Recycled Glass as Partial Replacement for Fine Aggregates in Concrete for Marine Structure Application

Michelle Daarol[1*], *Cyril Jane* Fullido[1], *Earl Jhon* Lazaga[1], and *Kyla Marie* Ayodoc[1]

[1]Civil Engineering Education, University of Mindanao, Davao City, Philippines

Abstract. The rapid rise in the generation of waste and the increased quantities of waste glass have created several environmental hazards. For effective remediation of the waste generated on a large scale, the prospects of using waste glasses within concrete have been explored. In marine environments, there is a high probability that concrete structures would degenerate. In concrete structures subjected to marine environments, the attack by sulfate and chloride ions causes degradation. To find effective alternatives for concrete components within marine environments, the feasibility of using recycled glasses has been explored. The feasibility and suitability of using waste glasses that have been recycled have been explored to replace the aggregate materials. Four different concrete mixes containing varying percentages of waste glasses that have been crushed have been investigated. The concrete specimens have been subjected to a marine environment for a period of 28 days. In the concrete specimens subjected to marine environments, the tidal wet-dry cycles lead to structural degradation by inducing internal microcracks due to salt crystallization. The main concerns of this study is the assessment for the chemical resistance based on the changes of mass and water absorption and to evaluate the compressive strength. From the experimental findings, it was evident that the increase in the amount of recycled glass resulted in the reduction of the compressive strength of the resulting concrete. On the other hand, the water absorption was found to be reduced with a steady rise in the rate of chemical resistance along with the increase of the recycled glass replacement. From the findings, it was evident that when the proportion of recycled glass was between 20 and 50 wt.%, there were substantial changes with regards to the performance of the resulting concrete. However, with the addition of recycled glass to the mixture, the strength was reduced; nonetheless, the durability was heightened, indicating that there was a balance of durability and strength at 30 wt%. This study illustrates the benefits to the environment with the utilization of recycled glass as partial replacement of fine aggregates in the concrete exposed in the marine environment.

*daarol_michelle@umindanao.edu.ph

1 Introduction

There has been rapid increase in industrial wastes because of an increase in population, leading to environmental pollution [1]. Production and creation of huge amounts of waste glass every day have presented difficulties and challenges in disposing and managing them [2]. To mitigate these difficulties, many researchers have shifted their focus to utilizing waste glass in construction, (e.g., concrete). Concrete is the most widely used construction material in the industry, and its use continues to grow steadily. One application of concrete is in marine structures, where it is exposed to seawater erosion and tidal forces [3]. Concrete is susceptible to severe deterioration in aquatic environment, because of combined injurious action of sulphate and chloride attacks, especially in tropical climates. According to studies, addition of waste glass to the concrete mix can enhance its mechanical properties and reduce its dead load [2]. It is also an environmental friendly approach, conserving gravel and sand natural resources by replacing conventional aggregate materials with it. Meanwhile, replacing partially the fine and coarse aggregates with waste glass may serve as a better economy in decreasing the cost and giving way to greener construction. Glass concrete mix and conventional concrete gave fairly close compressive strength results, 17.10 MPa and 18.966 MPa, respectively. In flexural strength, the values of glass concrete and conventional concrete are 3.548 MPa and 3.94 MPa, respectively, but within the desirable safe strength [2]. The mix design with 30% substitution of fine aggregate by waste glass powder gave the highest compressive, split tensile, and flexural strengths [4]. In the comparison analysis done on untreated and silane-treated concrete, it was noted that the untreated concrete with 30% and 50% fine glass aggregate had 13% and 5% reduction in compressive strength at 28 days as compared to that at 7 days [5]. In the case of the polymer concrete, mix design PC4, in which 20% replacement of sand was done by weight, showed the highest compressive and flexural strength at 7, 14, and 28 days [6]. In pursuit of sustainable concrete mix, an alternative for fine aggregate waste glass is compared with waste marble as an alternative for coarse aggregates. The mix showed an improvement in compressive strengths at 28 days for 20% waste glass and 50% waste marble at 28 MPa, an improvement of 21% and 12% over the control mix. For split tensile, 15% waste glass and 30% waste marble showed improvements of 65% over their control mix at 5.5 MPa. Another mix employed waste glass as an alternative for cement and waste rubber as an alternate for aggregates. With 15% waste glass fine powder and 25% waste rubber, an improvement in maximum compressive strengths of 31.14 MPa at 7 days and 47.48 MPa at 28 days was reported [7].

