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Enhanced Concrete Performance and Sustainability with Fly Ash and Ground Granulated Blast Furnace Slag – A Comprehensive Experimental Study

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ABSTRACT

This research paper explained in detail how well regular concrete works and how well concrete with fly ash and ground granulated blast furnace slag (GGBS) performs as a substitute for cement. Through a series of experiments, the objective of the study was to perform an experiment that promotes the usage of partial replacement-based concrete which can replace the conventional concrete as well as contributes to sustainable development. A dedicated methodology was developed for the study, focusing on the mechanical and durability properties of the materials with inducing sustainable materials. The methodology study examined the mechanical properties, durability, and microstructural attributes of concrete blends. Cement concrete specimens with binder ratios (%) of 0.3, 0.4, and 0.5 were tested for compressive strength, rapid chloride permeability, SEM, and XRD at 28, 56, and 90 days. Fly ash and GGBS were used to partially replace cement at 0% to 70% for all binder ratios by weight of cement. There were optimal replacement percentages for each binder ratio and fly ash; the concrete partially substituted with GGBS had similar or enhanced mechanical properties to conventional concrete. The novelty of the study is to incorporate microstructure analysis for the same samples that shall enable analysing the behaviour of the partial replaced materials with conventional concrete. In connection with the results, the study had found lower RCPT values in partial replacement concrete specimens, fly ash and GGBS increased chloride ion resistance. SEM and XRD analyses revealed the microstructural properties and phase composition of concrete mixtures, showing how supplementary cementitious materials refine pore structure and provide durable hydration products. This study shows that fly ash and GGBS can improve concrete performance as well as reduce impact on environment and applications in construction.

Keywords: sustainable concrete, compressive strength, RCPT, microstructure.

INTRODUCTION

Self-compacting concrete (SCC) is a type of concrete that achieves compaction only by the force of gravity [1, 2]. A structure with a high density of reinforcement is sufficiently robust to compress the concrete using traditional methods [3, 4, 5]. Thus, SCC concrete is a substitute material capable of self-flowing and self-compacting without the need for mechanical vibrations. In recent years, there has been a growing fascination with self-compacting concrete, which offers superior mechanical strength compared to conventional concrete [6, 7]. SCC has several uses, such as bridge decks, dams, and tall construction. The main characteristics of SCC include features such as strength, workability, and durability. Several researchers are investigating the flowability, durability, and strength characteristics of self-consolidating concrete (SCC) [8, 9]. In order for concrete constructions to be long-lasting, it is necessary to ensure that they are compacted adequately and appropriately. The topics of global warming and regular climate fluctuations are currently prominent worldwide [10, 11]. The growing demand for cement production and its use in concrete is linked to environmental pollution and the significant release of greenhouse gases [12, 13]. The production of 1 ton of binder releases an equivalent amount of CO_2 into the environment, contributing to 5 to 7% of global CO_2 emissions [14, 15]. In 2022, the global output of portland cement amounted to 4.1 billion tonnes, showing a growth rate of 12% since 2018 (U.S. Geological Survey). This statistic is expected to further rise in the upcoming decades as numerous countries are striving for rapid improvements in infrastructure to meet the demands of the expanding population [16, 17]. Housing and advanced infrastructure techniques are now more crucial than ever. Self-compacting concrete plays a crucial role in the construction and development of infrastructure in society [18, 19]. Utilizing Supplementary Cementitious Materials (SCMs) in this concrete can diminish the discharge of CO_2 into the environment. Currently, there is a growing global interest in the use of supplementary cementitious materials (SCMs) in blended concrete to minimise carbon emissions [20, 21]. This is achieved by significantly reducing the amount of cement used. The concrete that incorporates supplementary cementitious materials (SCMs) offers both cost and performance advantages when compared to traditional self-compacting concrete [22, 23]. Furthermore, the utilisation of end products, such as ground granulated blast furnace slag (GGBS), lime sludge, and FA will be increased, resulting in less pollution and lower embodied energy [24, 25]. This could perhaps assist in achieving compliance with the Green Building criteria [44, 45]. To address the issues arising from these end products, it is necessary to provide economically viable construction materials made from these wastes [26, 27]. Fly ash, which is produced as a byproduct of coal burning, is commonly utilised as a supplementary cementitious material. There are two primary categories of ash, known as Class F and Class C [28, 29, 30]. Both varieties can enhance several characteristics of concrete, including sulphate resistance, freeze-thaw resistance, abrasion resistance, and alkali-silica reaction [31, 32, 33]. Mineral admixtures, such as fly ash and GGBS are frequently used as substitutes for SCC. Replacing the binder in concrete with these commercial materials will greatly decrease the emission of greenhouse gases into the environment and prevent the issues related to disposal and pollution [34, 35, 36]. SCMs can be employed either independently or in conjunction with one another in concrete. Introducing supplementary cementitious materials (SCMs) into concrete mixtures to create blended self-compacting concrete mixes can improve the qualities of the concrete in both its early and final stages [37, 38, 39]. Utilising them can enhance the workability, strength, and durability of self-compacting concrete. The predominant substitutes for concrete include GGBFS, SF, FA, metakaolin, rice husk ash, and palm oil fuel ash [40, 41, 42]. FA, when used as a substitute for binders, enhances the qualities of concrete in both its fresh and hardened states. This is attributed to its binding ability and mineralogical composition, making it suitable for structural applications [46, 47]. It was found that the compressive strength and durability increase significantly when fly ash and GGBS are added. The use self-compacting concrete (SCC) has gathered significant attention in recent period due to its ability to compact itself without need of any kind of vibrations and can offer better advantages and similar with Conventional Concrete (CC) in properties like workability, strength, and durability. Moreover, the current study is expected to possess less environmental pollution than CC, methodology framed for this study adopted the partial replacement of cement by fly ash and GGBS.

