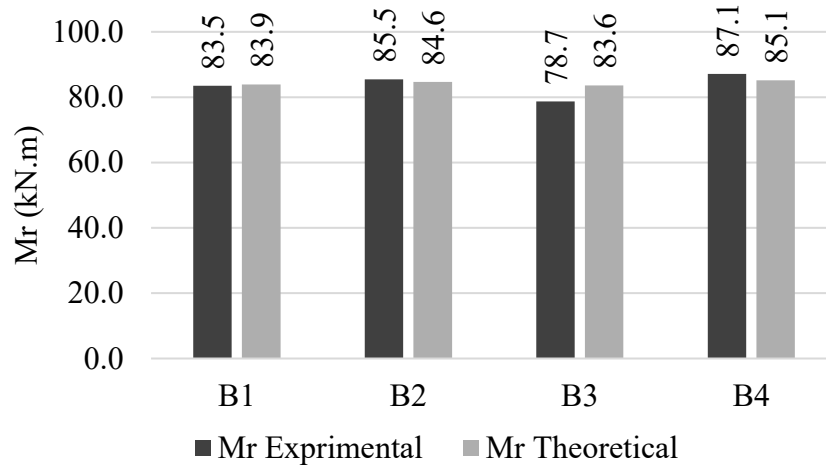


Figure 6.17 Experimental vs. theoretical moment resistance (M_r) values

6.8 Conclusion

This paper presented an AI-based meta model to predict the performance of concrete incorporating three types of waste materials: shredded rubber (SR), glass powder (GP), and biomass fly ash (BFA). Additionally, it develops a Monte Carlo-based back analysis to propose an optimal mix design to achieve the desired performance. The following are the main contributions of this study:

- A meta model is developed to collectively estimate all the concrete properties, including S, CS, GWP, RCPT, STS, AC, and BER, for each combination of the three waste materials, including SR, GP, and BFA. As discussed in the paper, the R^2 values exceed 0.9 for all test cases, indicating high prediction accuracy of the neural network.
- The Monte Carlo-based back analysis was employed to determine the optimal combination of waste materials in concrete to achieve the desired behavior based on the target concrete properties. The accuracy of this back analysis is demonstrated by an experimental sample prepared with the proposed optimal mix design, which falls within one-unit standard deviation of the estimated mean value, confirming close agreement with the predicted results.

- By limiting the concrete properties, including CS between 45 and 55 MPa, GWP less than 300 kg/m³ CO₂, and RCPT less than 1000 coulomb, an optimal mix design with average SR = 3.197%, GP = 25.79%, and BFA = 7.37% is achieved. This optimal mix design is validated through an experimental model, leading to the desired concrete behavior.
- The sensitivity analysis on the meta model revealed that SR has a positive effect on RCPT and GWP but has a relatively negative impact on the concrete's strength parameters. Conversely, GP affected most of the concrete parameters, particularly positively affecting RCPT, GWP, CS, and AC. BFA reduced GWP but degraded the concrete's strength and durability properties.
- The framework proposed in this study has the necessary capacity to develop similar models for concrete mixes using other materials such as type-C fly ash, slag, fibers, silica, etc.

CHAPTER 7: CONCLUSIONS AND FUTURE WORK

7.1 Summary

This study was conducted in four phases. In Phase I, the chemical (XRD, XRF) and physical (PSD, SEM) characteristics of the constituent materials, including cement, biomass fly ash (BFA), glass powder (GP), shredded rubber (SR), and aggregates, were evaluated. In Phase II, the early-age reactivity of the waste materials was investigated. In addition to evaluating the fresh properties of concrete, such as setting time, the early-age performance was assessed through energy-dispersive X-ray spectroscopy (EDX), BER and compressive strength tests conducted during the initial curing days. These assessments provided insight into the contribution of waste materials to the early development of mechanical and durability properties.

Phase III employed the RSM approach to develop 19 concrete mix designs incorporating SR, BFA, and GP. These mixes were assessed for durability (freeze-thaw resistance [FT], rapid chloride permeability test [RCPT], rapid chloride migration test [RCMT], bulk electrical resistivity [BER], and surface electrical resistivity [SER]), mechanical performance (compressive strength [CS], splitting tensile strength [STS], modulus of rupture [MOR]), workability (slump, air content), and environmental impact (global warming potential [GWP], service life [SL]). Following data collection, the data analysis was processed to derive the equation of the test results. These equations/models were validated using statistical metrics such as p-value, R^2 , adequate precision, and residual analysis. To further verify the robustness of the models, additional mixes were cast and tested, and the results were compared with the predicted values by the equations. Finally, an optimal mix space diagram was developed to identify the most effective proportions of waste materials that meet the performance requirements of standard concrete.

In the final phase (Phase IV), an AI-based meta model was developed using both literature-sourced data and the results generated from the RSM equations. This metamodel facilitates more accurate optimization of concrete mix designs by accommodating specific performance objectives and constraints. While the RSM model was limited to a replacement range of 0–20% for SR, BFA, and GP, the AI-based model expands this range up to 30%, allowing for the incorporation of higher waste materials. To evaluate the performance of the optimized low-carbon concrete in various structural applications, four large-scale reinforced concrete beams were cast based on the meta model.

7.2 Conclusions

Based on the results of experimental and analytical studies, the following conclusions can be drawn:

7.2.1 Conclusions from phase I

Proceeding with Phase I demonstrated the potential of using waste materials in concrete. The XRF results indicated a high SiO_2 content in the glass powder (GP), which supports the hydration reaction. Additionally, the physical properties and other elemental contents were within acceptable limits according to ASTM C1866. For instance, certain destructive components, such as Na_2O , known to contribute to expansion and cracking due to alkali-silica reaction (ASR), should be limited to less than 15% in glass powder. In this study, the Na_2O content in GP was recorded at 12.85%. The XRF results of biomass fly ash (BFA) showed a high CaO content, which is beneficial for both cementitious and pozzolanic activity. While GP is generally amorphous, XRD analysis revealed the presence of crystalline components in both GP and cement. PSD of the aggregate and SR met the requirements of ASTM C33.

7.2.2 Conclusions from phase II

This phase revealed how using waste material in concrete impacts the early-age reactivity of concrete, which is important for construction scheduling. To evaluate the component reactivity, in addition to the variations in the Ca/Si ratio observed across different concrete mixes, the inverse relationship between the Ca/Si ratio and both BER and SER highlights the significant role of the calcium to silica ratio in influencing the characteristics of cementitious materials. The increased reactivity of GP due to its pozzolanic nature was confirmed in the samples containing GP with a lower Ca/Si ratio. Also, the increase in surface and bulk electrical resistivity with the incorporation of GP was attributed to the pore-refinement effect of the C-S-H gel. However, the resulting C-S-H gel was not structurally dense enough to improve compressive strength at early ages.