In durable concrete structures, sulfate and chloride attacks are significant problems. Coastal structures are vulnerable to chemical sulfate attacks, physical salt attacks, or a combination of both, as capillary suction and evaporation can lead to supersaturation and salt crystallization in aboveground concrete. Mangi et al. studied the short-term effects of sulfate and chloride on concrete that includes coal bottom ash as a supplementary cement material, using 5% sodium sulfate (Na_2SO_4) and 5% sodium chloride (NaCl) solutions [8]. Concrete samples were placed on the seashore for 28-180 days after 3 days of curing to test the flexural strength of concrete with varying amounts of cement replacement under an actual marine environment with a pH of 8. The study conducted a marine exposure simulation to investigate the compressive strength and tensile characteristics of hybrid curable self-compacting concrete. Seawater conditions were simulated in a laboratory environment using an accelerated weathering tank to mimic harsh marine conditions.

Although various studies have investigated methods to improve the compressive strength of glass concrete, a research gap remains regarding its performance in a marine environment. This gap highlights the need for an investigation into the compressive strength of glass concrete after exposure in marine environment.

This study compares the compressive strength of conventional concrete with that of concrete containing waste glass as an alternative to fine aggregate under marine exposure. The specific objectives of the study are to: (a) characterize the crushed glass aggregates used in the glass concrete, (b) evaluate the compressive strength, mass gain, and water absorption of glass concrete with varying proportions of waste glass, particularly after subjecting samples to marine exposure, and (c) determine the best-performing mix design for marine application.

Waste reduction and the advocacy for a sustainable product are very vital for the creation of a circular economy. However, there are also concerns about the safe disposal of huge quantities of waste, including waste glass, and the extraction of huge quantities of natural resources. This study intends to contribute valuable insights concerning the addition of waste glass to the production of concrete and the resolution of the problem for the advancement of the circular economy and the creation of a sustainable environment here and abroad, specifically Davao City.

This study investigates the durability of concrete using recycled glass as an alternative for fine aggregates when exposed to a marine environment. The concrete specimens were subjected to the marine environment to assess their performance under real-world conditions. The study is limited to the short term effects of seawater on glass concrete and does not account for long-term field performance.

2 Materials and methods

2.1 Conceptual framework

Figure 1 shows the input-process-output framework of the study in which shows that the first phase of this experiment involved collecting materials. Following material collection, the crushed waste glass and seawater underwent characterization. Conventional concrete and glass concrete mixes were prepared, including a control specimen and a glass concrete mix with partial replacement of crushed waste glass at 3 different percentages. The mix designs, determined by weight, follow the ACI mix design method. Prepared samples underwent marine exposure testing, and in accordance with ASTM standards, mass gain, compressive strength, and water absorption were evaluated.

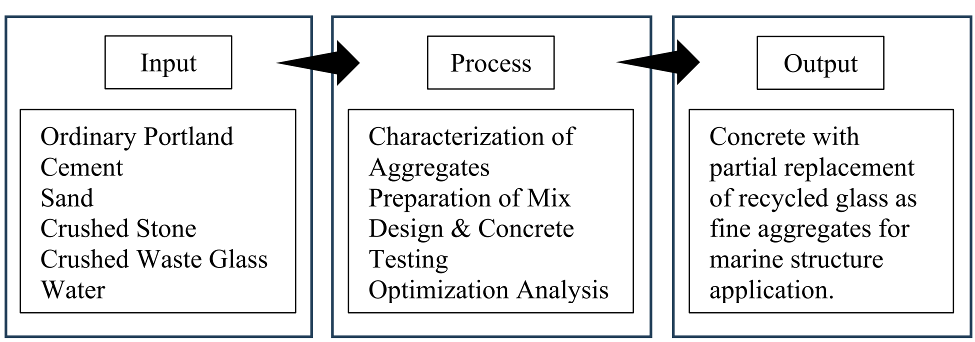

Fig. 1. Input - Process - Output

2.2 Materials and resources

Ordinary Portland Cement, river sand, and crushed stone were used as the primary materials, all purchased from a local hardware store at Mintal, Davao City. The coarse aggregates have