METHODOLOGY

For the current study, standard concrete mixtures were formulated utilising binder ratios of 0.3, 0.4, and 0.5, following established methodologies specified in ASTM or other pertinent standards. At 28, 56, and 90 days, the prepared concrete specimens were tested for mechanical properties and durability. GGBS and fly ash were both tested as possible alternatives to regular cement in concrete mixtures at the same time. All 0.3, 0.4, and 0.5 water-to-binder (w/b) ratios had replacement percentages from 0% to 70%. The batching and casting of the substituted mixtures of concrete were conducted with great attention to detail to maintain consistency and precision throughout the experimental configuration. After that, the specimens were tested for compressive strength, rapid chloride permeability (RCPT), SEM, and XRD. Compressive strength tests assessed the mechanical performance of concrete mixtures, while RCPT tests assessed their permeability. The microscopic structure and phase composition of concrete specimens were examined using SEM and XRD. The experimental methodology shown in Figure 1 employed a precise and rigorous strategy to investigate the impact of fly ash and GGBS as partial substitutes on the functionality of traditional concrete. This research made a significant contribution to the understanding of sustainable construction practices.

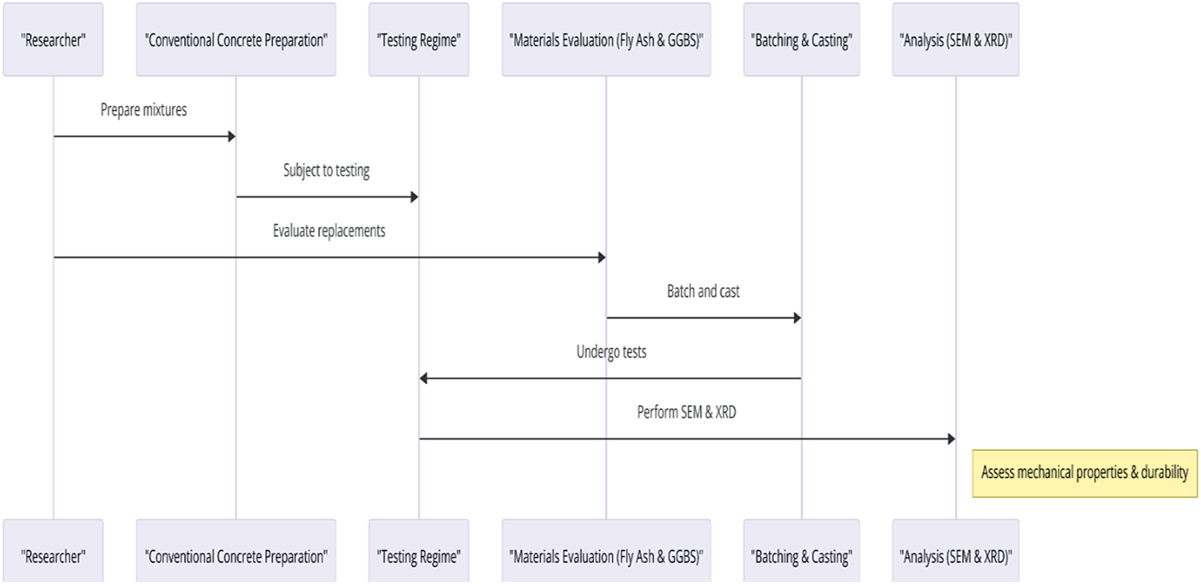

Figure 1. Flow of the work adopted for the study

RESULTS AND DISCUSSION

Analysis of compressive strength with W/B ratios of fly ash

The compressive strength data shows significant trends in the performance of concrete mixtures with varying water-to-binder (W/B) ratios (0.3, 0.4, and 0.5) and fly ash replacement percentages, with a focus on 30%. Irrespective of the water-to-binder ratios, there is a continuous correlation: as the proportion of fly ash used as a substitute increases, the compressive strength of the concrete generally decreases. The decline in strength mostly results from the dilution effect generated by the incorporation of fly ash, which first diminishes strength by substituting a portion of the cementitious material. Moreover, the impact of the W/B ratio is clearly apparent, as the 0.3 W/B ratio consistently demonstrates superior strength, compared to the 0.4 and 0.5 ratios. The concrete strength can be negatively impacted by the higher water content in higher water-to-binder ratios. Figures 2, 3, and 4 show the trend of the strengths attained with CC with 0.3, 0.4, 0.5 binder ratios of fly ash. Notably, the data also highlights the importance of curing length, as longer periods of curing (56-D and 90-D) consistently lead to enhanced compressive strength compared to the 28-D results, particularly in combinations that include fly ash. A 30% replacement of fly ash at a water-to-binder ratio of 0.3 was found to be the most useful mix in regard to the perfect ratio of mix.