For BFA samples, both reactivity and resistivity were lower than the control sample, indicated by a higher Ca/Si ratio and reduced C-S-H gel formation. This lack of sufficient C-S-H gel led to decreased strength at the early ages of 7 and 14 days, making BFA less effective as an early strength enhancer when used as a partial replacement of cement. Comparing BFA and GP to slag, the increased resistivity suggested a denser microstructure, and the higher degree of hydration resulted in greater strength at early ages. The notable increase in strength at 14 days for the 30% slag replacement suggests that a longer curing duration would enhance overall strength.

7.2.3 Conclusions from phase III

Phase III presents the experimental tests that covered various aspects of concrete, including workability, durability, mechanical, and environmental properties, which are essential for developing a performance-based mix design. In the analytical phase, the RSM model demonstrated the potential of incorporating waste materials. The results indicated that GP not only enhances the

properties of concrete but also mitigates the negative effects of SR and BFA on durability and mechanical performance. Mixes incorporating higher levels of GP, particularly 20%, demonstrated the best balance between performance and sustainability. These mixes adhered to the 30 MPa compressive strength and 50-year service life criteria while significantly reducing carbon emissions. This enables the use of more waste materials, contributing to lower carbon emissions while still meeting the required standards.

In this section, the equation for each test was derived, and constraints were applied based on the target mix design—for example, a mix with medium compressive strength (30–40 MPa), high resistance to chloride penetration ($\text{RCMT} < 1000$ coulombs), and low carbon emissions ($\text{GWP} < 297 \text{ kg CO}_2/\text{m}^3$). By applying these constraints to each test, the optimal mix space was identified. Within this acceptable range, a combination of SR, BFA, and GP was found that meets the specified requirements. Optimal design mix incorporating GP, BFA, and SR reduces GWP to 240 kg CO_2 at least, representing a minimum 102 kg CO_2 decrease in carbon emissions.

7.2.4 Conclusions from phase IV

A comprehensive and flexible meta-model was developed to accurately predict the target mix design. An iterative process was performed within a computational loop to refine the governing distribution of input variables as precisely as possible, thereby reducing uncertainty regarding the statistical characteristics of the optimal mix design. Subsequently, a Monte Carlo-based back analysis was employed to propose an optimal mix composition to achieve the desired performance.

To evaluate its accuracy, the optimal mix design was cast in the laboratory and tested. The results demonstrated that the optimized mix achieved high accuracy, with predicted values falling within one standard deviation of the mean. Using this meta-model, four concrete mixtures were designed

for specific applications: freeze-thaw resistance, chloride penetration resistance, combined freeze-thaw/chloride penetration resistance, and a control mix.

Following performance validation, the structural behavior of reinforced beams incorporating these mixtures was investigated. Despite slight fluctuations in ductility, peak load, energy absorption, and deformation for each beam, the moment resistance varied by approximately 5 kN·m. Compared to the control sample, a concrete mixture incorporating waste materials and reduced cement content can be designed to release lower carbon emissions while maintaining similar structural performance and improved resistance to freeze-thaw cycles and chloride penetration.

7.3 Recommendations for Future Work

This research has demonstrated the potential of low-carbon concrete incorporating biomass fly ash (BFA), glass powder (GP), and shredded rubber (SR) to reduce environmental impacts while maintaining structural performance. While the findings are promising, several directions remain for future exploration to expand the understanding and application of these materials. Fire resistance testing is strongly recommended to determine how these eco-concretes behave under high-temperature conditions, especially for structural applications where fire safety is a critical consideration. Given that BFA does not neatly fit into existing fly ash classifications (e.g., Class F or Class C), more in-depth research is needed to better understand its characteristics and how it performs, particularly in combination with other pozzolans like GP. Investigating whether binary or ternary blends can replace traditional fly ash more effectively will improve both material performance and sustainability.

Another important direction is the inclusion of new supplementary materials in future studies. These may include ground granulated blast furnace slag (GGBFS), metakaolin, natural pozzolans,

limestone powder, Class C fly ash, silica fume, and other recycled powders (e.g., ceramic). These materials should be studied not only for their mechanical and durability effects but also through the development of meta models, AI-driven frameworks capable of predicting performance based on material characteristics and mix designs. The meta model presented in this research can be expanded to handle such complexities and enable broader optimization strategies.

Furthermore, the transition from lab-scale testing to large-scale structural testing is crucial. Casting and evaluating full-scale columns, slabs, and beams made from optimized sustainable mixes will provide critical insight into constructability, structural integrity, and real-world applicability. These tests will also support code development and provide validation for field implementation.

It is also recommended to apply the proposed methodologies to other types of concrete, such as self-consolidating concrete (SCC) and high-strength concrete (HSC). These specialized concretes have different rheological and mechanical requirements and understanding how alternative binders interact within these systems is key to broadening the applicability of sustainable materials.

Lastly, future research should aim to expand the AI-based framework to include a wider range of input variables and performance metrics, including circular economy or environmental impact factors such as CO₂ emissions and embodied energy. This will support the development of more comprehensive and intelligent mix design tools aligned with low-carbon construction practices and the global transition toward sustainable infrastructure.

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Appendix 4.1

This Appendix presents the equations derived for the tests.

