PERFORMANCE OF GLASS WASTE POWDER INCORPORATED SELF COMPACTING CONCRETE IN MARINE ENVIRONMENT

FINAL YEAR PROJECT UG 2019

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This is to certify that the Report entitled

"Performance of Glass Waste Powder Incorporated Self-Compacting Concrete in Marine Environment"

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ABSTRACT

In this thesis, thorough experimentation was conducted to investigate the effects of using glass waste powder as a secondary cementitious material in self-compacting concrete used in marine environments i.e., concrete that is exposed to seawater. The main goal was to assess the effects of replacement levels of cement with glass powder at 10%, 20%, and 30%. Each percentage was tested in three marine environments: fully submerged, partially submerged, and wetting and drying cycle. Fresh, mechanical, and durability properties of the concrete were tested. The glass powder being used as a cement substitute was obtained from finely grounding waste glass. This addresses the serious waste management and environmental issues faced in Pakistan and worldwide. A significant improvement in the concrete's mechanical and durability characteristics at the 20% replacement level was observed. This outcome was mostly related to the concrete mix's dense microstructure, which at this amount of replacement showed fewer voids and improved particle packing. This microstructure was shown to increase compressive and tensile strengths as well as durability properties. This study adds to the growing data of research on resource conservation, environmental sustainability, and the use of recycled materials in buildings. It creates fresh opportunities for further study into the use of waste glass in other building materials and under other circumstances.

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CHAPTER 1: Introduction

1.1 General:

The term "buildings in marine environments" can apply to a wide variety of man-made structures built in or near the water. Piers, sea barriers, and artificial islands are a few examples of these constructions, which may be constructed on or offshore. The marine sector is very significant to the economic development of many nations worldwide. Almost 37% of the total population lives within certain radius of coastal areas [1].But, the amount of cost required for the maintenance and refurbishment is very high and it keeps on increasing. According to previous research, almost half of budget is being spend on repair and maintenance of these structures [2]. Pakistan's constructure business experts have found out that almost 2 trillion Rs is being spent on maintenance and to rebuild buildings, roads and bridges [3]. The major damage of structures in marine environment is due to chloride permeability and steel corrosion. Almost 75% of the problems associated with concrete are caused because of corrosion, induction by carbonation and chloride ingress [4]. It affects the integrity, physical appearance, and reliability of the structures.

The deterioration in marine environment usually takes place due to fatigue, cracks propagation, corrosion, permeability, freeze and thaw and sulphate attacks etc. The marine structure can be completely, partially or exposed to wetting and drying cycles in corrosive seawater.

Mostly, structures near costal are exposed to domestically and industrially polluted seawater. Additionally, the structures that are not submerged in water present in the vicinity of coastal areas might face corrosion and other problems due to accumulation of salts and other harmful deposits. In the marine environment, concrete is the most used construction material. Concrete is made up of many inert materials known as coarse and fine aggregates which are bind together with water.

It is mostly used because of its mechanical, durability and low cost of construction comparative to other construction materials.

An important component of conventional concrete is Portland cement. Major elements in production of cement are Limestone with is a source of Calcium and the other one is clay which is a source of Silicon. Two major reactions occur during the production of cement. First reaction that occurs is conversion of limestone into lime and also carbon dioxide and this reaction takes place in the lower temperature portion of the kiln which is almost 900^{o}C. Another reaction that occur results in the formation of dicalcium and tricalcium silicates due to the bond formation of calcium oxides and silicates in addition to tricalcium Aluminate and tetra calcium Aluminoferrite in very less amount and this reaction takes place at a very high temperature which is about 1450^{o}C and this results in a new element which is called clinker [5].According to research, almost 4-8% of total carbon dioxide emission is because of production of cement. World Business Council for Sustainable Development (WBCSD) expects global cement production to grow by 12 to 23% by 2050, with increase in global population and migration into cities. As a result, direct carbon emissions from cement industry are expected to increase by 4% globally by 2050 [6].

Also, in marine environment, corrosion and chloride permeability can be controlled by either densifying the concrete matrix or by using fiber reinforced plastic. By densification of cement matrix, the permeability decreases, and concrete becomes less susceptible to the infiltration of solutions which may contain chemicals detrimental to concrete such as acids, chlorides, and salts. Use of FRP reduces crack growth and increases impact strength. It gives resistance against freezing and thawing and reduces permeability. It gives high chemical resistance and corrosion isn’t a concern.

For densification of concrete matrix, Supplementary Cementitious Materials (SCMs) can be used to replace the Cement. The usage of clinkers is reduced because of the substitution of SCMs for OPCs, lowering related carbon emissions and increases the sustainability of the building sector. An SCM typically replaces 20% of the cement.

Agricultural waste (Rice Husk), natural pozzolans (Volcanic Ash), and industrial byproducts (Fly Ash, Silica Fumes) are common sources of SCMs. The addition of SCMs causes a pozzolanic reaction in addition to hydration, which results in the conversion of the calcium hydroxide generated by hydration into secondary calcium silicate hydrate, increasing the strength, density, and ion diffusion resistance of concrete.

1.2 Waste glass powder as SCM:

When using such industrial by-products in place of cement, there is a decrease in associated CO2 emissions as well as effects that lessen the environmental impact of landfills and waste. Every year, millions of tons of glass waste is being produced all over the world.

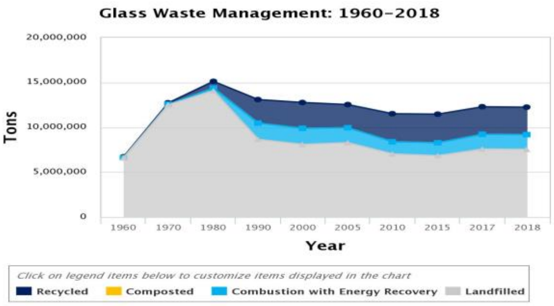


Figure 1: Production of GW in USA per year [7]

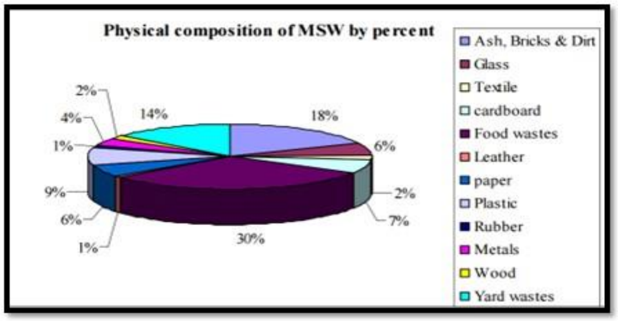


Figure 2: GW Contribution in total MSW in Pakistan [8]

Waste glass is a component with a composite profile containing approximately 70% SiO2 and exhibits confirmed pozzolanic activity when it reacts with cement during hydration. Incorporating waste glass as fine particles in concrete holds promise for enhancing its long-term performance. This is attributed to its capacity to reduce concrete permeability, thereby improving durability through increased pozzolanic activity and micro-filling of pores within the cement matrix. Research studies have documented the utilization of waste glass as fine particles resulting in reduced permeability and improved durability of concrete.

By improving the performance of concrete, the need for maintenance and repair is reduced, which leads to a decrease in costs for end-users. This, in turn, contributes to the social aspect of using concrete as it becomes a more cost-effective and efficient construction material. The resulting decrease in maintenance intervals is expected to have a significant impact on reducing costs associated with repair and maintenance, further enhancing the economic and social benefits of using concrete [9]. So, replacing cement by waste glass waste will not only reduce the CO_2 emission but also prevent the glass waste going into landfill.

1.3 Self Compacting Concrete

SCC flows more easily and uniformly than traditional concrete, which allows it to fill complex forms and reach confined areas without the need for external vibration which minimizes voids in highly reinforced concrete. This results in better compaction and higher quality concrete. SCC requires less labor than traditional concrete because it does not require external vibration, which means it can be poured more quickly and with fewer workers.

SCC has higher strength and better resistance to permeability than traditional concrete [10]. This means it is less likely to crack and is better able to resist the effects of saltwater and other harsh environmental conditions.

1.4 Problem Statement

To minimize greenhouse gas emissions and address the issue of permeable concrete, it is crucial to research and create sustainable alternatives to cement that densify the concrete matrix, while simultaneously enhancing durability and impermeability of concrete structures in marine environment.

1.5 Research Objectives

1. To develop a mix design for glass powder incorporated SCC to be used in marine environment.
2. To study fresh and mechanical properties of glass powder incorporated SCC.
3. Simulation of three artificial marine environment conditions in the lab
4. To study durability properties of glass powder incorporated SCC in marine environment
5. To carry out life cycle assessment of developed concrete to determine impact on environment

CHAPTER 2: Literature Review

2.1 Concrete in Marine Environment

The marine industry makes a major contribution to the world economy. By enabling the flow of goods and services around the world, marine development and infrastructure, such as ports, harbors, and shipping routes, support global trade and commerce. An essential component of a country's economic success is marine development [11]. For the purpose of increasing living space and resources, the development and use of the ocean have become crucial issues. A lot of construction materials are needed for marine development. Concrete is widely used and serves a variety of purposes in marine structures. The worst environmental conditions in the engineering world are often present for marine concrete [12]. Understanding the durability deterioration of concrete under marine environment is crucial given the rise in offshore structures such as civil and military terminals, offshore airports, offshore wind power stations, sea lighthouses, radar stations, island reefs, and fortifications [13] [14]. Ben Faraj et al. [15] have stated that designing concrete structures in marine environment heavily relies on durability considerations.

2.2 Durability of Concrete

Concrete's durability can be described as its capacity to withstand abrasion, chemical attack, weathering action, and other mechanisms of deterioration while maintaining its original shape. The cover layer's resistance to transport mechanisms such as penetration, absorption, and diffusion of gas and liquid is closely correlated with the degree of deterioration [16]. Concrete's transport characteristics, including porosity, chloride diffusion, and capillary absorption, are frequently used to assess its durability. High durability performance by concrete in marine environment is necessary to build a safe structure and to provide long service life.

2.3 Self-Compacting Concrete

One of the most notable developments in recent decades in concrete technology is self-consolidating concrete (SCC). SCC is a type of concrete that can self-compact under its own weight alone without the need for vibration. In heavily reinforced concrete members, it fills reinforcing holes and spaces very efficiently, and it flows without segregating [17]. Previous studies revealed that using fly ash in SCC decreased the amount of superplasticizer required to achieve a comparable slump flow as compared to concrete composed only of Portland cement. Additionally, the use of fly ash in the concrete mix increased its rheological characteristics and decreased thermal cracking [18].

Numerous studies have examined the durability characteristics of vibrated concrete (VC) and self-consolidating concretes (SCC) with comparable strength ratings. Ryan and O'Connor [19] showed that VCs were more chloride resistant than SCCs under steady state-chloride migration circumstances. According to several studies, SCCs have better durability characteristics (lower open porosity, sorptivity, and chloride permeability values) than VCs [20] [21]. Assie et al. [22] did, however, find that VCs and SCCs performed equally well in terms of durability. Shadkam et al. [23] also discovered that SCCs and VCs with the same cement paste quality (i.e., identical w/c ratio) had the same durability characteristics. Reduced segregation and bleeding, improved compaction, reduced permeability and higher strength are usually associated with SCC which in turn gives better durability performance.

Overall, even though numerous studies have assessed the performance of vibrated or self-consolidating cementitious specimens in stable or unstable control or rich chloride environments, the performance assessment in various marine environmental conditions is necessary.

2.4 Glass Waste as Cement Replacement

There are an increasing number of studies revealing waste glass' potential as an environmentally friendly substitute for Portland cement (with particle size of below 100 m) or fine aggregate (with size of below 4.75 mm) in concrete due to its production of approximately 100 million tonnes per year and its low recycling rate of 26% [24]. Glass is an amorphous, non-crystalline substance with a high silicon quantity [25]. The production of glass is known to be an energy-intensive process, with 1 kilogram of glass sheet producing an estimated 16.9 M.J. (million Joules) of waste heat and 0.57 kg of CO2 [26]. Although it can be recycled continuously [27], due to the expense and energy involved in the recycling process, it is usually more cost-effective to landfill it [28]. The soda-lime-based glass is generally the most readily available glass material and is regarded as solid waste [29]. This type of glass consists of more than 70% silica [30]. It can dissolve in concrete mixture's highly alkaline media and participate in the hydration of OPC by interacting with calcium hydroxide to form calcium silicate hydrate (C-S-H) [31]. This formation of C-S-H gel leads to dense microstructure and better durability performance of concrete.

Due to the high alkali levels associated with glass, it is frequently researched whether concrete containing glass powder is susceptible to the alkali silica reaction (ASR). According to research, employing finely ground glass powder in concrete with typical sizes lower than 75 m could reduce the ASR [32] [33] [34] [35]. Additionally, replacing cement with glass powder could help in lowering the harmful expansion related to ASR.

The pore structure of concrete containing glass powder continues to change and be refined, improving the durability performance of the binder system and significantly extending the service life of concrete exposed to marine environments [36].

CHAPTER 3: Materials and Methodology

3.1 Materials

3.1.1 Glass Waste Powder

Glass Waste Powder (GWP) was obtained from glass cutting workshops located in Faizabad. Originally in wet powder form due to the process it underwent in the shops during cutting, it had to be oven dried at 110° C for at least 5 hours. After oven drying the GWP was tamped using a rammer in order to remove any remaining clumps and obtain fine powder. It was then sieved through sieve no. 200 so that particles of size less than or equal to 75 micrometers could be separated for use in the concrete.


(a) (b)

Figure 3: GWP (a) being tamped (b) after tamping

3.1.2 Fly Ash

Class F fly ash was used as a secondary cementitious material. Fly ash particles are smaller than concrete, between 10 and 100 microns, which allows for denser, less permeable concrete. Fly ash particles are also spherical in shape which allows for greater workability. Both properties are desired in self-compacting concrete (SCC) exposed to marine environment, hence why it is used in the mix design for the concrete. Moreover, fly ash is pozzolanic in nature so it contributes to greater compressive strengths over time.