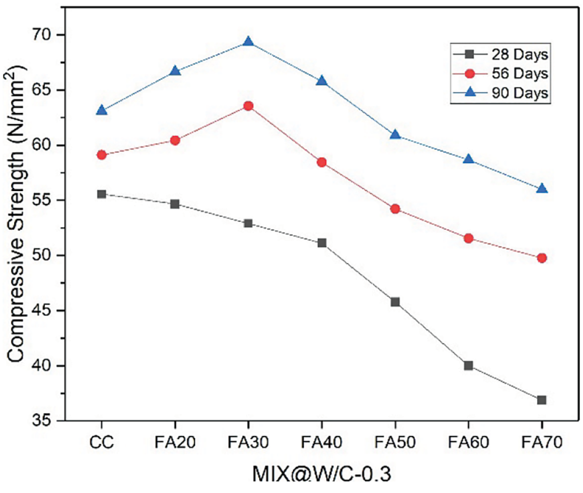

Figure 2. CC and W/B (0.3) with FA

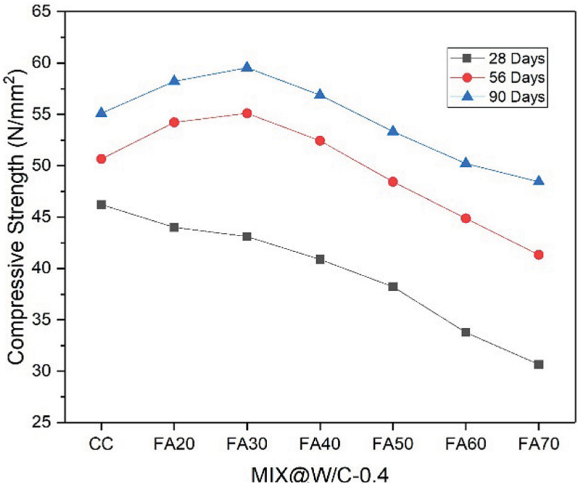

Figure 3. CC and W/B (0.4) with FA

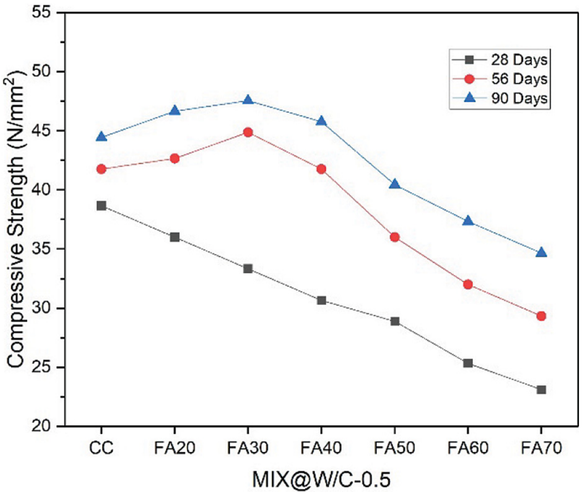

Figure 4. CC and W/B (0.5) with FA

The two combined into a harmonious balance in which ecological sustainability and still enough compressive strength are achieved. It is a technology that comes with some advantages that include the increase in sustainability through the reduction of carbon emissions, higher competitiveness through prolonged curing, cost effectiveness, and enhanced durability emanating from pozzolanic reactions. This study presents the possibility of extra cementitious materials like fly ash promoting environment-friendly construction means without having to compromise concrete performance. Thus, the sustainability of buildings is likely to be obtained from concrete having good compressive strength through the best combination of ingredients where 30% of the cement is replaced by fly ash, and the water-to-binder ratio is 0.3. The combination of those new blends effectively demonstrates the principles of the circular economy in saving primary raw materials and, by far, shrinking the carbon footprint that comes with the concrete production process. Though the initial compressive strength of this concrete might be slightly lesser compared to that of normal concrete, the point to be noted is that with enhanced curing periods of 56 days and 90 days, the brought in development of strength is significantly large. The indicated phenomenon means that the curing process is quite important in the further continuous advance of pozzolanic reactions, which provides the long-term competitive strengths. The cost-effectiveness of this combination is featured by the reduced requirements for the cement, saving the financial resources of the construction projects. Such longer life spans and lower maintenance bills are very inviting, particularly when considering the ecologically friendly construction practices that emphasise performance and being stewards of the environment.