Slump (cm)	$\text{Sqrt}(\text{Slump (cm)}) = 4.28 + 0.11 \times \text{SR (\%)} - 0.002 \times \text{GP (\%)} + 0.23 \times \text{BFA (\%)} - 0.006 \times \text{SR (\%)}^2 - 0.039 \times \text{BFA (\%)}^2$	(1)
Compressive strength day 28	$\text{Day 28 CS (MPa)} = +33.18 - 2.67 \times \text{SR (\%)} - 0.49 \times \text{GP (\%)} - 0.15 \times \text{BFA (\%)} + 0.05 \times \text{SR (\%)} \times \text{BFA (\%)} + 0.10 \times \text{SR (\%)}^2 + 0.03 \times \text{GP (\%)}^2$	(2)
Compressive strength day 90	$\text{Day 90 CS (MPa)} = +37.62 - 2.79 \times \text{SR (\%)} - 0.56 \times \text{GP (\%)} - 0.06 \times \text{BFA (\%)} + 0.025 \times \text{SR (\%)} \times \text{GP (\%)} + 0.048 \times \text{SR (\%)} \times \text{BFA (\%)} + 6.64\text{E} - 003 \times \text{GP (\%)} \times \text{BFA (\%)} + 0.087 \times \text{SR (\%)}^2 + 0.028 \times \text{GP (\%)}^2$	(3)
RCMT Day 28	$\text{RCMT Day 28 (10}^{-12} \text{ m}^2/\text{s)} = +14.68 + 0.46 \times \text{SR (\%)} - 0.55 \times \text{GP (\%)} - 0.34 \times \text{BFA (\%)} - 0.013 \times \text{SR (\%)} \times \text{GP (\%)} + 0.021 \times \text{GP (\%)} \times \text{BFA (\%)} - 0.032 \times \text{SR (\%)}^2$	(4)
RCMT Day 90	$\text{RCMT Day 90 (10}^{-12} \text{ m}^2/\text{s)} = +10.38 + 0.48 \times \text{SR (\%)} - 0.94 \times \text{GP (\%)} + 0.16 \times \text{BFA (\%)} - 9.59\text{E} - 003 \times \text{SR (\%)} \times \text{BFA (\%)} - 6.08\text{E} - 003 \times \text{GP (\%)} \times \text{BFA (\%)} - 0.027 \times \text{SR (\%)}^2 + 0.02 \times \text{GP (\%)}^2$	(5)
28-BER (ohm-m)	$\text{Sqrt}(28\text{-BER (ohm-m)}) = +2.60 - 0.07 \times \text{SR (\%)} + 0.016 \times \text{GP (\%)} + 8.11\text{E} - 003 \times \text{BFA (\%)} - 1.22\text{E} - 003 \times \text{SR (\%)} \times \text{GP (\%)} - 2.56\text{E} - 004 \times \text{SR (\%)} \times \text{BFA (\%)} + 3.11\text{E} - 003 \times \text{GP (\%)} \times \text{BFA (\%)} + 5.67\text{E} - 003 \times \text{SR (\%)}^2 + 3.54\text{E} - 003 \times \text{GP (\%)}^2 - 1.64\text{E} - 003 \times \text{BFA (\%)}^2$	(6)
90-BER (ohm-m)	$90\text{-BER (ohm-m)} = +7.004 + 0.022 \times \text{SR (\%)} + 1.23 \times \text{GP (\%)} - 0.11 \times \text{BFA (\%)}$	(7)
GWP (Kg CO2)	$\text{GWP (Kg CO2)} = +342.32 - 0.47 \times \text{SR (\%)} - 2.85 \times \text{GP (\%)} - 3.02 \times \text{BFA (\%)}$	(8)
Service life (year)	$\text{Sqrt}(\text{Service life (year)}) = +6.82 - 0.076 \times \text{SR (\%)} + 0.083 \times \text{GP (\%)} + 0.053 \times \text{BFA (\%)} + 3.10\text{E} - 003 \times \text{SR (\%)} \times \text{GP (\%)} - 3.83\text{E} - 003 \times \text{GP (\%)} \times \text{BFA (\%)} + 4.80\text{E} - 003 \times \text{SR (\%)}^2$	(9)
GWP/Service life	$\text{GWP/Service life} = +7.12 - 0.036 \times \text{SR (\%)} - 0.14 \times \text{GP (\%)} - 0.075 \times \text{BFA (\%)}$	(10)

Appendix 4.2

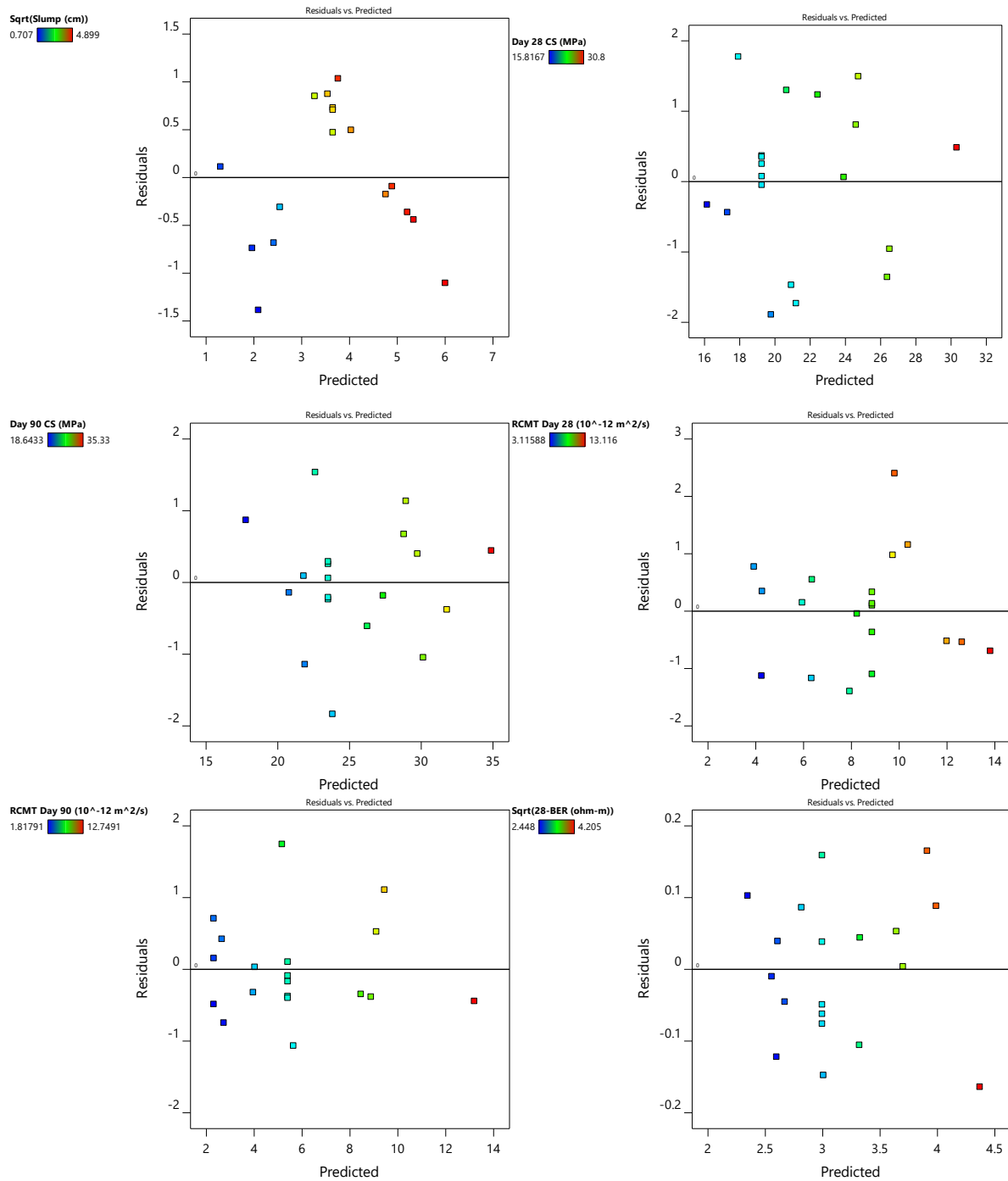
This appendix presents the statistical responses for the proposed equations, including the p-values of each parameter.