3.1.3 Cement

Type 5 Cement (Portland cement Type 5) was used as is the norm for coastal structures and other structures exposed to high risk of sulphate attack such as marine environments. It was preferred due to its low aluminate phase.

3.1.4 Fine Aggregate

Fine aggregate was obtained locally from retailers in Islamabad. Sieve analysis [37] was performed to determine the particle size gradation of the fine aggregates. The resulting gradation curve, which satisfies the upper and lower limits set by ASTM C33 [38] and is well graded, is shown in fig. 4. The fineness modulus of the aggregate was found to be 2.39 which means fine sand was used in the preparation of this concrete.

ASTM C127 was used to determine the specific gravity and absorption capacities of the aggregates [39]. The specific gravity of these aggregates was found to be 2.65 and the absorption capacity was 1.4% making these fine aggregates of good quality and suitable for use in developing the experimental concrete.

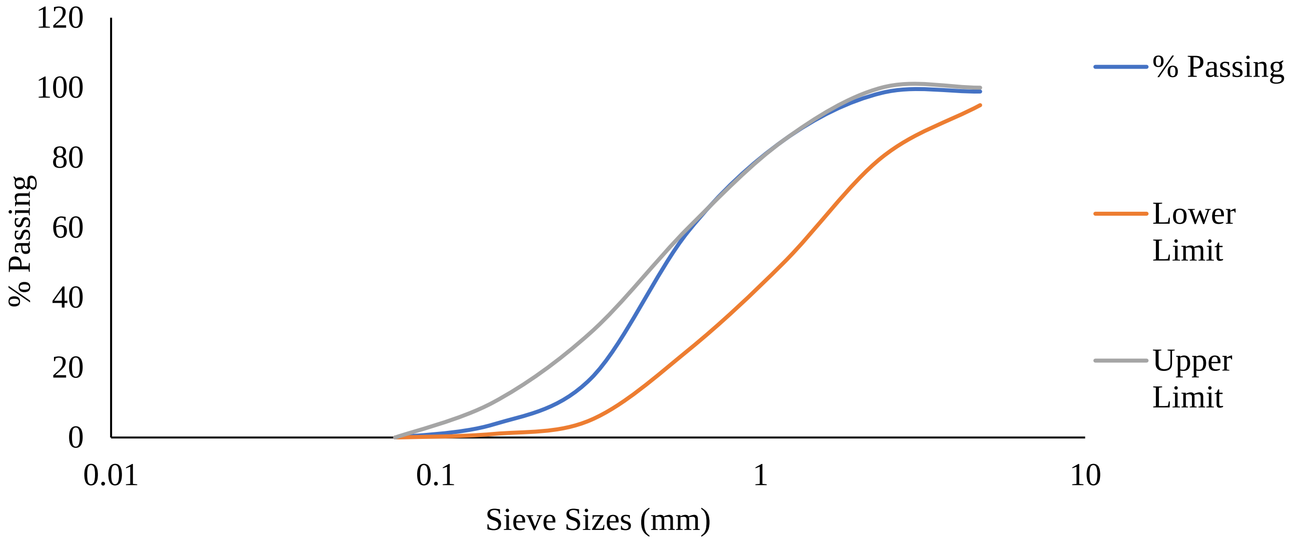


Figure 4: Particle Size Gradation of Fine Aggregate

3.1.5 Coarse Aggregate

Coarse Aggregate was obtained locally from retailers in Islamabad. After performing sieve analysis [37], the following gradation curve was obtained (fig. 5). The curve shows the coarse aggregates meeting the requirements set by ASTM C33 [38], i.e., which means it is well suited for use. The maximum aggregate size was found to be 1” whereas the maximum nominal size was found to be ¾”.

The specific gravity of this aggregate was found to be 2.67, which falls within the range of typical values set for usable aggregates. The absorption capacity for this aggregate was found to be 0.6%, which is also within the range of typical absorptive capacities of coarse aggregates. ASTM C127 was followed for determination of both aforementioned [39].

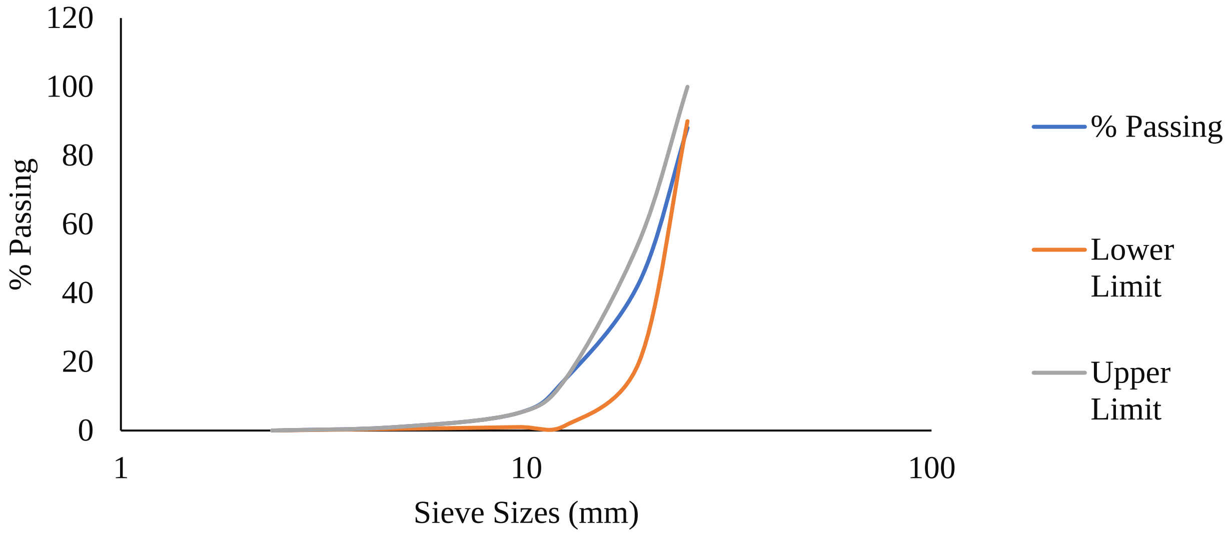


Figure 5: Particle Size Gradation of Coarse Aggregate

3.1.6 Superplasticizer

Sika ViscoCrete - 20 HE is a high range water reducing admixture and was acquired from the Rawalpindi Sika branch. This was used to increase the flowability of concrete and produce a denser, more well compacted concrete with as little negative impact on the workability as possible due to the addition of the GWP.

3.1.7 Salts

For creating artificial marine environment certain salts were acquired through local vendors. Marine environment was created as per ASTM D1141-98 [40]. The salts required for 1 Liter of water are noted in the table below:

Table 1: Artificial Seawater Composition ASTM D1141-98 [40]

Name	Chemical Formula	Amount (g/L)
Sodium Chloride	NaCl	24.53
Magnesium Chloride	$MgCl_2$	5.20
Sodium Sulphate	Na_2SO_4	4.09
Calcium Chloride	$CaCl_2$	1.16
Potassium Chloride	KCL	0.695
Sodium Bicarbonate	$NaHCO_3$	0.201
Potassium Bromide	KBr	0.101
Boric Acid	H_3BO_3	0.027
Strontium Chloride	$SrCl_2$	0.0025
Sodium Flouride	NaF	0.003

3.2 Mix Design and Specimen

3.2.1 Mix Design

The mix design for the control concrete i.e., Non-Glass Waste (NGW) was selected from literature [41]. Cement was then substituted at 10%, 20% and 30% using glass waste powder for the experimental mix designs. The proportions of materials were as follows:

Table 2: Mix Design of Concrete

Concrete	Cement (kg)	Fly Ash (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	Water (kg)	Superplasticizer (g)	Glass Waste (g)
NGW	1	0.28	2.01	1.16	0.52	1.14	0
GW 10%	0.9	0.28	2.01	1.16	0.52	1.14	100
GW 20%	0.8	0.28	2.01	1.16	0.52	1.14	200
GW 30%	0.7	0.28	2.01	1.16	0.52	1.14	300

3.2.2 Specimen

Specimen were divided into four groups: specimens having no glass waste i.e., non-glass waste specimens (NGW), specimens having 10% glass waste powder (GW10), specimens having 20% glass waste powder (GW20), and finally specimens having 30% glass waste powder (GW30). 23 specimens were prepared from each group to be tested in the artificially prepared marine environment which made for 92 specimens in total. Besides these an additional 92 specimens were to be cast using the exact same procedure which would not be put in the marine environment to act as control specimens.

3.3 Casting and Curing

3.3.1 Casting

Materials were weighed using a large scale and added to a rotary drum mixer. Concrete mixing took a total of eight minutes. The first two minutes were spent on dry mixing. The next minute of mixing was spent adding 80% to 90% of the water. The remaining water was mixed with superplasticizer and added in during the fourth minute. The mixing continued for four more minutes in order to evenly distribute all the materials throughout the paste. The mixer would be stopped after the sixth minute in order to perform manual mixing so that all pockets of dry materials stuck in the sides and hard to reach places of the drum could also be incorporated into the mix. However, this activity was limited to 30 to 40 seconds only and the mixer would at once be switched on afterwards in order to complete the remainder of the eight minutes.

After mixing concrete was poured into pre prepared cylindrical concrete molds of 100 mm x 200 mm. After 24 hours the cylinders were demolded and subsequently taken for curing.

3.3.2 Curing

Cylinders were cured in water for 27 days. After all the samples had been cast and cured specimens were placed in the accelerated test setup for 7 days. After this wetting and drying cycles began.

Figure 6: Cured NGW Cylinders (before being put in accelerated test setup)

3.4 Accelerated Test Setup

Four tanks were set up containing identical solutions of water. The solution consisted of water with eight times the normal concentration of salt as compared to sea water. This was done in order to speed up the weathering processes so that notable results could be obtained within the limited time frame and was observed being done in other sea water related studies found during the literature review [42].

The tanks were made to replicate three possible scenarios for structures constructed in marine environment: fully submerged, partially submerged and wetting and drying cycles.

The fully submerged tank was full to the brim with the solution and contained cylinders at the four (0%, 10%, 20%, 30%) different percentages submerged in it as shown in fig 7 (a).

Two identical tanks were used to simulate the partially submerged scenario. Each tank was half full of the solution and contained cylinders of the four different percentages arranged so that the solution came up to the 100 mm mark on the cylinders i.e., half the height of the cylinders. This is displayed in fig 7 (b).

(a) Fully submerged environment

(b) Partially Submerged Environment

(c) Wetting and Drying Cycles

Figure 7: Test Setups

The last tank was used to simulate the wetting and drying cycles and is shown in fig 7 (c). It was identical to the fully submerged tank except the cylinders would be removed for one week at a time for the drying cycle and then returned for one week for the wetting cycle. This was repeated for the duration of the 52 days the samples were put in the accelerated test setup for.

CHAPTER 4: Testing program

4.1 Fresh properties

4.1.1 Slump flow

According to ASTM C143-78 [43], The slump test was performed for workability for concrete. The concrete slump cone used for this test had an upper diameter of 4 inches, a bottom diameter of 8 inches, and a height of 12 inches.

Figure 8: Slump Flow Test

4.1.2 V Funnel Test

The UTC-0540 V Funnel apparatus was used to perform the flow time of self-compacting concrete. The test set consists of a stainless-steel funnel that is mounted on a supporting stand. A lid that can be opened is attached to the discharge orifice at the bottom of the funnel. The maximum aggregate size possible for this test is 22.4 mm due to the sizes of funnel openings.

4.2 Mechanical properties

4.2.1 Compressive strength

According to ASTM C39 [44], a compressive strength test was performed. Cylinders were cast and cured and then placed in three different simulated conditions: totally submerged, partially submerged and wetting & drying cycles, and finally tested. Compressive strength was measured using CyberPlus UTM Model H011-01N, keeping the loading rate to 0.25 MPA/sec. Fig. 9 shows failure of specimens in compressive strength test.

(a) *(b)*

Figure 9: Compressive Strength Test Performed on GW30 Sample (a) before failure (b) after failure

4.2.2 Split Tensile Strength

ASTM standard C496 [45] was used to perform the split tensile test on cylinder. Test Method C 39/C 39M was used for this test. Loads were applied within the range 0.7 to 1.4 MPa/min at a constant rate until the specimen failed. Fig 10 shows the split tensile test being performed on the samples.

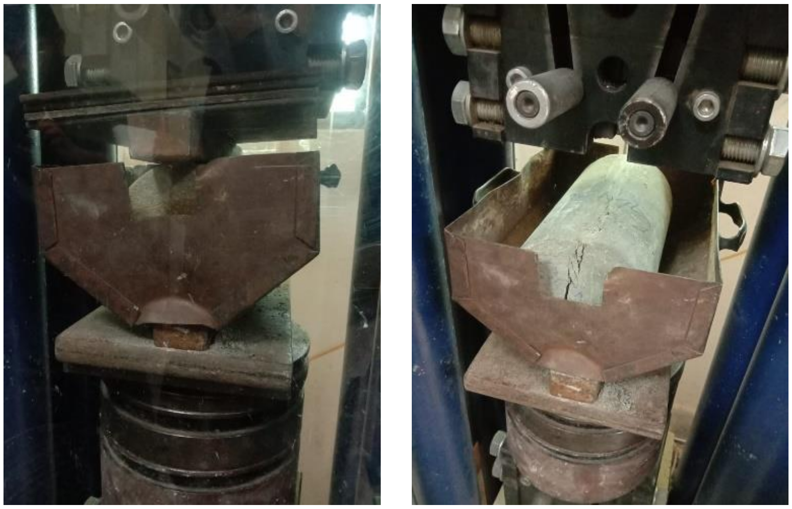

(a) (b)

Figure 10: Split Tensile Test Being Performed on Samples (a) before failure (b) after failure

4.2.3 Dynamic Modulus

Dynamic Modulus was indirectly determined by performing the Ultra sonic pulse velocity test according to ASTM C597 [46]. The following formula was then applied to obtain the final values for dynamic modulus:

$$\mathbf{E}_{\boldsymbol{d}} = \boldsymbol{\rho V^2} \frac{(\mathbf{1} + \boldsymbol{\mu_{pr}})(\mathbf{1} - \mathbf{2}\boldsymbol{\mu_{pr}})}{(\mathbf{1} - \boldsymbol{\mu_{pr}})}$$

The symbols used are explained below:

Ed = dynamic modulus of elasticity (MPa)

ρ = density of concrete (kN/m^3)

V = pulse velocity (km/s)

μ_{pr} = Poisson’s ratio of concrete

4.2.4 Flexure Test

Flexure Test was performed according to ASTM C293 [47]. The 400mm beams were loaded onto the test setup as shown in fig 11 and center point loading was applied until failure.