 https://doi.org/10.1051/e3sconf/202669401002

a maximum size of ¾ inch (19 mm), while the fine aggregates have a maximum size of 4.75 mm. The type of glass to be used in this study is beverage glass bottles. The glass was acquired through collection and purchasing at local junk shops. The following procedure converts beverage glass bottles into crushed waste glass, which passes through a 4-mesh screen with a nominal size of 4.75mm, using a bottle crusher.

2.3 Methods and procedures

2.3.1 Characterization of aggregates and crushed waste glass

The characterization of fine and coarse aggregates was tested according to ASTM C136, ASTM C128, and ASTM C127 for particle-size distribution, specific gravity, and water absorption, respectively. For particle size distribution (ASTM C136), aggregates were oven-dried, passed through a series of progressively finer sieves, and the mass retained on each sieve was recorded to determine gradation. The specific gravity and water absorption of fine aggregate were tested according to ASTM C128, and those of coarse aggregate were tested according to ASTM C127. In these procedures, aggregates were soaked in water for 24 hours, brought to a saturated surface-dry (SSD) condition, weighed, and then oven-dried to determine specific gravity and the percentage increase in weight due to water absorption.

Additional crushed waste glass was prepared by cleaning the collected waste glass and then crushing it. The crushed waste glass was characterized according to ASTM C128 for water absorption and specific gravity, and according to ASTM C136 for particle-size distribution by sieve analysis.

2.3.2 Characterization of seawater

The seawater samples were collected at Toril Beach, Davao City. The seawater samples were transported to Davao Analytical Laboratories Inc., where the seawater's characteristics, including chloride content, pH, salinity, sulfate, and chlorate, were determined.

2.3.3 Mix design

A constant water-cement ratio of 0.48 was applied to design the mixture formula; the maximum water-cement ratio to attain a maximum average strength of 34.5 MPa is 0.48, which satisfies the minimum average strength for concrete exposed to seawater of 27.6 MPa, as per ACI 318-19. Table 1 shows that the four mixtures, including the control, were designed by varying the fine aggregates, with waste glass partially replacing 20 wt.%, 30 wt.%, and 50 wt.% of the weight of natural fine aggregate.

Table 1. Mix designations and quantities in kg/m^3

Label	Replacement in Percentage of Fine Aggregate	Cement (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Water (kg/m^3)	Glass Waste (kg/m^3)
CO	0%	389	1051	984	187	0
F20	20%	389	1051	787	187	197
F30	30%	389	1051	689	187	295
F50	50%	389	1051	492	187	492

2.3.4 Casting and curing

A 100 mm diameter cylinder with a height of 200 mm was cast by thoroughly mixing the concrete and placing it into oiled molds in three layers, each compacted with 25 uniformly applied strokes with a tamping rod to eliminate air voids. After finishing the top surface and labeling the molds, the samples were left undisturbed for 24 ± 2 hours at a controlled temperature of 20-25°C under high humidity. The specimens were demolded and cured by immersion in a water tank maintained at 23 ± 2°C for 28 days to ensure proper hydration. Following the curing period, the cylinders were transported to a tidal zone on a beach, where they were securely positioned to undergo exposure to tidal cycles for further testing under marine conditions.

2.4 Testing

2.4.1 Chemical resistance through mass gain

The test for chemical resistance was performed, which exposed the concrete to a marine environment, as opposed to being immersed in a sulfate solution. This test was performed with a concrete cylinder, 100 mm in diameter. Samples were immersed for 28 days in a normal water curing environment. After that, they were put securely in the tidal zone, which exposed them to a natural environment over a period of 28 days. There were two significant tests, which measured the loss in weight or gain in weight, along with a loss in compression strength. All samples were marked and weighed. After the completion of 28 days of marine exposure, the sample masses were again recorded. Then the compressive tests were conducted on the cured sample, following the process described in ASTM C39. Before the test began, the sample was inspected for any cracks or flaws. Then the specimen was carefully positioned at the center of the compression test machine so that the applied compression is even. A constant loading rate of 0.25 ± 0.05 MPa/s was applied on the sample until breakage occurred. During the experiment, the maximum compression applied to the sample before breakage occurred was documented. Results and the average for the experiment were documented for its accuracy and consistency.