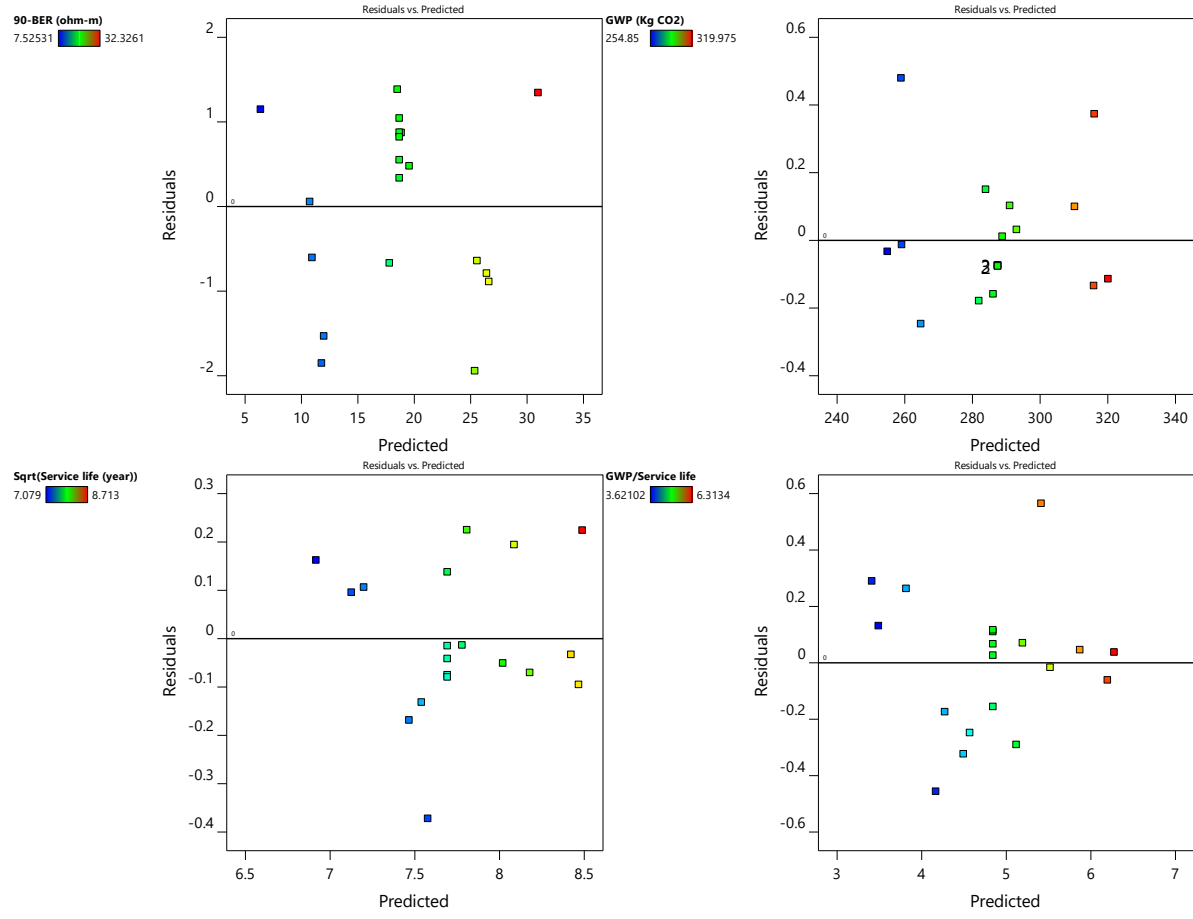
	Source	Model	Intercept	A-Shredded Rubber (%)	B-Glass Powder (%)	C-Biomass Fly Ash (%)	AB	AC	BC	A ²	B ²	C ²
Slump (cm)	P-Value	< 0.0001	-	0.8384	0.8931	< 0.0001				0.0005		0.0003
	Coef	-	4.28	0.081	-0.017	-1.63				-0.13		-0.79
Compressive strength day 28	P-Value	< 0.0001	-	< 0.0001	0.0494	0.0152		0.0614		0.0006	0.0215	
	Coef	-	19.21	-3.13	0.89	1.16		1.09		2.07	1.14	
Slump (cm)	P-Value	< 0.0001	-	< 0.0001	0.0016	0.0011	0.1558	0.0526	0.6908	0.001	0.018	
Compressive strength day 90	Coef	-	23.49	-3.87	1.52	1.62	0.67	0.97	0.18	1.73	1.02	
RCMT Day 28	P-Value	0.0002	-	0.0751	< 0.0001	0.1341	0.4367		0.2319	0.0968		
	Coef	-	8.89	-0.68	-2.94	-0.56	-0.36		0.57	-0.64		
RCMT Day 90	P-Value	< 0.0001	-	0.9385	< 0.0001	0.5909		0.5783	0.6378	0.0743	0.0155	
	Coef	-	5.49	0.02	-3.24	0.14		-0.19	-0.16	-0.54	0.79	
28-BER (ohm-m)	P-Value	0.0002	-	0.9711	< 0.0001	0.2202	0.573	0.9287	0.1766	0.0451	0.0303	0.5035
	Coef	-	3	-1.58E-03	0.6	0.057	-0.033	-	0.083	0.11	0.13	-0.033
90-BER (ohm-m)	P-Value	< 0.0001	-	0.7671	< 0.0001	0.1442						
	Coef	-	18.6	0.1	7.31	-0.52						
GWP (Kg CO2)	P-Value	< 0.0001	-	< 0.0001	< 0.0001	< 0.0001						
	Coef	-	287.49	-2.11	-16.98	-13.51						
Service life (year)	P-Value	0.0003		0.0558	< 0.0001	0.2413	0.2785		0.1868	0.1204		
	Coef		7.70	0.12	0.46	0.07	0.08		-0.10	0.09		
GWP/Service life	P-Value	< 0.0001		0.0510	< 0.0001	0.0006						
	Coef		4.85	-0.16	-0.85	-0.34						

A: Shredded rubber (%), B: Glass powder (%), C: Biomass fly ash (%)

Appendix 4.3

This appendix shows the residual plot illustrating the differences between the observed and predicted test results, used to assess the accuracy and distribution of model errors.





Appendix 5.1

Summary of coefficient estimates, 95% confidence intervals, and VIF values for all response models. VIF values close to 1 indicate that multicollinearity among independent variables is negligible, supporting the reliability of the model coefficients.