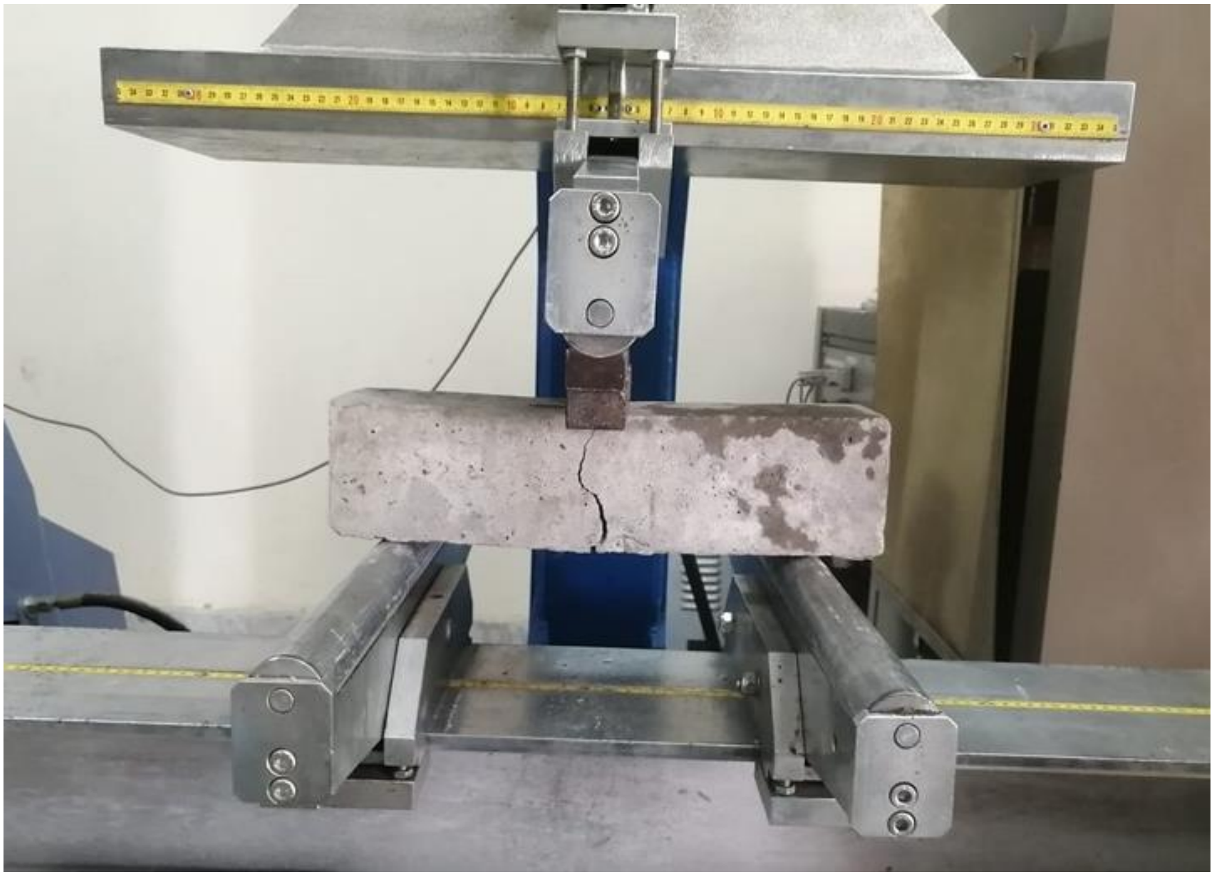


Figure 11: Specimen loaded into test setup

4.3 Durability Properties

4.3.1 Water Absorption

This test was performed according to ASTM Standard C140 [48]. The concrete cylinders were first dried as shown in fig. 12, then weighed. The cylinders were then immersed in water for 24 hours and weighed again. The percentage increase in weight indicates their absorption.

Figure 12: Samples Set to Dry for Water Absorption Test

4.3.2 Permeability

The permeability of cylinder was determined by measuring the depth of penetration of water under pressure in the concrete specimens. Samples were set in the apparatus and water was applied at a controlled pressure to the top and bottom surfaces of the cylinder. The cylinders were then broken into halves and a tape measure was used to measure the water ingress. Fig 13 shows samples set in the apparatus for permeability test.

Figure 13: Samples Set in Apparatus for Permeability Test

4.3.3 Carbonation

Carbonation test was performed according to the in-situ procedure of spraying phenolphthalein indicator on the inside surface of samples cut in half. When the surface turns purple it means no carbonation took place and if no color change takes place, it means carbonation took place on those samples.

4.3.4 Porosity

Porosity was performed according to ASTM C642 [49]. Dry mass (M1), saturated dry surface mass (M2), saturated mass in water (M3) was measured and was put in the following formula:

$$Vv = \frac{M3 - M2}{M3 - M1} \times 100$$

CHAPTER 5: Results and discussion

5.1 Fresh Properties

5.1.1 Slump Flow

Slump flow test results for each percentage of glass powder are compared in Figure 14 which demonstrates that glass powder has a negative impact on slump flow diameter. This can be explained by taking into consideration the sharp and angular shape of glass powder particles. Due to these geometric properties glass powder particles have increased friction and thus lower slump flow diameters. Moreover, the glass waste powder tends to absorb water, which also reduces the flowability and workability of concrete.

Compared to NGW concrete, incorporation of 10% GWP caused a decrease of 6.58% in slump flow, 20% GWP caused a decrease of 9.21% whereas 30% GWP caused a decrease of 12.5%.

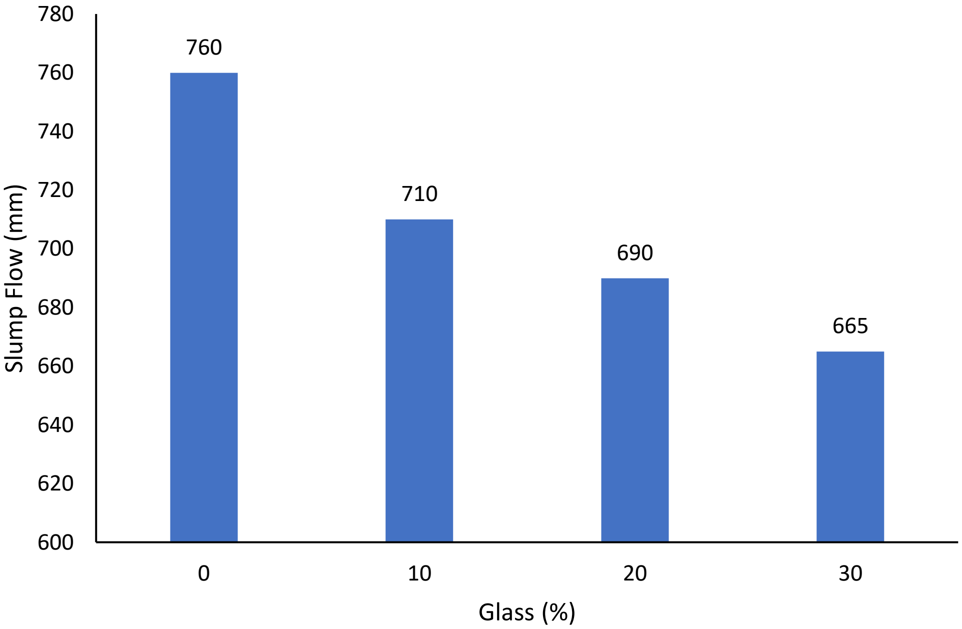


Figure 14: Comparison of Slump Flow for Different Percentages of GWP

5.1.2 V funnel test

Fig. 15 shows comparative results of V-funnel test times at the four different glass powder percentages. As the percentage of glass powder increases so does the V-funnel test time.

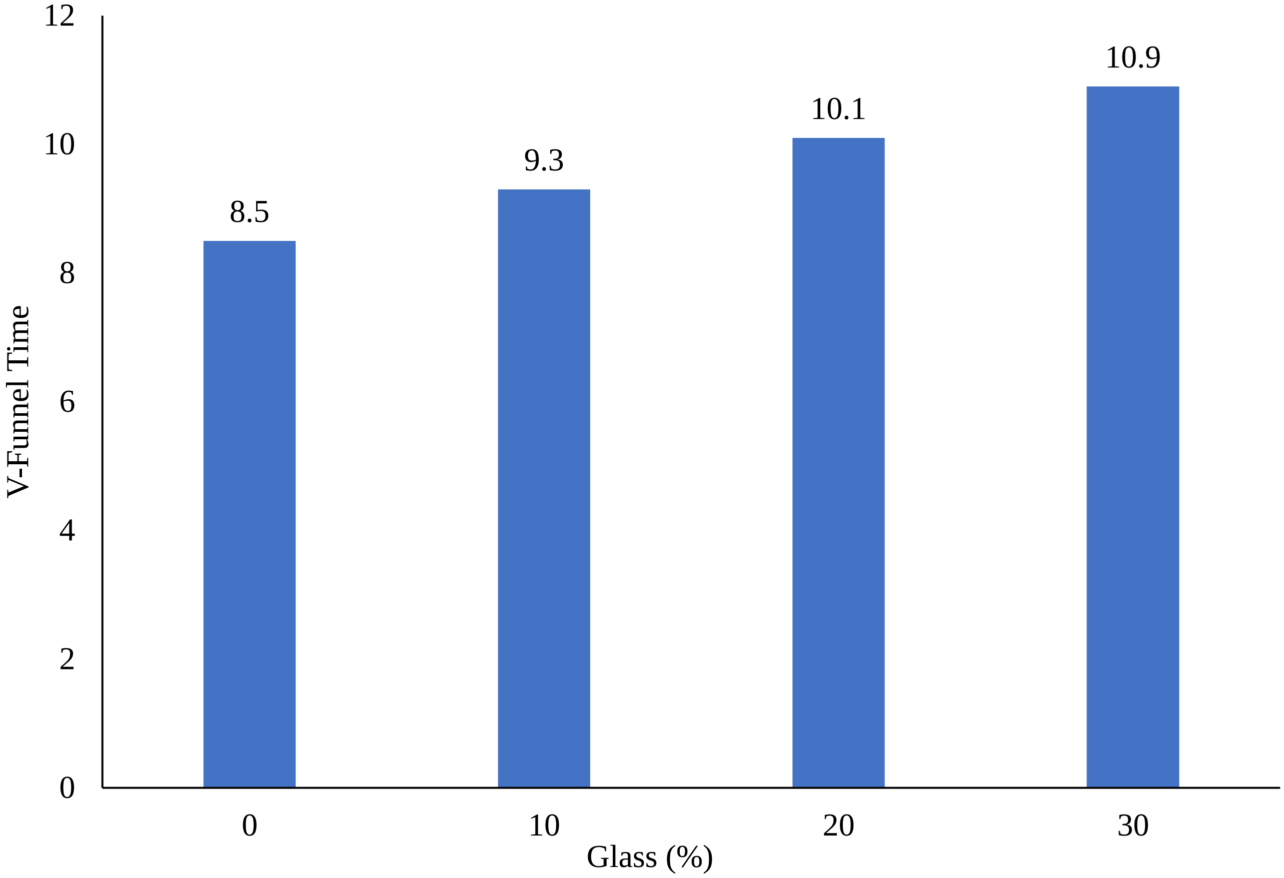


Figure 15: Comparison of V-Funnel Times for the different percentages of GWP

5.2 Mechanical properties

5.2.1 Compressive strength

Fig 16 shows a comparison between the compressive strengths of concrete at different GWP percentages as well as different marine environments. Across all three environments 20% GWP gives the highest compressive strength. This increase is attributed to filling effect of glass particles in concrete matrix.

In a completely submerged condition, SCC incorporating GWP exhibits high compressive strength as compared to partially submerged condition and wetting and drying cycle. This can be due to the least destructive phenomenon observed in completely submerged environment. There is no evaporation of water as the cylinders are never exposed to air so there are no excess stresses developed in the pores from constant expansion and contraction. The absence of drying shrinkage and the continuous curing provided by the water can also help

In partially submerged environment water from the bottom half (that is submerged in marine water) takes in water which travels upwards via capillary action and enters in the pores of the top half of the concrete exposed to air. The water then evaporates from here which develops stress as the pores expand and contract which weakens the specimen.

In a wetting and drying cycle, the specimen are exposed to alternating periods of wetting and drying, which can lead to cracking and reduced strength over time. In wetting and drying cycles, the continuous evaporation of water when the cylinder is placed in air causes the same expansion and contraction of pores observed in partially submerged environment but here it takes place throughout the complete length of the cylinder which reduces the strength even more and produces worse results.