2.4.2 Water absorption

The cured samples were tested for water absorption. This was done in accordance with the test guideline prescribed in ASTM C642. This involves a series of procedures like preparing the tests specimens. This includes the cleaning process, which consists of cleaning the cylindrical samples, to remove dirt or any other materials. The samples were oven dried at a constant temperature of 105 °C ± 5°C (221°F ± 9°F) for at least 24 hours. After drying, the specimens were weighed to obtain their dry weight. The dried concrete specimens were immersed in water for 24 hours. The sample should be completely submerged to ensure complete saturation. The specimens were then weighed again to determine the wet weight.

2.5 Statistical analysis

In this study, a One-Way Analysis of Variance (ANOVA) was employed to assess the effect of different recycled glass replacement levels (20%, 30%, and 50%) on the compressive strength of concrete. When significant differences were identified, the Tukey HSD Post Hoc test was conducted to optimize the mix design.

3 Results and discussion

3.1 Properties of aggregates

3.1.1 Sand and gravel

Properties of sand (fine aggregate) were within ASTM C128. The gradation and properties of sand are presented in Figure 2 and Table 2, respectively. The percentage passing value at the #4 sieve indicates that it falls within the required specification range of 95%-100%. At the same time, the gradation and properties of coarse aggregates are specified in ASTM C136 and ASTM C127, respectively. Overall, the values confirm that the fine and coarse aggregates are well-graded and appropriate for use in concrete.

3.1.2 Crushed waste glass

The gradation and properties of crushed recycled glass as fine aggregates were also presented in Figure 2 and Table 2, respectively. The properties of waste glass are comparable to those of fine aggregate, with only a slight difference.

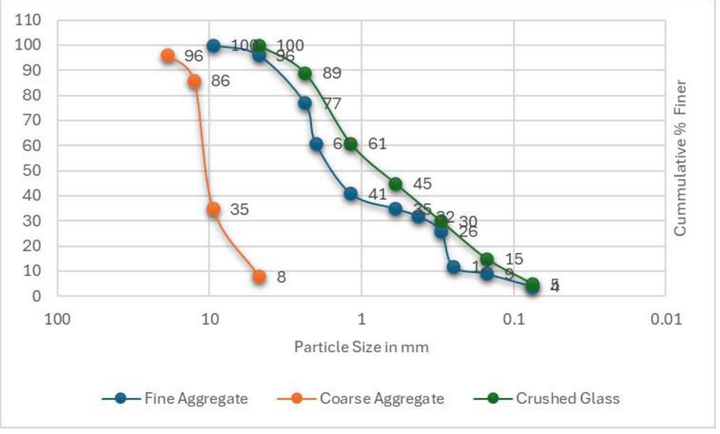

Fig. 2. Particle Size Distribution

Table 2. Specific gravity and absorption percentage of aggregates

Materials	Specific Gravity	Absorption
Fine Aggregates	2.678	2.44%
Coarse Aggregates	2.69	2.33%
Crushed Glass	2.63	2.33%

3.2 Properties of seawater

The properties of seawater were tested at Davao Analytical Laboratories Inc. and WVN Research and Laboratory Supplies. Table 3 below presents the results of seawater analysis.

Table 3. Seawater properties

Chloride (mg/L)	pH (@25°C)	Salinity (PSU)	Sulfate (mg/L)	Chlorates (ug/ml)
18,632	7.92	33.2	1170	<0.01

3.2.1 Mass gain

A change in the mass of samples exposed to the actual marine environment was observed. Concrete mixtures gained mass after exposure to marine environments. Figure 3 shows the average mass gain after 28 days of exposure to an actual marine environment. The control recorded the largest mass change of 3.81%, whereas mixture F30 had the smallest at 1.24%. The mass gain of concrete is primarily due to the absorption of salt ions and water. Seawater also has salt, which may be either NaCl and/or MgSO4, that dissolve and go into the pores and has chemical reactions with the hydrates, and also crystals will form within the pores following the continuous pattern of a wet/dry cycle [9].