Tests	Factor	Coefficient Estimate	95% CI Low	95% CI High	VIF
Air content (%)	Intercept	3.47	3.2	3.74	
	A-Shredded Rubber (%)	0.0048	-0.1209	0.1306	1
	B-Glass Powder (%)	-0.36	-0.4857	-0.2342	1
	C-Biomass Fly Ash (%)	-0.4104	-0.5361	-0.2846	1
	AB	0.3187	0.1544	0.4831	1
	AC	-0.2688	-0.4331	-0.1044	1
	BC	-0.8563	-1.02	-0.6919	1
	A ²	0.5624	0.424	0.7008	1.16
	B ²	0.5447	0.4063	0.6832	1.16
	C ²	0.8364	0.698	0.9748	1.16
Durability factor (%)	Intercept	21.66	-8.38	51.69	
	A-Shredded Rubber (%)	-8.42	-22.53	5.69	1
	B-Glass Powder (%)	-14.52	-28.63	-0.4172	1
	C-Biomass Fly Ash (%)	-23.9	-38.01	-9.8	1
	AB	8.58	-9.85	27.01	1
	AC	-7.03	-25.46	11.4	1
	BC	-12.84	-31.27	5.59	1
	A ²	11.9	-3.63	27.42	1.16
	B ²	10.1	-5.42	25.63	1.16
	C ²	11.31	-4.22	26.84	1.16
Day 28 CS (MPa)	Intercept	19.21	17.8	20.62	
	A-Shredded Rubber (%)	-3.13	-4.02	-2.25	1
	B-Glass Powder (%)	0.8872	0.0026	1.77	1
	C-Biomass Fly Ash (%)	1.16	0.276	2.05	1
	AC	1.09	-0.0633	2.25	1
	A ²	2.07	1.14	3	1.05
	B ²	1.14	0.2057	2.07	1.05
MOR (MPa)	Intercept	4.9	4.54	5.26	
	A-Shredded Rubber (%)	-0.1327	-0.3006	0.0351	1

	B-Glass Powder (%)	-0.3432	-0.5111	-0.1753	1
	C-Biomass Fly Ash (%)	-0.5386	-0.7064	-0.3707	1
	AB	-0.0816	-0.301	0.1377	1
	AC	0.2335	0.0142	0.4528	1
	BC	-0.2519	-0.4712	-0.0325	1
	A ²	-0.2271	-0.4119	-0.0423	1.16
	B ²	-0.1426	-0.3274	0.0422	1.16
	C ²	-0.3362	-0.5209	-0.1514	1.16
SER (k Ω .cm)	Intercept	19.9	17.61	22.18	
	A-Shredded Rubber (%)	-0.2315	-1.3	0.8402	1
	B-Glass Powder (%)	4.55	3.48	5.62	1
	C-Biomass Fly Ash (%)	0.2228	-0.8489	1.29	1
	AB	-1.97	-3.37	-0.5697	1
	AC	-0.86	-2.26	0.5403	1
	BC	1.62	0.2239	3.02	1
	A ²	-1.15	-2.33	0.0273	1.16
	B ²	1.39	0.2101	2.57	1.16
	C ²	-0.9502	-2.13	0.2294	1.16
STS (MPa)	Intercept	2.43	2.25	2.61	
	A-Shredded Rubber (%)	-0.2497	-0.3344	-0.1649	1
	B-Glass Powder (%)	-0.0753	-0.1601	0.0095	1
	C-Biomass Fly Ash (%)	-0.1281	-0.2129	-0.0433	1
	AB	-0.1189	-0.2297	-0.0082	1
	AC	-0.037	-0.1478	0.0738	1
	BC	-0.0615	-0.1722	0.0493	1
	A ²	-0.1217	-0.215	-0.0284	1.16
	B ²	-0.1139	-0.2072	-0.0206	1.16
	C ²	-0.0644	-0.1577	0.029	1.16
GWP (Kg CO2)	Intercept	287.49	287.38	287.61	
	A-Shredded Rubber (%)	-2.11	-2.24	-1.99	1
	B-Glass Powder (%)	-16.98	-17.1	-16.85	1
	C-Biomass Fly Ash (%)	-13.51	-13.64	-13.39	1
Dynamic Young's modulus (GPa)	Intercept	39.92	38.83	41.02	
	A-Shredded Rubber (%)	-3.47	-4.37	-2.57	1
	B-Glass Powder (%)	-0.8305	-1.73	0.072	1

RCPT6 (Coulombs)	C-Biomass Fly Ash (%)	-0.9016	-1.8	0.0009	1
	AB	-1.37	-2.55	-0.1927	1
	A ²	-2.43	-3.35	-1.5	1
	Intercept	1198.03	959.48	1436.58	
	A-Shredded Rubber (%)	-73.37	-185.4	38.65	1
	B-Glass Powder (%)	-984.61	-1096.64	-872.59	1
	C-Biomass Fly Ash (%)	125.64	13.62	237.67	1
	AB	64.3	-82.07	210.67	1
	AC	-85.65	-232.02	60.72	1
	BC	-69.49	-215.86	76.88	1
	A ²	-55.28	-178.58	68.02	1.16
	B ²	402.54	279.24	525.84	1.16
	C ²	133.61	10.31	256.91	1.16

Note:

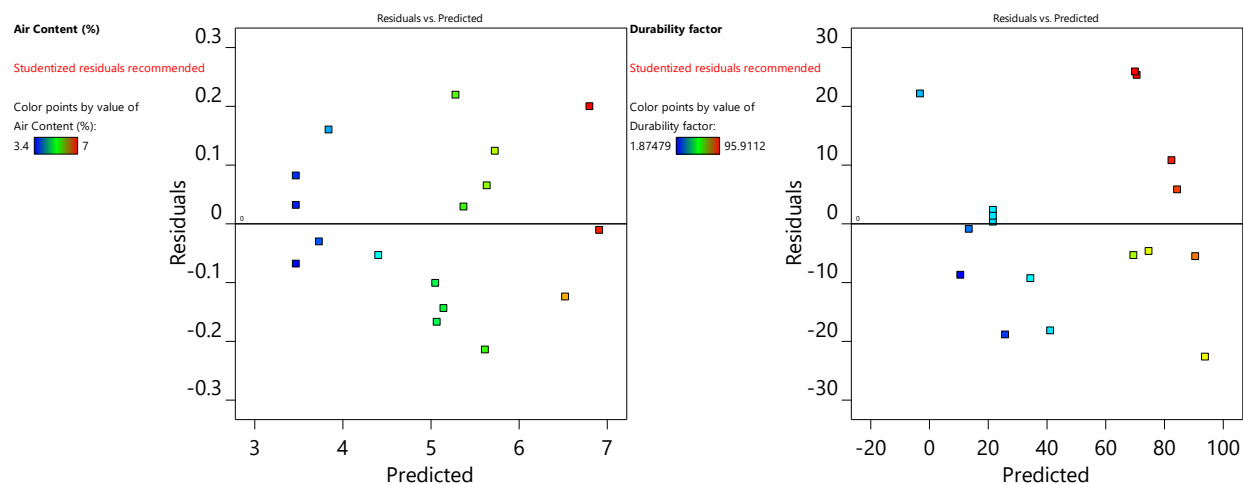
A = Shredded Rubber (%)