Compressive strength decreases with the increase of percentage of glass powder but gives a maximum value at 20%.

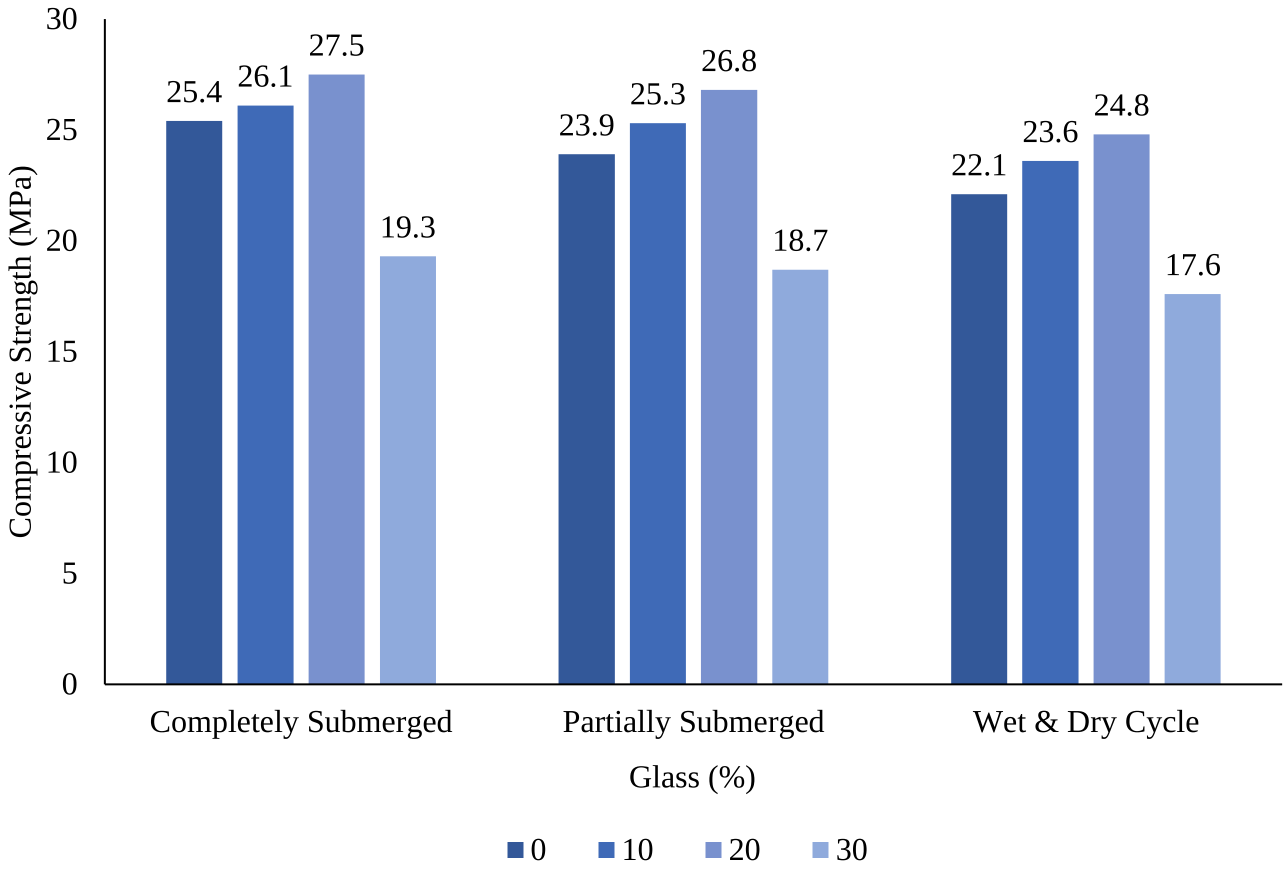


Figure 16: Comparison of Compressive Strengths

5.2.2 Split Tensile Strength

The comparative results illustrated in fig 17 show the addition of glass waste powder has a positive impact on the split tensile strengths of the concrete cylinders across all environments until the 20% replacement mark. After that, at 30% replacement of cement the split tensile strength has a sharp decline.

Although the difference in split tensile strengths is much less widely spread than for compressive strengths, the optimum replacement level still comes out to be 20%.

The trend seen across the marine environments in the compressive strength test is observed here as well, with completely submerged showing the best results followed by partially submerged and then wetting and drying cycles due to the same phenomenon previously described.

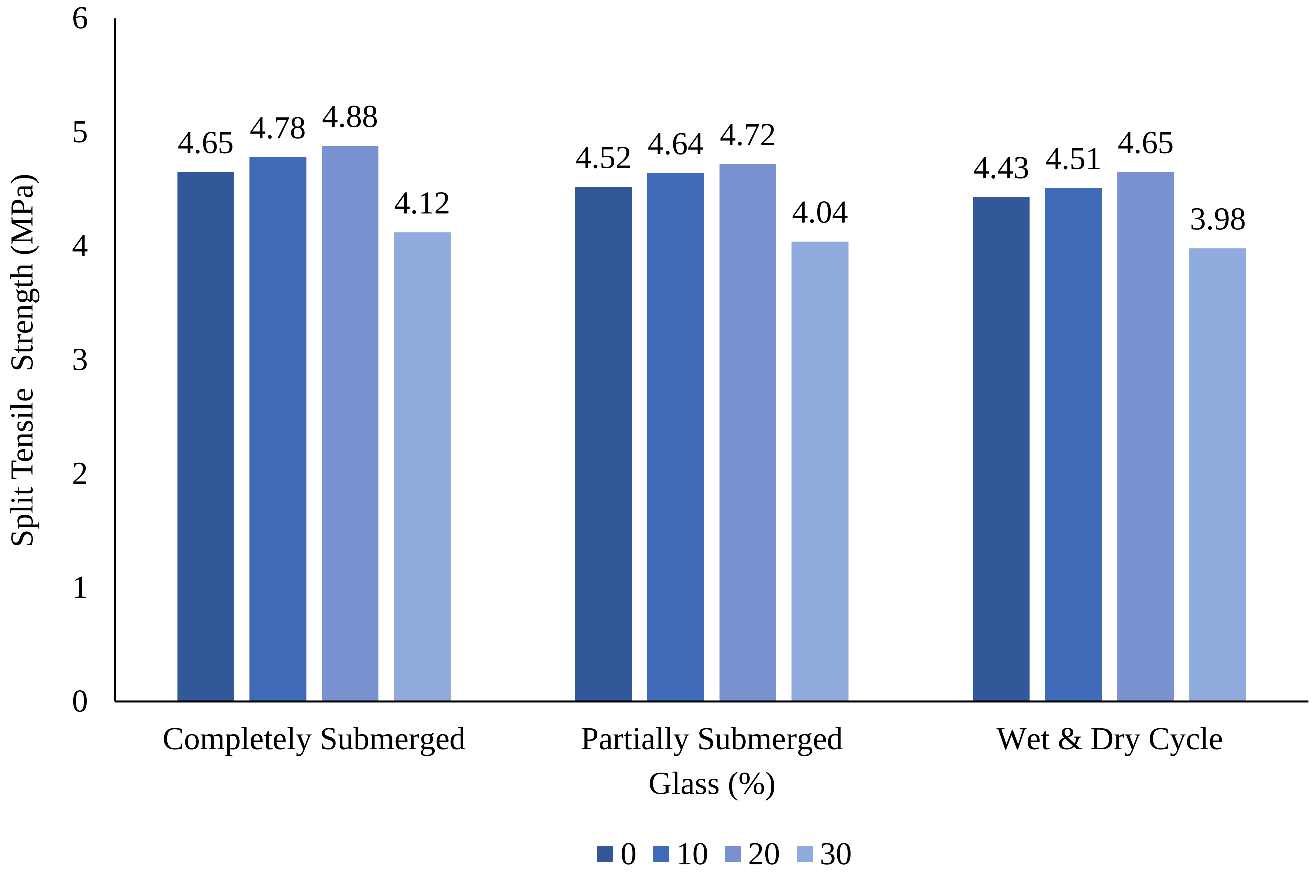


Figure 17: Comparison of Split Tensile Strengths

1.2.3 Dynamic Modulus

The dynamic modulus of concrete is a measure of its stiffness or elasticity under dynamic loading conditions. It quantifies the ability of concrete to resist deformation and recover its shape when subjected to dynamic forces. The dynamic modulus is determined through ultra-sonic pulse velocity test and is an important parameter in assessing the structural behavior and performance of concrete under varying loading conditions.

The dynamic modulus test shown in fig 18 reveals same aforementioned results across different marine environments, with fully submerged conditions demonstrating the highest performance for all concrete samples, followed by partially submerged conditions, and wetting and drying cycles. The penetration of moisture, accompanied by chemical reactions and physical processes like freeze-thaw cycles, induces damage and degradation within the concrete matrix. Consequently, the stiffness and strength of the concrete are reduced, resulting in poorer performance. This explains why normal concrete, which is more susceptible to durability issues in marine environments, exhibits worse results compared to the denser specimens that incorporate glass waste products (GWP). The denser GWP specimens offer improved resistance to these durability challenges, resulting in better performance in the dynamic modulus test.

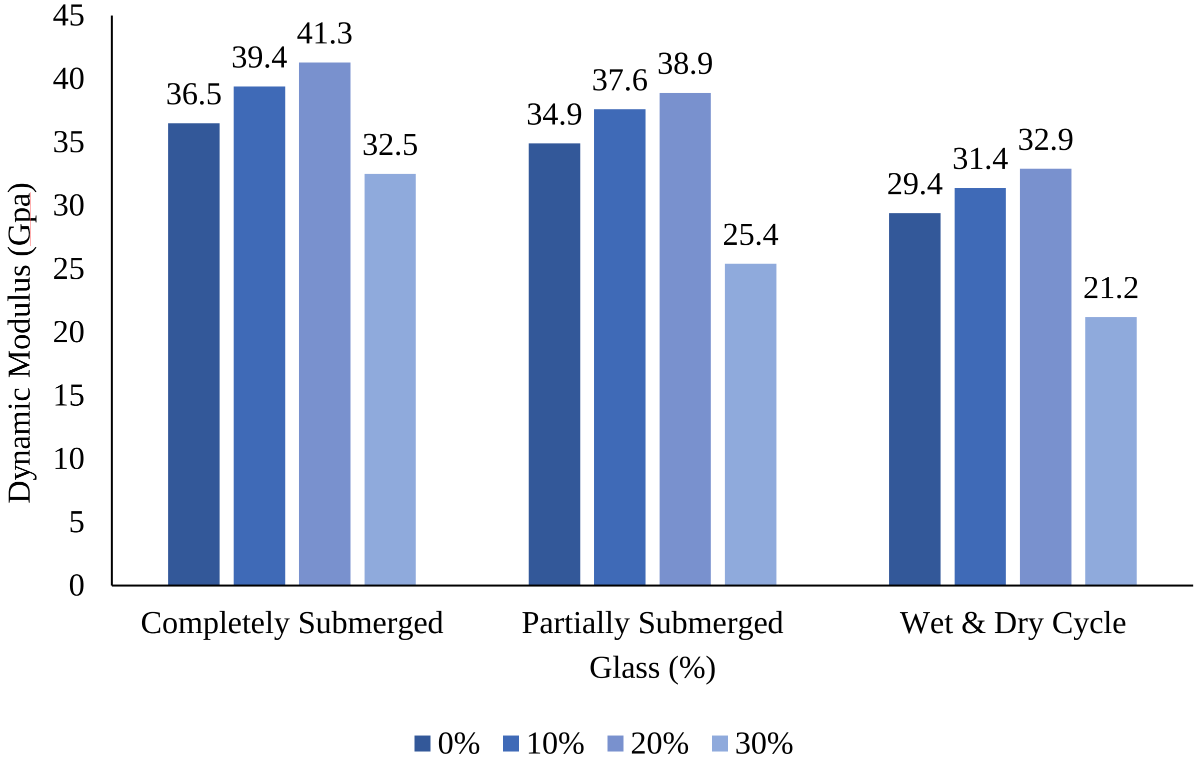


Figure 18: Comparison of Dynamic Moduli

1.2.4 Flexural Strength

As can be seen in fig 19 when up to 20% of cement is replaced with glass waste, the resulting concrete exhibits the greatest flexural strength. This is because of its greater particle packing as compared to the lower percentage replacement specimen. Glass waste particles can fill in the voids between cement particles, resulting in a denser and more compact concrete matrix. Glass waste particles act as microfillers, occupying the interstitial spaces between larger aggregate particles. This microfiller effect improves the overall homogeneity of the concrete mix and enhances its resistance to flexural cracking. Results start to decrease beyond 20% replacement. The same trend from before was observed in marine environments with completely submerged environment exhibiting better results followed by partially submerged marine environment and wet and dry cycles.