Furthermore, ANOVA results have shown that there exists a significant difference among the samples. Results of the Tukey HSD Post Hoc test show that concrete containing recycled glass with a 30% volume fraction has the highest mean differences with the control and that the F30 has the lowest mass gain among percentages.

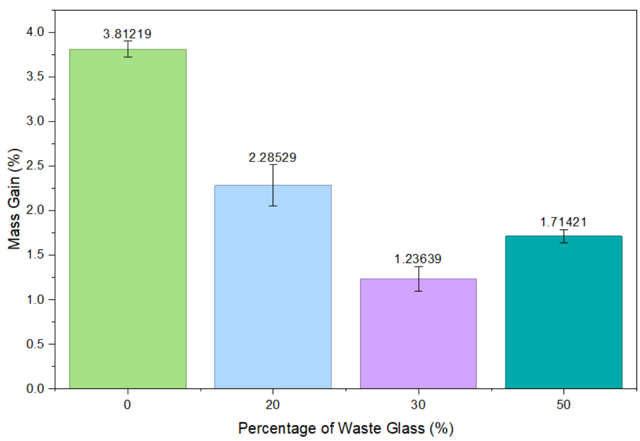

Fig 3. Mass gain of concrete in percentage

3.2.2 Compressive strength

The compressive strength of concrete samples before and after exposure to actual marine conditions is shown in Figure 4. The results demonstrate a decrease in compressive strength resulting from the partial substitution of fine aggregate with recycled waste glass. Among the tested mix designs, control exhibited the highest compressive strength after exposure to the actual marine environment with an average of 33.6 MPa. An increase in recycled glass content in the concrete mixture decreases strength, likely due to the high proportion of waste glass, which weakens the bond with the cement paste [10]. However, it was also observed that mixture F20 was better compared to other recycled glass mixtures, with the mixture having a strength of 32.6 MPa. Figure 5 illustrates the consistent rate of loss of strength for the mixes, ranging between 4.36 and 4.66 percent. Exposed to the marine environment, the compressive strength of the exposed concrete reduces due to the effects of salt crystallization and chemical attack by chlorides and sulphates. In addition, porosity and poor bonding also contribute to the weakening of the structure.

An ANOVA analysis test shows that the compressive strength of concrete is significantly different after the incorporation of recycled glass. The aim of the analysis was to determine whether there is an effect or difference brought about by recycled glass on the compressive strength of concrete after a 28-day exposure to marine conditions. Incorporating recycled glass into the concrete specimen materials yielded significant differences in the four types. From the Tukey HSD Post Hoc test, all pairs were significant. Also, according to ACI 318-19, the minimum required average compressive strength after 28 days of exposure for concrete exposed to a marine environment is 27.6 MPa; among the three containing glass, only F20 and F30 achieved this.

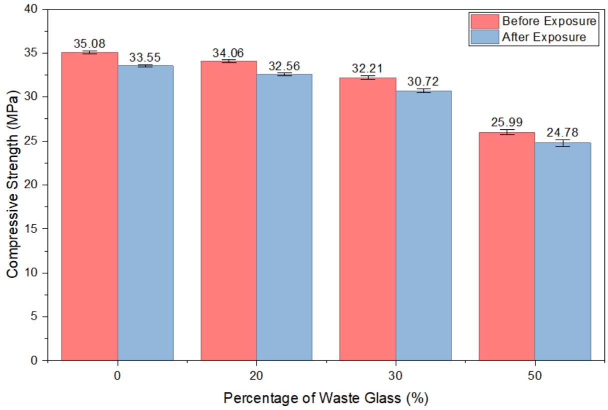

Fig. 4. Comparison of Average Compressive Strength of Concrete Between Two Conditions