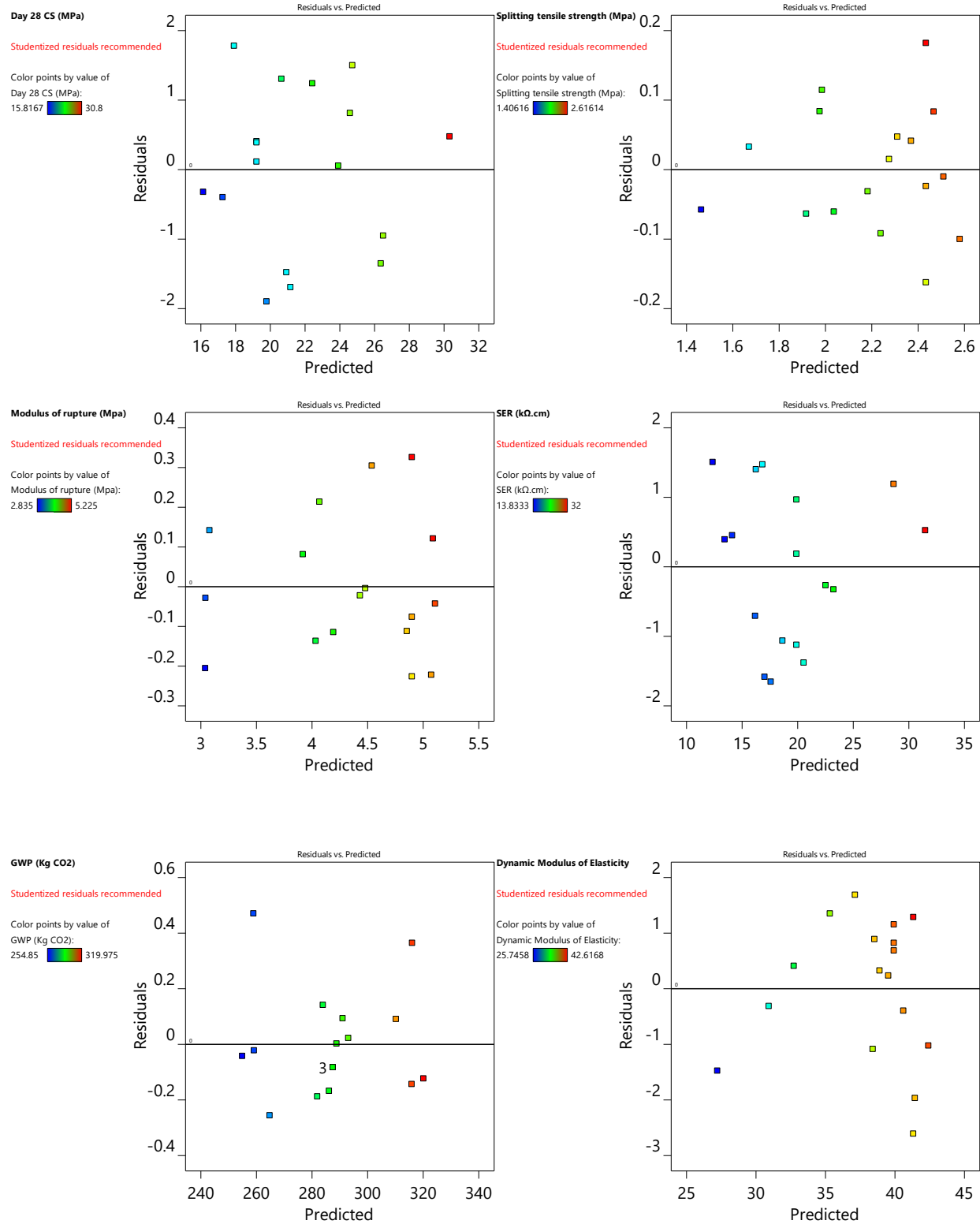
B = Glass Powder (%)

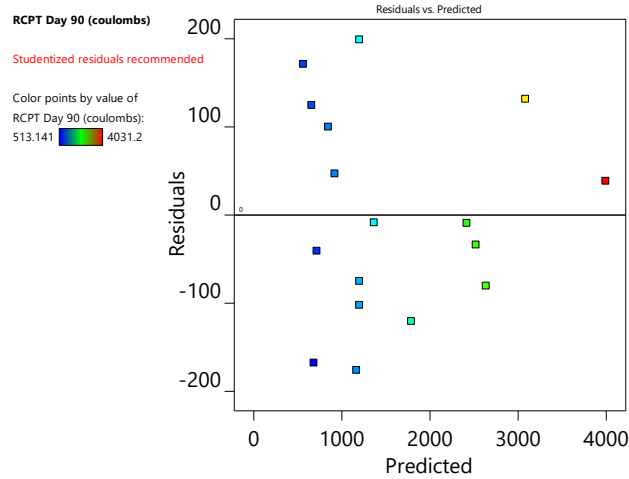
C = Biomass Fly Ash (%)

Appendix 5.2

Appendix presents the residuals versus predicted values plot for the RSM analysis, providing insight into the model's accuracy and the distribution of errors in predicting the test result.