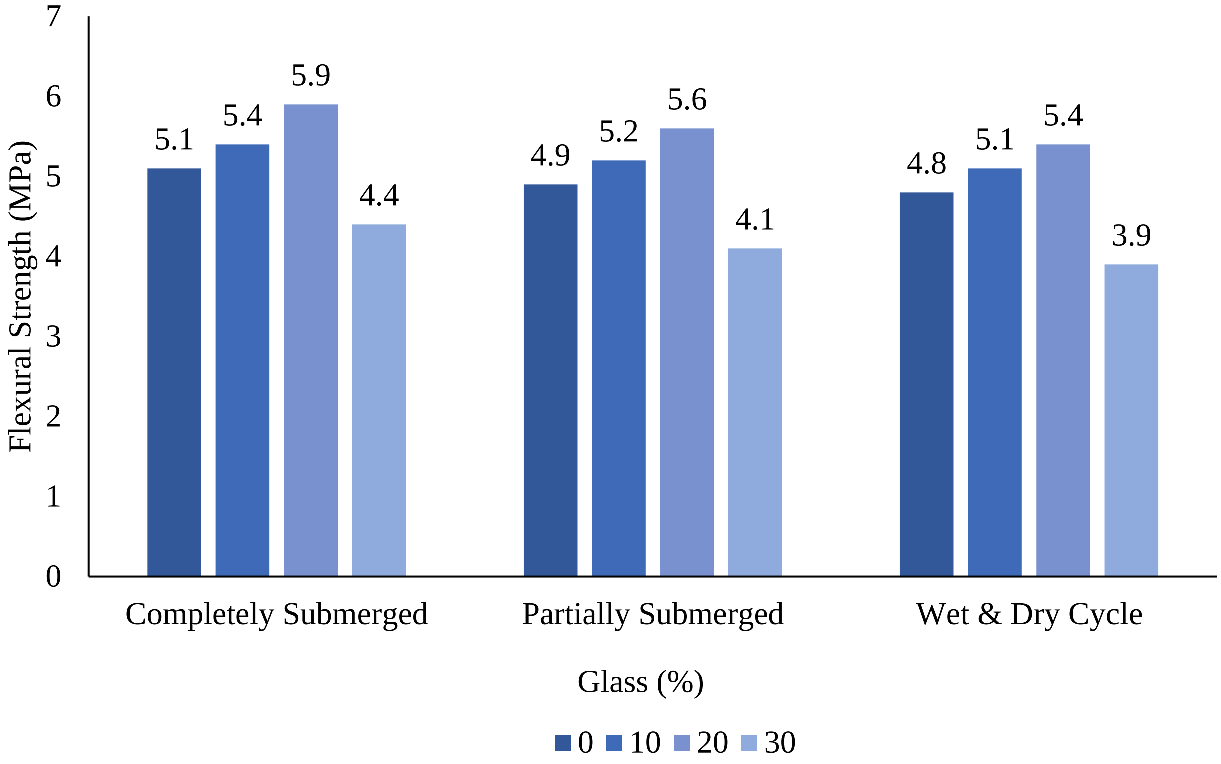


Figure 19: Comparative Results of Flexure Test

5.3 Durability Properties:

5.3.1 Water Absorption

The water absorption results shown in fig 20 demonstrate that regardless of the marine environment, the lowest water absorption is observed in the GW30 specimens. This can be attributed to the density of the matrix, as water absorption is influenced by the presence of pores. A denser matrix allows for fewer pores, resulting in reduced water absorption. Consequently, the NGW specimens, which have the least density, exhibit the highest water absorption. As the percentage of cement replaced by glass waste (GWP) increases, the density of the matrix increases, leading to a decrease in water absorption.

When comparing the different marine environments, fully submerged conditions yield the best results in terms of water absorption. This is because fully submerged concrete is not affected by capillary action or the expansion and contraction of pores. On the other hand, partially submerged conditions exhibit the second-best results, while wetting and drying cycles result in the worst water absorption performance. The trend observed in the results aligns with the aforementioned phenomena, where fully submerged conditions are most favorable, followed by partially submerged conditions, and wetting and drying cycles pose the greatest challenge in terms of water absorption.

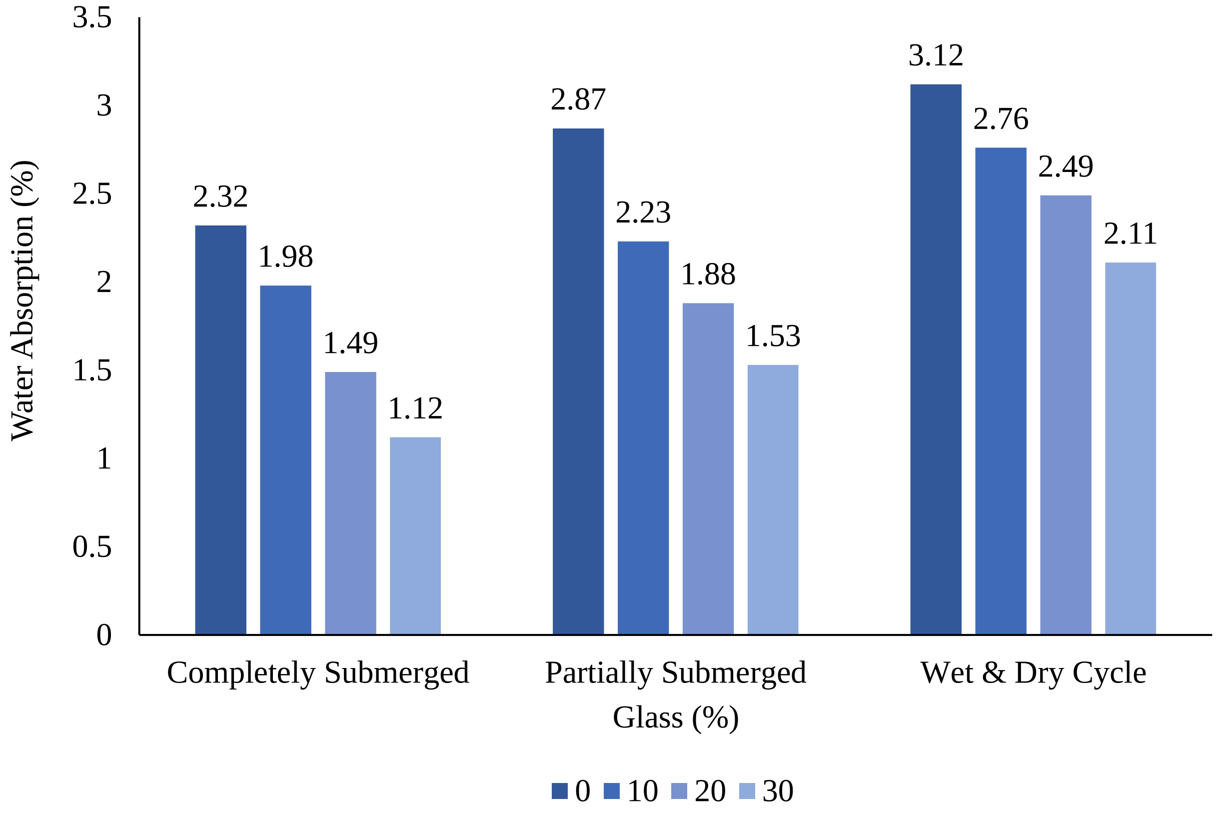


Figure 20: Comparative Water Absorption Results

5.3.2 Permeability

The trend observed is the decrease of permeability depth with the increase in glass waste incorporation across all marine environments. This is due to the densification of the matrix performed by the glass powder particles. The highest permeability depth is shown in non-glass waste concrete which has the least dense matrix, and the lowest permeability depth is found in GW30 samples where the most cement replacement by glass waste was done which caused densification.

With regards to the performance of the samples in different marine environments permeability depth shows a general increase in water depth ingress across the environments with the lowest depths observed in completely submerged environment, then in partially submerged and the greatest depths in wetting and drying cycles.

In wetting and drying cycles, the stresses formed from the continuous contraction and expansion of the pores of concrete weakens the matrix and allows for the widening of existing capillaries which allows in more water than for the other two environments.

In partially submerged environment the capillary action allows for some weakening of the matrix but not as much as in wetting and drying cycles.

In fully submerged environment the matrix is the most homogenous and undisturbed therefore the capillaries are left closest to their original states as they were before the samples were placed in the marine environments. Therefore, the permeability depths are smallest in completely submerged marine environments, then increase for the samples placed in partially submerged environments and are worst in wetting and drying cycles.

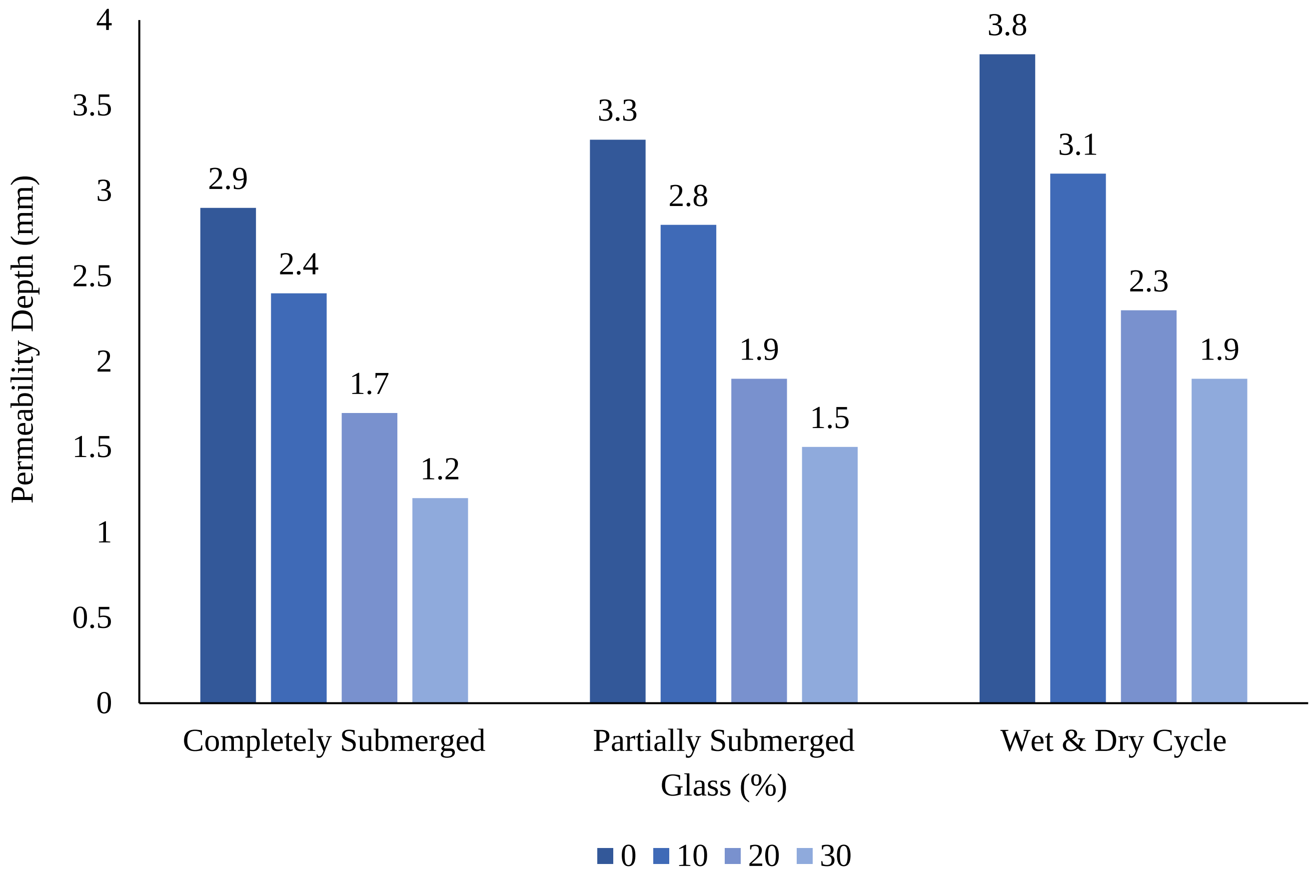


Figure 21: Comparison of Permeability Depth

5.3.3 Carbonation

All samples were tested negative for carbonation across all marine environments regardless of the percent replacement of cement with glass waste. This can be due to the short duration the samples were kept in marine environment for (56 days).

It is possible the difference GWP makes would be more apparent if the tested samples had been kept for longer in marine environments and allowed carbonation to properly take place.

(a) *(b)*

Figure 22: Samples showing purple color after phenolphthalein indicator was used

5.3.4 Porosity

As can be seen in fig 23, the more the cement in concrete is partially replaced with glass waste, the more the porosity of the concrete decreases. The porosity is highest in samples with no glass waste (NGW) in all environments because these samples have the least compact structure. However, as the percentage of glass waste increases, the density of the concrete increases. This is because additional C-S-H gel forms, filling the pores and reducing the number of empty spaces. The mix with 30% glass waste (GW30) has the highest density, resulting in the lowest porosity.

Considering the effect of different environments on porosity, when the concrete is fully submerged in marine environment, it yields the best results in terms of porosity reduction. On the other hand, subjecting the concrete to wetting and drying cycles produces the worst results, leading to higher porosity.