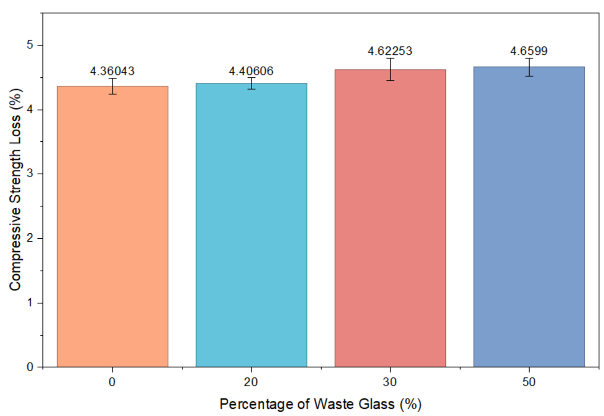

Fig. 5. Average Compressive Strength Loss of Concrete

3.2.3 Water absorption

All the samples were then subjected to water absorption tests after undergoing the oven drying procedure. During this time, the weights of each specific sample for the mixes were carefully taken. Figure 6 illustrates the percentages of water absorption for the mixes with different percentages of recycled glass. From the experimental findings, it was evident that the concrete mix with 20% recycled glass had a somewhat greater water absorption percent (4.27%) compared to the controlled mix (4.16%). However, the other two mixes with 30% and 50% recycled glass had lower percentages of water absorption (3.94% and 3.55%, respectively).

In the ANOVA test, the results for the concrete water absorption test have statistically shown significant differences when the recycled glass is used for the concrete production. Therefore, the test concluded that the addition of recycled glass enhanced the water absorption properties in the concrete. Consequently, the Tukey HSD Post Hoc test indicated that the water absorption sample for the concrete made up of 50% recycled glass replacement has statistically significant differences compared to all the samples. Hence, the F50 has shown enhanced performance compared to the rest for the water absorption properties.

The more percentage of water absorption, the greater the porosity. This in turn, adversely impact the resistance to chemicals [3]. Mix F20 had the highest mean difference of 0.725% in water absorption percentage compared to the control mix. Mix F50 had the least percentage of water absorption when exposed to chemicals in marine conditions, recording an average of 3.55%. This property of having non-porous material, as seen in the incorporation of glass, reduces the capillary pores of the resulting mixture. This limit the extent to which the material will allow water to be absorbed after such an attack [5]. Moreover, as the percentage of material to be added to the mixture rises, the percentage of water absorption decreases. This implies that the incorporation of recycled glass enhances the material's resistance to chemical attacks.

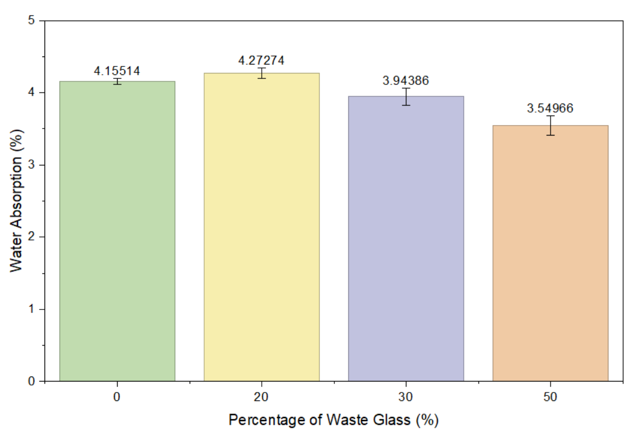

Fig. 6. Average Water Absorption of Concrete

Concrete exhibits an inverse relationship between mechanical and durability properties ; a higher water absorption rate indicates a more porous structure, which generally results in weaker compressive strength [11]. Thus, achieving a balance between these properties results in stronger, more durable concrete. Indeed, according to the test results, F20 had the highest compressive strength after tidal exposure, the highest water absorption rate, and the most mass gain among all the mixtures. On the other hand, mixture F50 had the lowest water absorption and lower mass gain; it failed, however, to reach the standard in terms of compressive strength. On the contrary, mixture F30 has a lower water absorption than F20, the least mass gain, and its compressive strength met the standards.