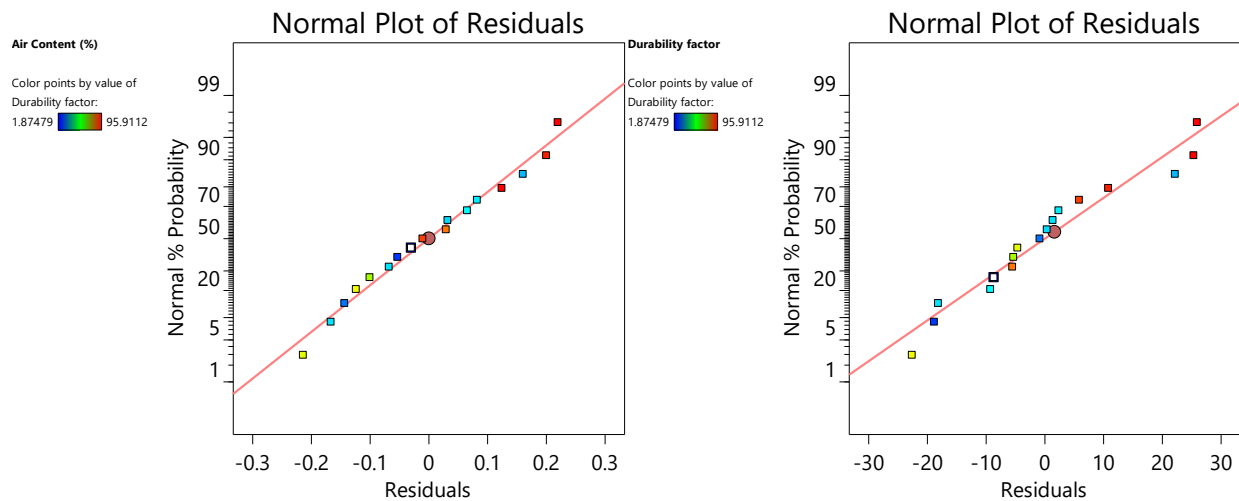


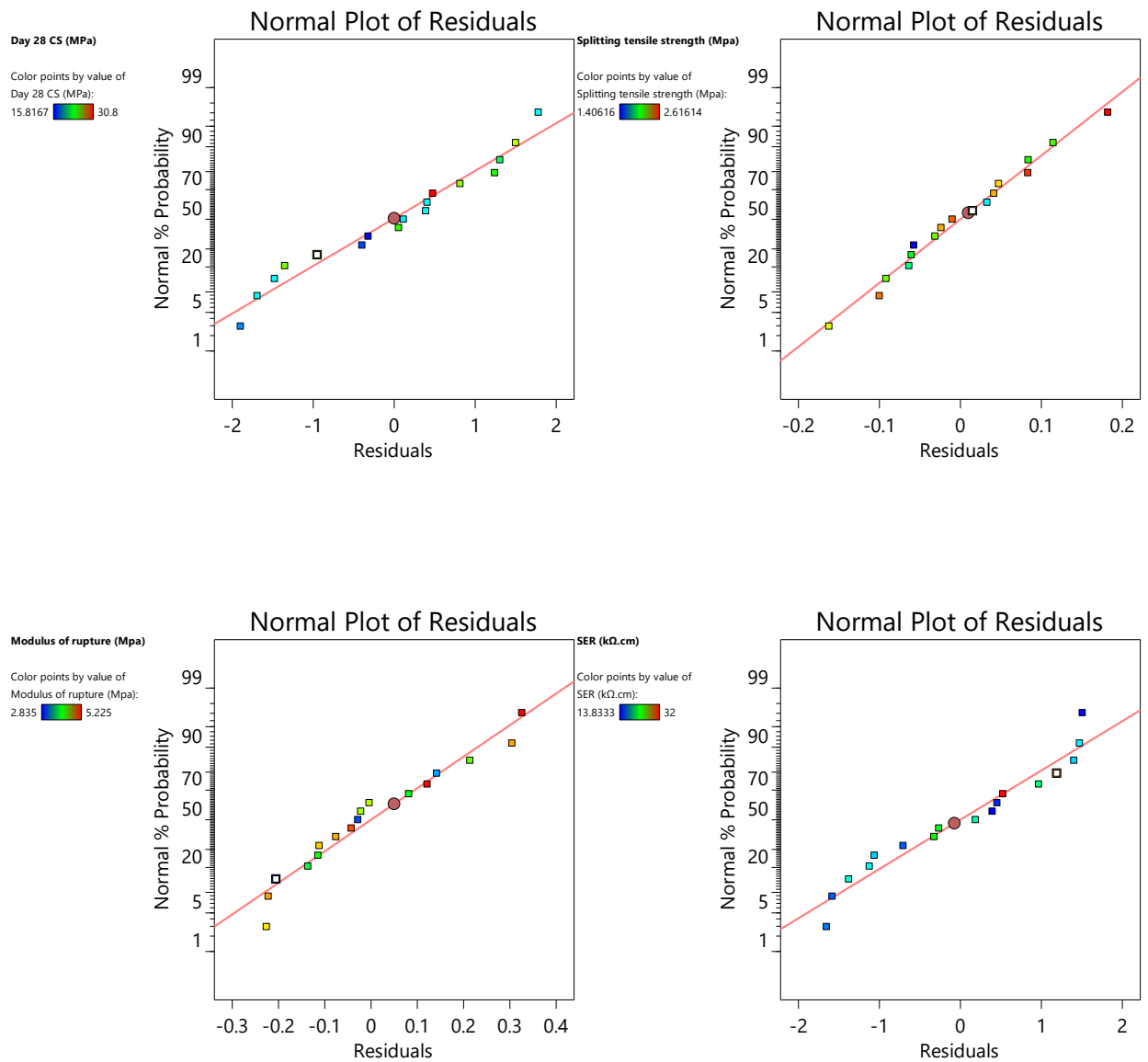


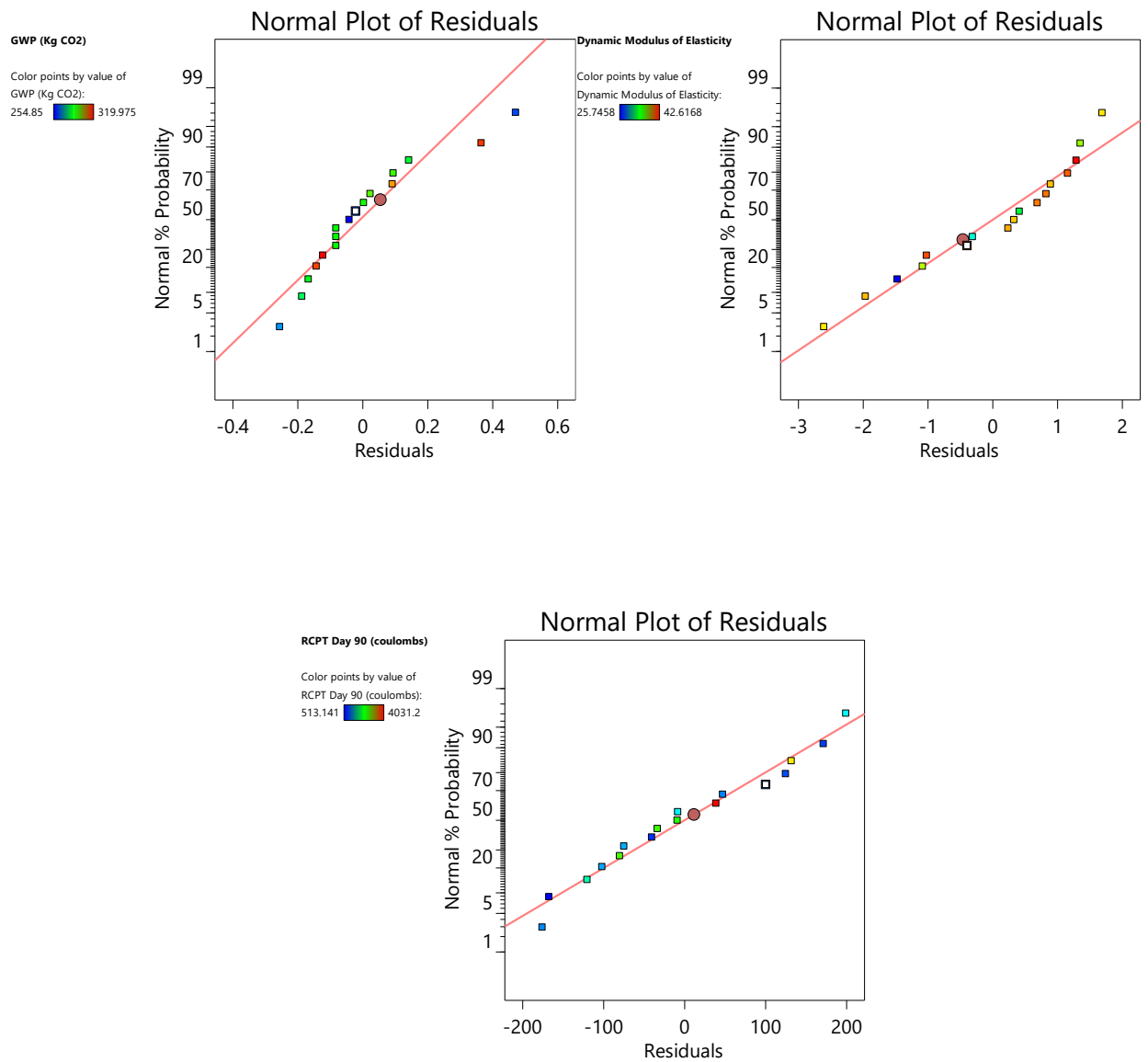


Appendix 5.3

Appendix represents the normal probability plots of residuals for all tested responses, showing residuals plotted against normal % probability to assess the normality of errors and the adequacy of model fit.