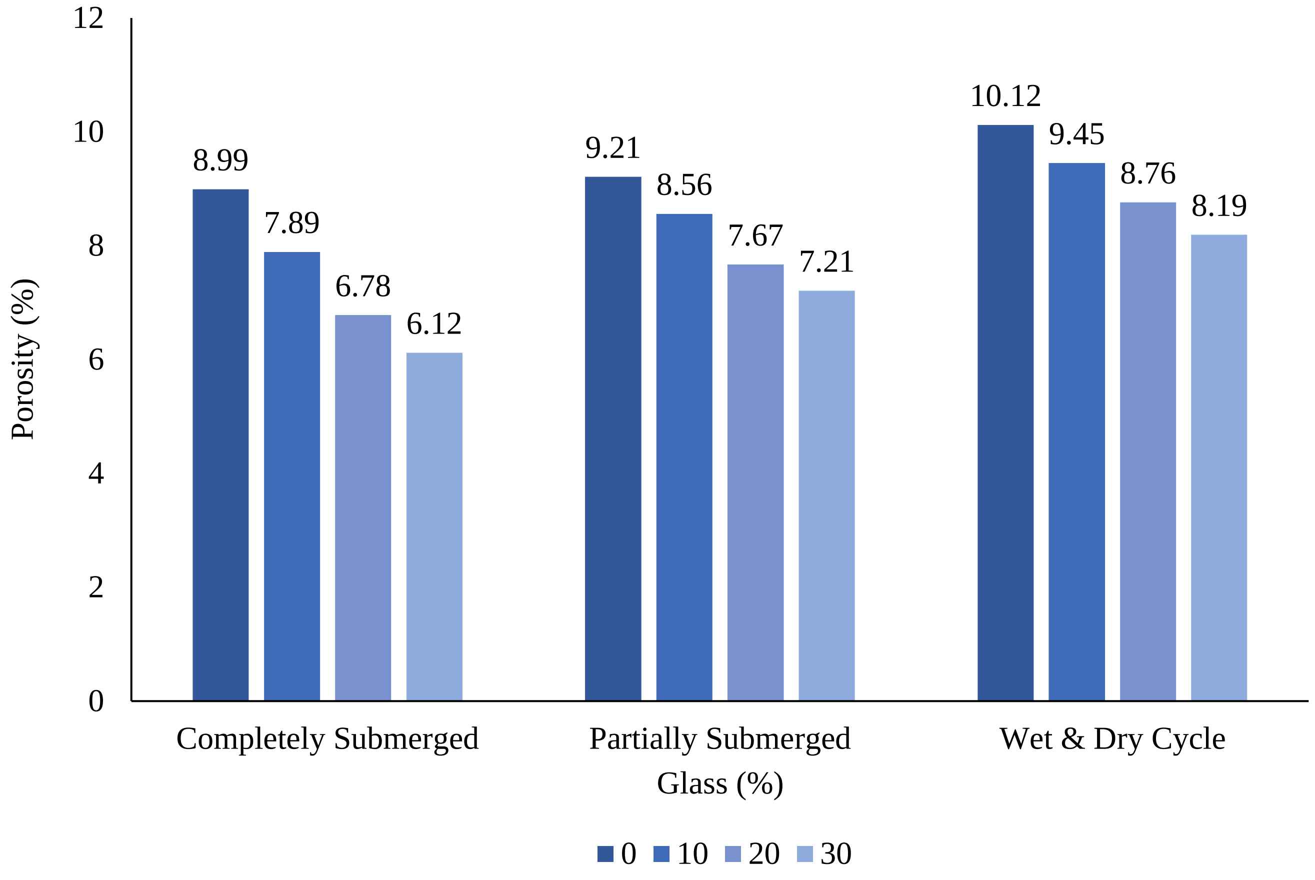


Figure 23: Comparative Porosity Results

CHAPTER 6: Life Cycle Assessment

6.1 Introduction

A systematic methodology called life cycle assessment (LCA) is used to calculate the environmental effects of any process or product based on various footprint matrices [50]. LCA has been widely used to evaluate the environmental impact of concrete [51], [52] as well as for self-compacting concrete with glass waste, demonstrating its ability to lower the greenhouse gas (GHG) emissions associated with concrete production [53].

In this study, LCA has been used to evaluate the environmental impact of self-compacting concrete containing glass waste powder as cement replacement, proposed in this study. This chapter presents the LCA methodology and results.

6.2 LCA Methodology

In accordance with ISO 14040 and 14044, LCA was carried out for both Normal Concrete (NC) and Self-Compacting Concrete (SCC) [54], which outlined four processes to perform LCA i.e., Goal and Scope, Life Cycle Inventory analysis, Life Cycle Assessments and Interpretation.

LCA was performed using OpenLCA software, which is an open source LCA software owned by Nexus.org [55]. The Eco invent database was utilized to import life cycle inventory data,whereas ILCD Midpoint method was used.

6.3 Life Cycle Assessment

6.3.1 Goal and Scope

The objective of this study is to evaluate and compare the environmental effects of self-compacting concrete containing glass waste with normal concrete, using a Cradle-to-gate methodology. The cradle describes the extraction of raw materials, while gate describes the processing of final product, which is concrete in this case. Other methods include Cradle-to-Gate and Gate-to-Grave, which takes into account the product's service life up until its destruction or recycling.

The glass waste powder content is selected based on the optimum replacement levels as mentioned in erstwhile chapter, with the functional unit being used as "1 m^3" of concrete. The normal concrete mix was selected with strength comparable to that of SCC, therefore a concrete mix with strength up to 25-30MPa was selected from existing literature. The systems boundaries used in this study are presented in fig 24 and fig 25.

6.3.2 Life cycle inventory analysis

In order to perform LCA, life cycle inventories of the materials involved in the production of NC and SCC are also required. The Eco invent database was used as a primary source for the inventory data, while some data was also collected from existing literature [53], [56].

Since industrial wastes like fly ash fall are considered by-products under European Union Directive

[57] because their use is certain at the time of production, by and large as an SCM in concrete mix. Therefore, they must be treated as by product and shall not be regarded as waste anymore, subsequently an allocation coefficient will be used to calculate their environmental impacts [58]. ISO 14041 provides a number of methods for allocation, without any preferences and

implications of a particular approach. Due to this, a process is considered as a multifunctional process, which is an activity that performs multiple functions (e.g., Coal power plants generates both electricity and fly ash), and the overall environmental impact is split between two processes according to allocation method [59]. In this study an economic allocation approach is used, and the environmental burden that fly ash will cause from all the emissions from coal power plants is calculated using an economic allocation coefficient (C_e) that is determined in fig 26. C_e was determined to be 0.053 (5.3%). Previous study found C_e to be 0.043, which is closer to the value in this study [60].

6.3.3 Life Cycle Impact analysis

ILCD Midpoint method, which includes a wide range of impact categories to analyze environmental impacts, was used to perform LCA. In this study 6 impact categories were selected, whereby the environmental effects of self-compacting concrete with glass waste were determined and compared with that of the normal concrete containing OPC as binder altogether. The selected impact categoriesare presented in table 3.

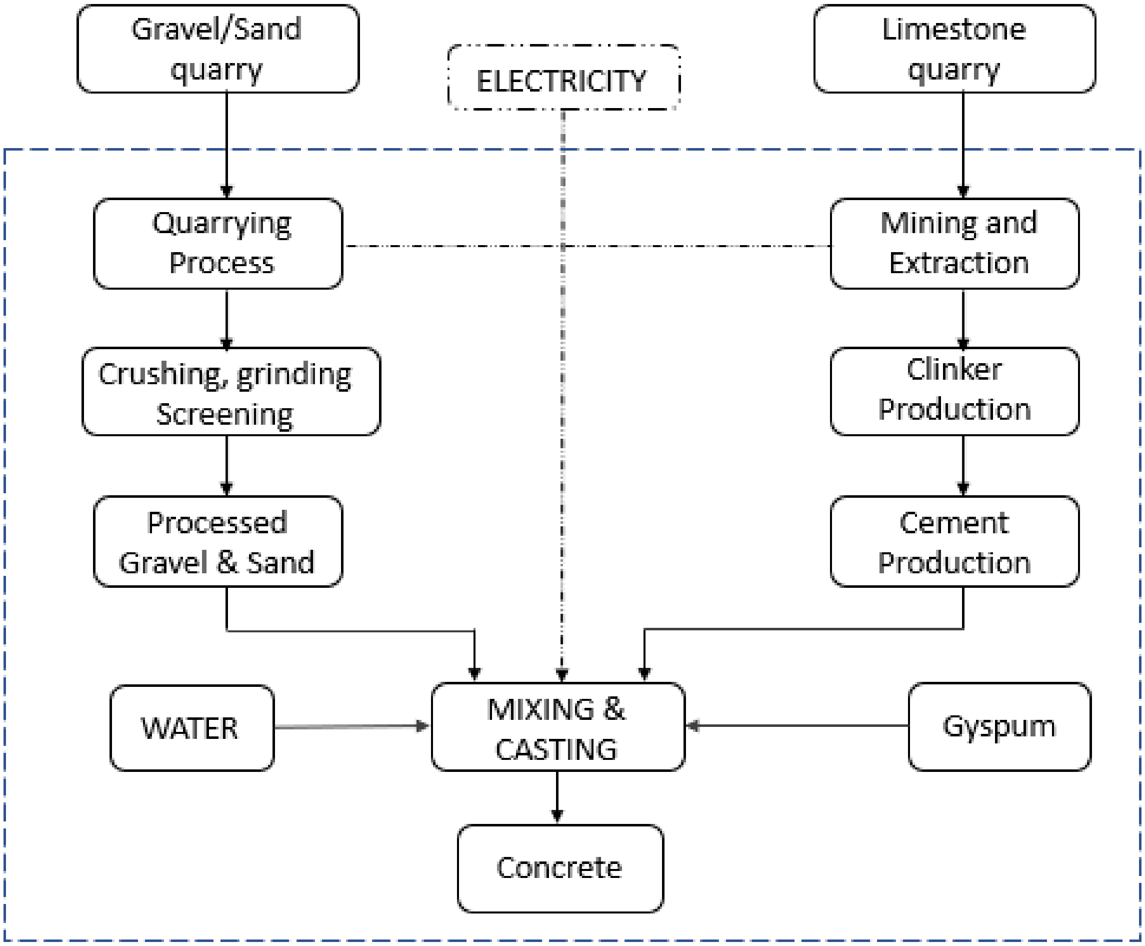


Figure 24: System Boundary Normal Concrete

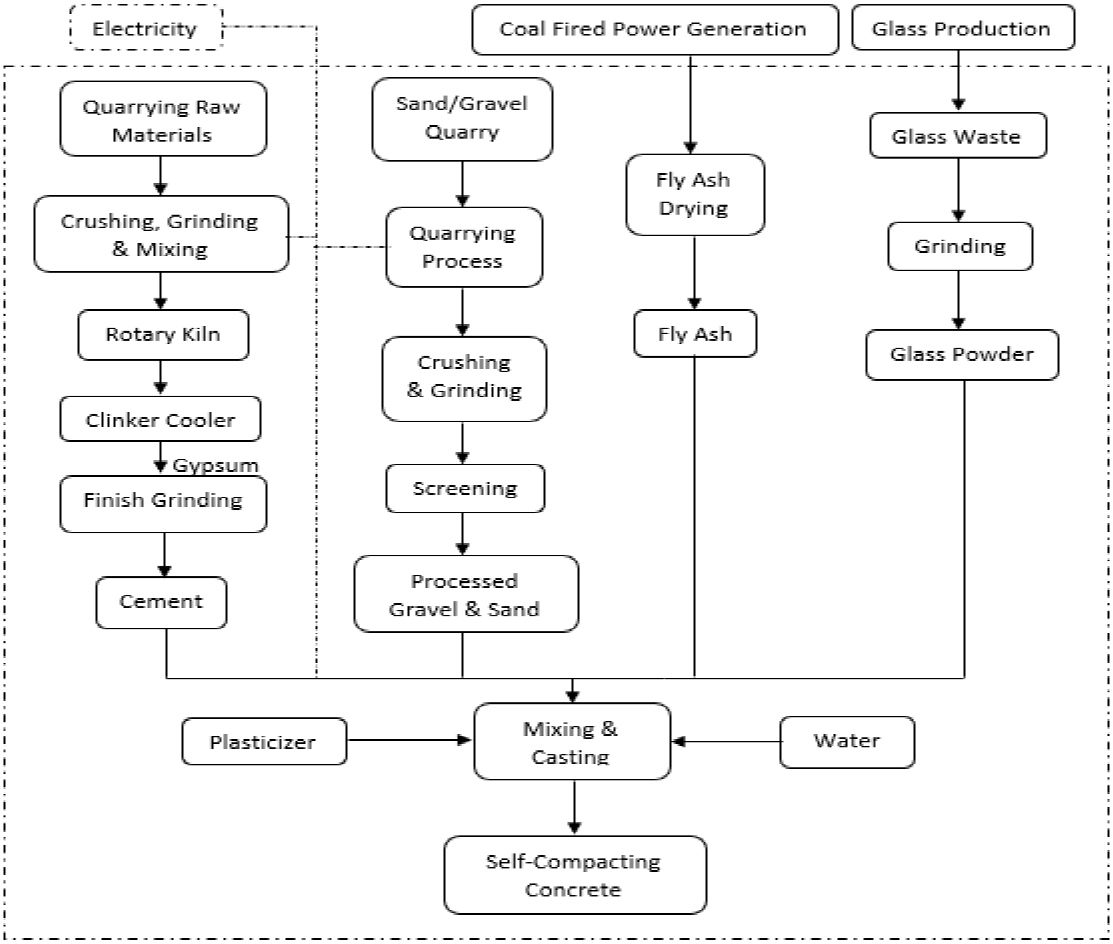
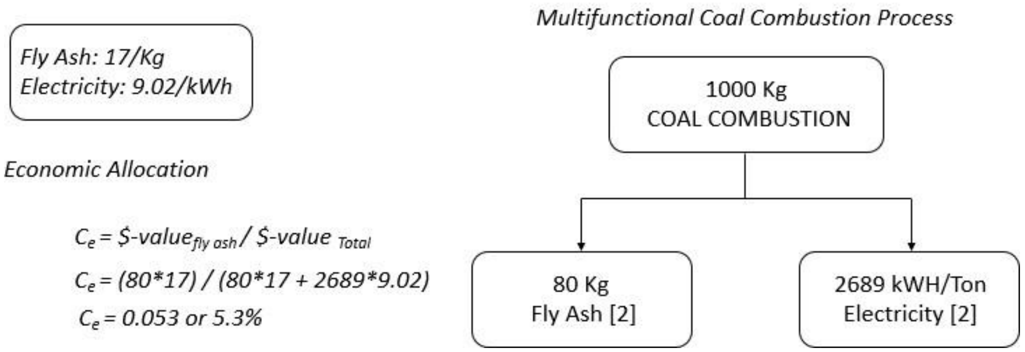


Figure 25: System Boundary Self Compacting Concrete with Glass Waste



$$C_e = \$\text{-value}_{fly\ ash} / \$\text{-value}_{Total}$$

$$C_e = (80*17) / (80*17 + 2689*9.02)$$

$$C_e = 0.053 \text{ or } 5.3\%$$

Figure 26: Economic allocation coefficient determination, Babbitt and Lindner (2005)

Table 3: Impact Categories

Impact Categories	**Unit**
Climate Change – GWP500	Kg CO_2-Eq
Marine Eutrophication – MEP	Kg N-Eq
Terrestrial Acidification TAP500	Kg SO_2-Eq
Ozone Depletion – ODPinf	Kg CFC-11-Eq
Particulate Matter Formation – PMFP	Kg PM2.5-Eq
Abiotic Depletion	Kg Sb-Eq

6.3.4 Interpretation of LCA results

The results for Life Cycle assessments of 1m^3 of Self-Compacting concrete proposed in this study(containing industrial waste powder i.e., glass waste powder) and a normal concrete of equivalent strength are presented in fig 27.