4 Conclusion and future works

The study concludes that partial replacement of the finer aggregate using the recycled glass material does affect the performance of the concrete. Exposure to the marine environment using the concrete affects the mechanical and durability properties of the concrete because the tidal action facilitates the penetration of the sodium chloride ionic species. The addition of the glass mixture therefore increased the resistance to chemical attacks, implying an increased durability, as depicted by the observed lowered rate of mass gains. Conversely, there was a corresponding observed decrease in the compressive strengths with an increased glass mixture addition. Regardless, the 20% and 30% glass mixture concrete possessed compressive strengths beyond the minimum standards for concrete intended for marine environments. Statistical analysis verified the significance of the observed differences in the changes in the masses and the compressive strengths for the different concrete mixtures prepared. This gives an indication that the replacement level for the finer mixture should approximately 30%.

This study proves that the use of recycled glass in the production of the mixture for maritime structures reduces waste and encourages green building. Further studies should focus on the potential to utilize supplementary cement materials to improve the porosity of the compound and the potential for using type II cement to strengthen the mixture with the benefits of using recycled glass.

References

1. E. Aydın, "Utilization of large amounts of industrial wastes to improve sustainability of the construction sector." InIOP Conference Series: Materials Science and Engineering, vol. 800, no. 1, p. 012007, doi: 10.1088/1757-899X/800/1/012007.
2. B. Leron, A. M. B. Guevarra, A. R. G. Roluna, J. R. Tan, and S. J. L. G. Zalun, "Innovative Construction Reinforcement Medium Using Crushed Glass: An Experimental Risk-Waste Reduction Research."
3. M. M. Al-Tayeb, Y. I. A. Aisheh, S. M. A. Qaidi, and B. A. Tayeh, "Experimental and simulation study on the impact resistance of concrete to replace high amounts of fine aggregate with plastic waste," Case Studies in Construction Materials, vol. 17, Dec. 2022, doi: 10.1016/J.CSCM.2022.E01324.
4. L. D. Pampana, Y. Paluri, Y. Rebka, and A. Hemanth, "Evaluating the Mechanical Performance of Waste Glass Powder as a Fine Aggregate Substitute to Enhance Sustainability in Concrete Production," IOP Conf Ser Earth Environ Sci, vol. 1280, no. 1, 2023, doi: 10.1088/1755-1315/1280/1/012021.
5. F. W. Al-Awabdeh, M. J. Al-Kheetan, Y. S. Jweihan, H. Al-Hamaiedeh, and S. H. Ghaffar, "Comprehensive investigation of recycled waste glass in concrete using silane treatment for performance improvement," Results in Engineering, vol. 16, Dec. 2022, doi: 10.1016/J.RINENG.2022.100790.
6. A. I. Thari, S. A. Salih, and S. S. Hasan, "Influence of using different percentages of waste materials on the strength properties of polymer concrete," IOP Conf Ser Mater Sci Eng, vol. 737, no. 1, Mar. 2020, doi: 10.1088/1757-899X/737/1/012067.
7. S. Sudan and S. Dhiman, "Impact of glass waste and rubber waste over the environment and their applications in concrete," IOP Conf Ser Earth Environ Sci, vol. 1110, no. 1, 2023, doi: 10.1088/1755-1315/1110/1/012051.

8. S. A. Mangi, M. H. Wan Ibrahim, N. Jamaluddin, M. F. Arshad, and R. Putra Jaya, “Short-term effects of sulphate and chloride on the concrete containing coal bottom ash as supplementary cementitious material,” Engineering Science and Technology, an International Journal, vol. 22, no. 2, pp. 515–522, Apr. 2019, doi: 10.1016/J.JESTCH.2018.09.001.
9. Y. Yi, D. Zhu, S. Guo, Z. Zhang, and C. Shi, “A review on the deterioration and approaches to enhance the durability of concrete in the marine environment,” Cem Concr Compos, vol. 113, Oct. 2020, doi: 10.1016/J.CEMCONCOMP.2020.103695.
10. M. Z. Y. Ting, K. S. Wong, M. E. Rahman, and S. J. Meheron, “Deterioration of marine concrete exposed to wetting-drying action,” J Clean Prod, vol. 278, Jan. 2021, doi: 10.1016/J.JCLEPRO.2020.123383.
11. K. Moolchandani, A. Sharma, and D. Kishan, “Enhancing Concrete Performance with Crumb Rubber and Waste Materials: A Study on Mechanical and Durability Properties,” Buildings, vol. 14, no. 1, Jan. 2024, doi: 10.3390/BUILDINGS14010161.