Appendix 6.1

This Appendix presents the equations employed to generate the data.

Slump	$\text{Sqrt}(\text{Slump (cm)}) = 4.28 + 0.11 \times \text{SR (\%)} - 0.002 \times \text{GP (\%)} + 0.23 \times \text{BFA (\%)} - 0.006 \times \text{SR (\%)}^2 - 0.039 \times \text{BFA (\%)}^2$	(1)
Compressive strength	$\text{CS (MPa)} = +33.18 - 2.67 \times \text{SR (\%)} - 0.49 \times \text{GP (\%)} - 0.15 \times \text{BFA (\%)} + 0.05 \times \text{SR (\%)} \times \text{BFA (\%)} + 0.10 \times \text{SR (\%)}^2 + 0.03 \times \text{GP (\%)}^2$	(2)
RCPT	$\text{Sqrt}(\text{RCPT (coulombs)}) = +76.34 - 0.38 \times \text{SR (\%)} - 2.29 \times \text{GP (\%)} + 0.93 \times \text{BFA (\%)} + 0.095 \times \text{SR (\%)} \times \text{GP (\%)} - 8.054\text{E-}003 \times \text{SR (\%)} \times \text{BFA (\%)} - 0.042 \times \text{GP (\%)} \times \text{BFA (\%)} - 0.10 \times \text{SR (\%)}^2 - 3.61\text{E-}003 \times \text{GP (\%)}^2 - 0.028 \times \text{BFA (\%)}^2$	(3)
BER	$\text{Sqrt}(28\text{-BER (ohm-m)}) = +2.60 - 0.07 \times \text{SR (\%)} + 0.016 \times \text{GP (\%)} + 8.11\text{E-}003 \times \text{BFA (\%)} - 1.22\text{E-}003 \times \text{SR (\%)} \times \text{GP (\%)} - 2.56\text{E-}004 \times \text{SR (\%)} \times \text{BFA (\%)} + 3.11\text{E-}003 \times \text{GP (\%)} \times \text{BFA (\%)} + 5.67\text{E-}003 \times \text{SR (\%)}^2 + 3.54\text{E-}003 \times \text{GP (\%)}^2 - 1.64\text{E-}003 \times \text{BFA (\%)}^2$	(4)
GWP	$\text{GWP (kg CO}_2\text{-eq/m}^3\text{)} = +342.32 - 0.47 \times \text{SR (\%)} - 2.85 \times \text{GP (\%)} - 3.02 \times \text{BFA (\%)}^2$	(5)
Air Content	$\text{AC (\%)} = 7.97 - 0.44 \times \text{SR (\%)} - 0.21 \times \text{GP (\%)} - 0.29 \times \text{BFA (\%)} + 0.012 \times \text{SR (\%)} \times \text{GP (\%)} - 0.013 \times \text{SR (\%)} \times \text{BFA (\%)} + -0.032 \times \text{GP (\%)} \times \text{BFA (\%)} + 0.0282806 \times \text{SR (\%)}^2 + 0.015 \times \text{GP (\%)}^2 + 0.042 \times \text{BFA (\%)}^2$	(6)
STS	$\text{STS (MPa)} = 1.73 + 0.09 \times \text{SR (\%)} + 0.10 \times \text{GP (\%)} + 0.05 \times \text{BFA (\%)} - 0.004 \times \text{SR (\%)} \times \text{GP (\%)} - 0.001 \times \text{SR (\%)} \times \text{BFA (\%)} - 0.002 \times \text{GP (\%)} \times \text{BFA (\%)} - 0.006 \times \text{SR (\%)}^2 - 0.003 \times \text{GP (\%)}^2 - 0.003 \times \text{BFA (\%)}^2$	(7)

Appendix 6.2

The table below lists the reviewed articles used for data extraction and the formation of the dataset utilized in the present study. This table specifies the type of waste materials and the experimental outputs reported for each survey.

Appendix 5.2 Dataset of concrete properties collected from different research works.

	Glass powder	Fly ash	Shredded rubber	Slump	Compressive strength	Splitting tensile	Air content	BER	RCPT	GWP	references
1	√				√						[293]
2	√		√	√	√				√		[294]
3	√				√	√					[295]

4	√		√						√	[296]
5		√			√	√				[297]
6		√								[298]
7	√		√		√					[299]
8	√		√	√	√	√			√	[300]
9	√				√	√				[301]
10			√	√	√	√				[302]
11			√		√	√				[303]
12			√		√					[304]
13	√		√	√	√		√			[95]
14	√		√	√	√			√	√	[305]
15			√	√	√					[306]
16			√		√					[307]
17				√	√					[308]
19		√	√		√					[309]
20			√		√					[310]
22			√		√	√				[311]
23			√	√	√	√				[312]
24			√	√	√		√			[313]
25	√		√	√	√					[314]
26	√			√	√		√		√	[315]
27		√			√	√				[316]
28	√		√		√	√		√	√	[317]
29		√	√						√	[318]
30	√		√		√					[319]
31			√	√	√		√			[320]
32	√		√	√	√				√	[321]
33			√	√	√				√	[322]
34		√	√		√		√			[323]
35			√	√	√	√	√		√	[324]
36			√		√				√	[325]
37		√	√		√				√	[162]
38		√		√	√				√	[326]
39	√				√				√	[150]
40	√				√					[327]
41	√			√	√			√		[294]
42	√				√				√	[328]
43		√			√		√	√		[329]
44			√	√	√	√				[330]
45			√		√		√			[331]

46			√	√	√						[332]
47			√		√	√					[333]
48			√								[334]
49			√								[335]
50	√				√				√		[314]
51			√		√				√		[32]
52	√		√		√	√					[336]
53	√	√	√	√	√	√			√		[337]
55	√				√			√	√		[338]
56		√		√			√				[339]
57	√		√	√	√		√		√		[340]
58			√	√	√						[341]
59			√	√	√	√		√	√		[342]