Table 4: LCA Results

Impact Category	**Normal Concrete**	**Self-Compacting Concrete (with Glass Waste)**	**Units**
Climate Change – GWP500	3.92E + 02	2.78E + 02	Kg CO_2-Eq
Marine Eutrophication - MEP	3.82E - 01	2.45E - 01	Kg N-Eq
Terrestrial Acidification - TAP500	1.368	1.139	Kg SO_2-Eq
Ozone Depletion - ODPinf	6.52E - 07	5.44E - 07	Kg CFC-11-Eq
Particulate Matter Formation - PMFP	1.02E - 01	0.85E - 01	Kg PM2.5-Eq
Abiotic Depletion	2.75E - 03	2.31E - 03	Kg Sb-Eq

Replacing cement with glass waste in concrete resulted in reduced environmental impact in every LCA impact category:

(a) **Climate Change**: Climate change pertains to enduring modifications in the Earth's climate system, including temperature, patterns of precipitation, wind dynamics, and various other factors. The primary cause of this phenomenon is human activities, specifically the release of greenhouse gases into the atmosphere, leading to global warming and subsequent ramifications on ecosystems and human societies. After replacing cement by glass waste, climate change tendency reduced by 41%.

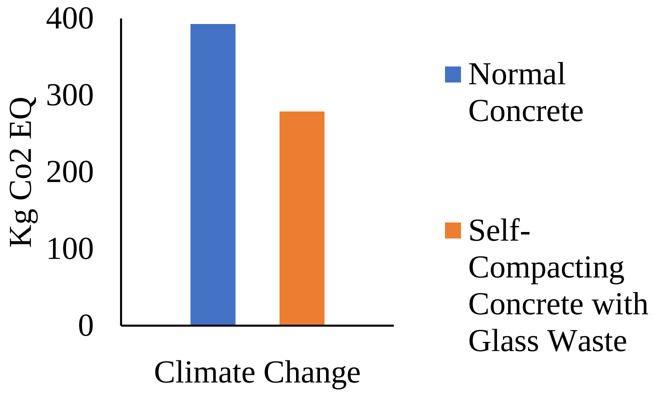
(b) **Marine Eutrophication**: Marine eutrophication refers to the enrichment of marine environments with excessive nutrients, notably nitrogen and phosphorus. This process stimulates the excessive growth of algae and other aquatic plants, causing disturbances in the equilibrium of marine ecosystems. Consequently, it can lead to oxygen depletion and the proliferation of harmful algal blooms. Marine eutrophication reduced by 56% after replacing cement by glass waste.

(c) **Terrestrial Acidification**: Terrestrial acidification refers to the process of acidifying terrestrial ecosystems, typically caused by the deposition of acidic pollutants such as sulfur and nitrogen compounds from human activities. It can have detrimental effects on soil, vegetation, and overall ecosystem health. Reducing cement content led to a reduction by 20% in terrestrial acidification.

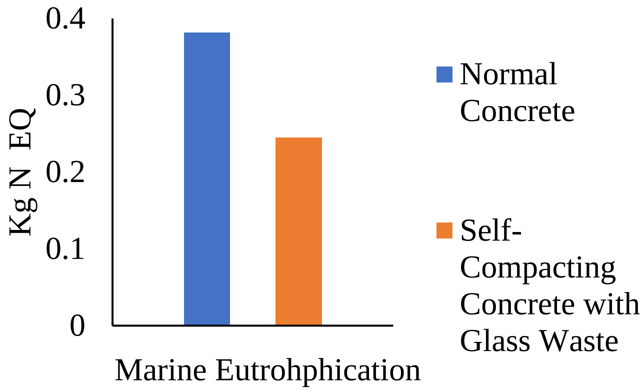
(d) **Ozone Depletion**: The depletion of the ozone layer in the Earth's stratosphere, known as ozone depletion, is primarily a result of the release of specific chemicals such as chlorofluorocarbons (CFCs). This depletion facilitates increased exposure to harmful ultraviolet (UV) radiation from the Sun, which poses risks to both human health and ecosystems. In this study, ozone depletion was reduced by 20%.

(e) **Particulate Matter Formation**: Particulate matter formation refers to the process by which solid or liquid particles are generated and suspended in the air. These particles, varying in size and composition, can have adverse effects on human health and contribute to air pollution and respiratory issues. This problem was reduced by 20%.

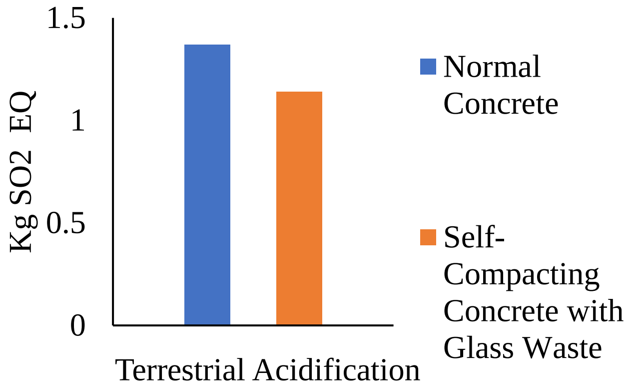
(f) **Abiotic Depletion**: Abiotic depletion refers to the reduction or exhaustion of non-living natural resources, such as minerals or fossil fuels, due to extraction or utilization. It is a consequence of human activities and can have long-term environmental and economic impacts. Abiotic depletion was reduced by 19% by reducing cement content.


400
300
200
100
0
Kg Co2 EQ
Climate Change
■ Normal Concrete
■ Self-Compacting Concrete with Glass Waste

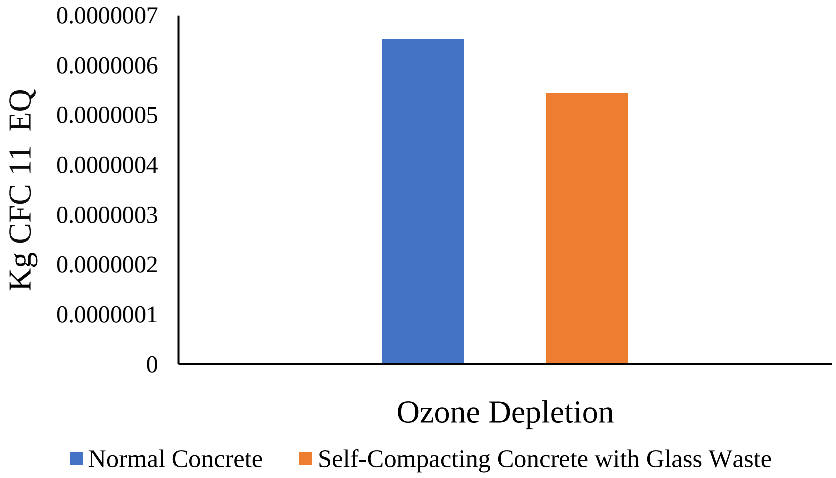
(a)


0.4
0.3
0.2
0.1
0
Kg N EQ
Marine Eutrohphication
■ Normal Concrete
■ Self-Compacting Concrete with Glass Waste

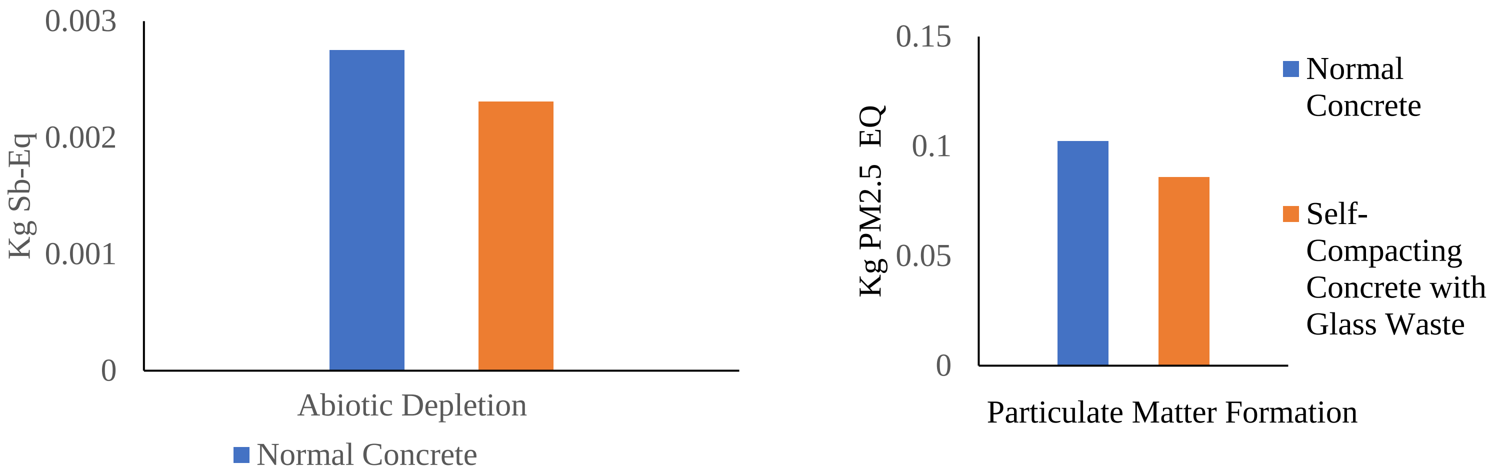
(b)


1.5
1
0.5
0
Kg SO2 EQ
Terrestrial Acidification
■ Normal Concrete
■ Self-Compacting Concrete with Glass Waste

(c)

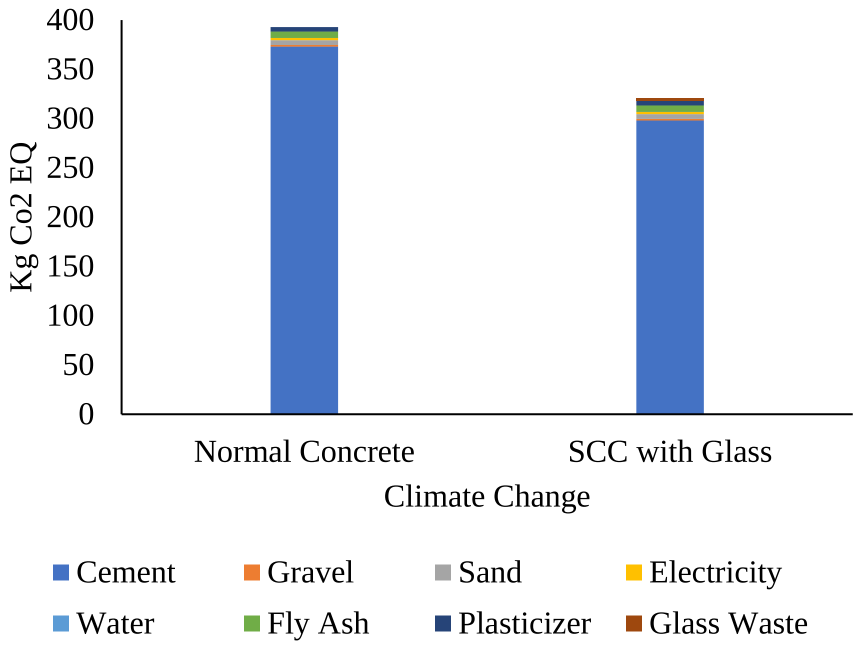

0.0000007
0.0000006
0.0000005
0.0000004
0.0000003
0.0000002
0.0000001
0
Kg CFC 11 EQ
Ozone Depletion
■ Normal Concrete
■ Self-Compacting Concrete with Glass Waste

(d)

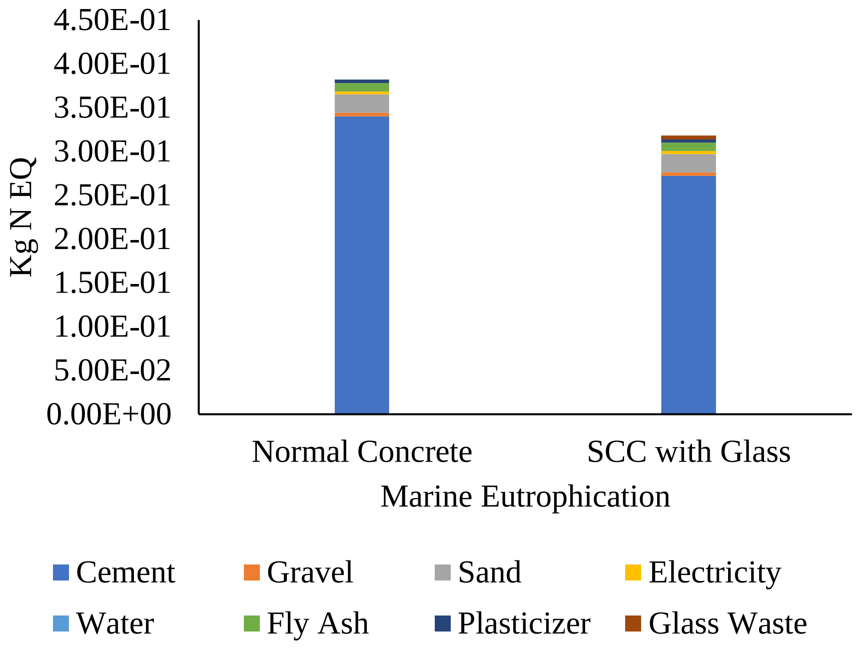


(e) *(f)*

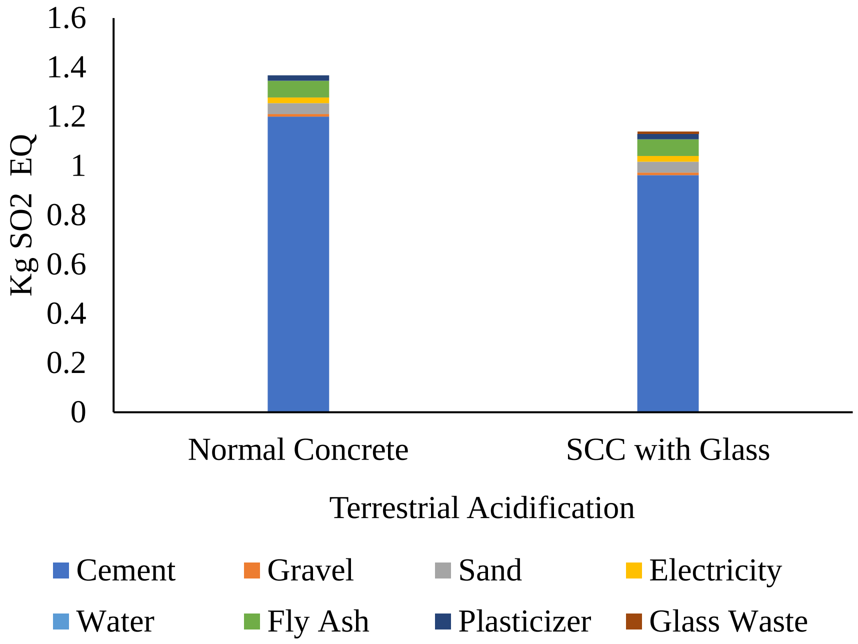
Figure 27: LCA Result


400
350
300
250
200
150
100
50
0
Kg Co2 EQ
Normal Concrete
SCC with Glass
Climate Change
Cement
Gravel
Sand
Electricity
Water
Fly Ash
Plasticizer
Glass Waste

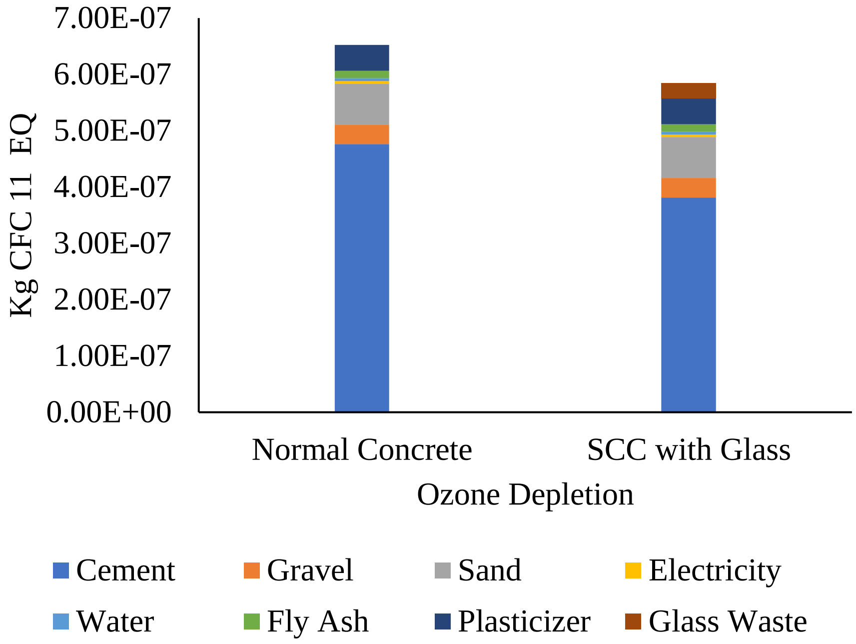
(a)


4.50E-01
4.00E-01
3.50E-01
3.00E-01
2.50E-01
2.00E-01
1.50E-01
1.00E-01
5.00E-02
0.00E+00
Kg N EQ
Normal Concrete
SCC with Glass
Marine Eutrophication
Cement
Gravel
Sand
Electricity
Water
Fly Ash
Plasticizer
Glass Waste

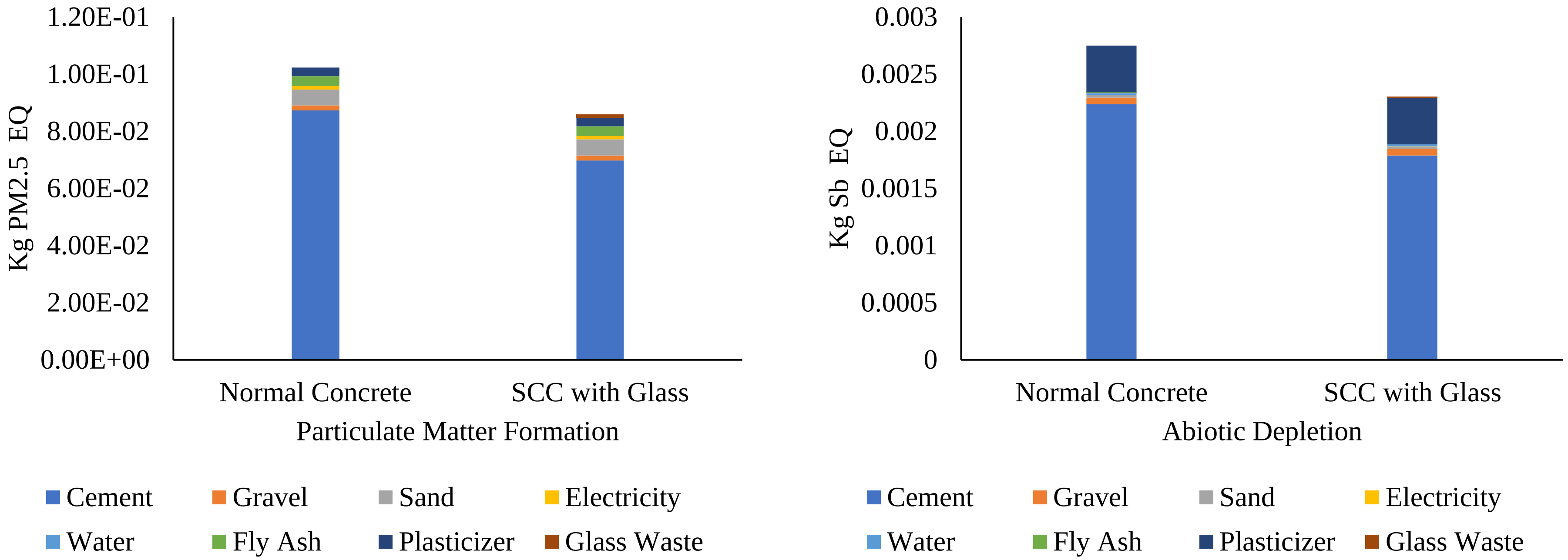
(b)


1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Kg SO2 EQ
Normal Concrete
SCC with Glass
Terrestrial Acidification
Cement
Gravel
Sand
Electricity
Water
Fly Ash
Plasticizer
Glass Waste

(c)


7.00E-07
6.00E-07
5.00E-07
4.00E-07
3.00E-07
2.00E-07
1.00E-07
0.00E+00
Kg CFC 11 EQ
Normal Concrete
SCC with Glass
Ozone Depletion
Cement
Gravel
Sand
Electricity
Water
Fly Ash
Plasticizer
Glass Waste

(d)



(e) *(f)*

Figure 28: Process Contributions

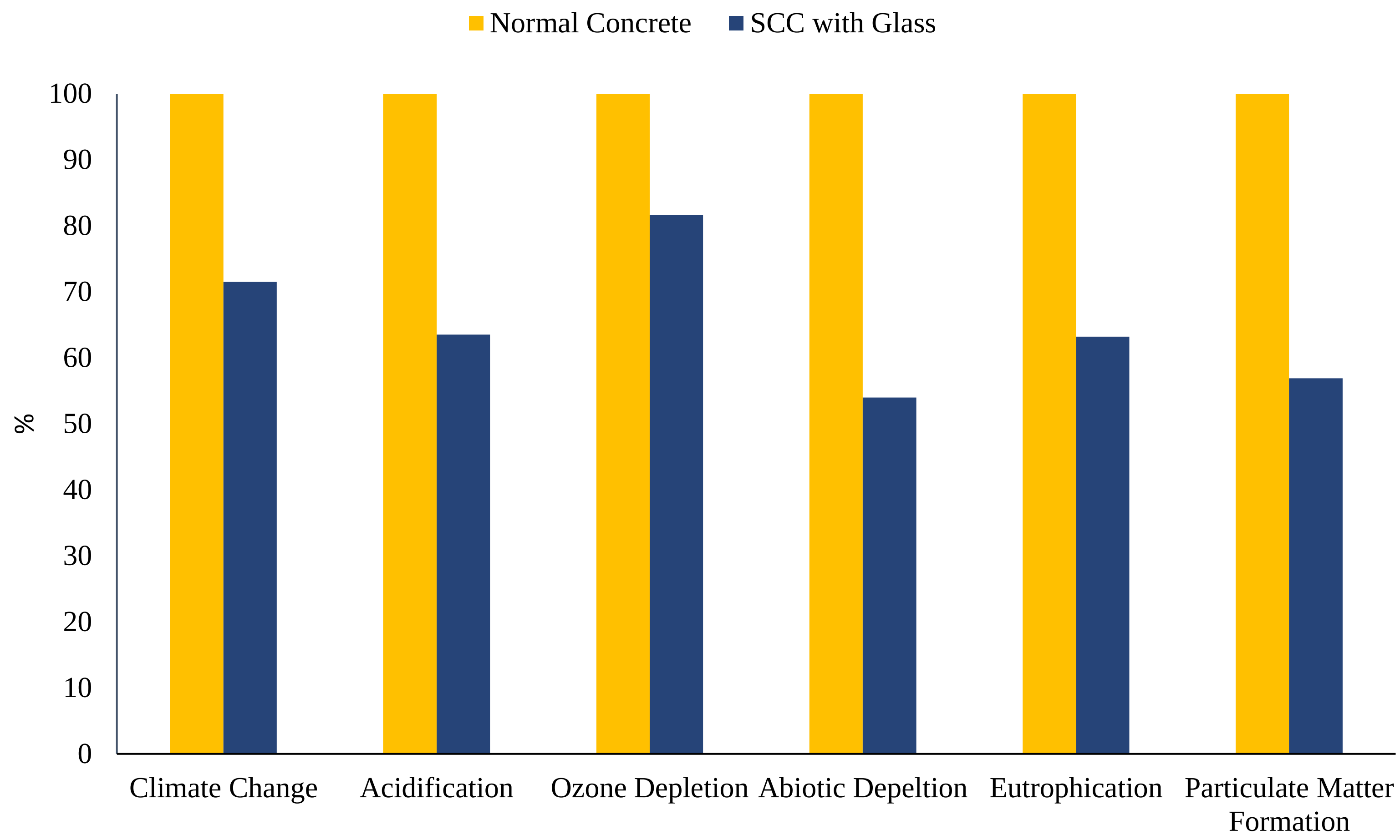


Figure 29: Relative Results

CHAPTER 7: Conclusion

The developed concrete was tested in fresh, mechanical and durability properties after being kept in three different marine environments; completely submerged, partially submerged, and wetting and drying cycles.

- It was found that incorporation of GWP decreased the workability of concrete. This can be due to the sharp, angular shapes of the GWP particles that increase the friction. Therefore, if high workability is required it is advisable to avoid using GWP incorporated concrete as it is difficult to increase workability to the required levels.
- Mechanical property tests had improved results on incorporation of GWP because of its small size, using fine glass waste powder as a substitute help in improving the particle packing in the concrete mix till 20%. It was because of concrete construction that is denser and more compact, with fewer voids. Also, the pozzolanic reaction of glass, which is silica-rich material, results in formation of additional cementing compounds including alkali silica gel (ASG) which contribute to high strengths.
- The optimum percentage of replacement of cement with glass powder was found to be 20%. After this percentage, strength started decreasing because of reduced hydration which is necessary for the formation of CSH gel. Also, if the concrete mix is exposed to high moisture settings, the extra silica from the glass contributes to ASR at higher replacement levels. As a result, a gel may develop, which swells as it absorbs water and damages the concrete by cracking.
- Durability properties show that across all marine environments 30% is the optimum replacement level for cement. This is because the durability of concrete depends on the

density of its matrix and GWP increases the density which provides resistance to destructive environments and acid attacks. So as the amount of GWP in the concrete increases so does the density which minimizes water absorption, permeability depth, porosity and can have a positive impact on carbonation as well.

- Concrete was tested in different marine environments i.e., partially submerged, completely submerged, and wetting and drying cycles. Most optimum results were found in completely submerged compared to other environments. Because in wetting and drying cycle, continuous expansion and contraction of voids causes distress and cracks propagation. This expansion and contraction are because of evaporation in drying cycle and filling of pours in wetting cycle.
- Optimum results in completely submerged is because the only prominent phenomenon that might cause the deterioration of concrete is capillary transport while in other environments, salt crystallization, evaporation, ion migration towards the surface and wick action of water also take part in deterioration.
- However regardless of marine environment 20% remains the optimum replacement level for cement for mechanical properties. Whereas, for durability properties 30% remain the optimum replacement in all marine environments.
- A life cycle assessment was performed, and it was found out that self-compacting concrete containing glass waste powder reduced greenhouse gas emission by 48%.

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