Comparison of optimal binder ratio with fly ash

Taking, for example, the data of compressive strength for different binder ratios and curing durations, 0.3 showed maximum strength after 28 days, where in this case the concrete mix was stupendous at 55.56 MPa. This surpasses the strengths of the mixtures with water-to-binder ratios of 0.4 and 0.5 by great margins, which are 8.89 MPa and 17.90 MPa, respectively. Nevertheless, one interesting change is observed when the process of curing proceeds until the age of 56 days. The 0.4 W/B ratio has shown incredible strength improvement to reach 54.22 MPa, which is vastly larger in comparison with the 0.3 and 0.5 ratios by 5.78 MPa and 6.66 MPa. This illustrates how the period of curing affects the improvement of the performance of the 0.4 mix. Moreover, with the passing of 90 days, the growing strength is sustained and reaches excellent 60.88 megapascals, which exceeds the ratios of 0.3 and 0.5 by essential margins of 6.77 and 5.22 megapascals, respectively. The study has shown the importance of selecting the right binder percentage and proper cure duration. The 0.4 water to binder ratio mix is, thus, shown to be the best with very good strength progression. This makes it a potential option for structural applications that require both immediate and long-lasting performance.

Analysis of compressive strength with W/B ratios of GGBS

The interesting observations to be found by the data analysis are on the influence of GGBS substitution to compressive strength for various water/binder (W/B) ratios. As the proportion of GGBS substitution is increased, the compressive strength enhances continually and considerably. This phenomenon is attributed to the pozzolanic properties of GGBS that facilitate better hydration resulting in developing more solid and denser concrete. Furthermore, it was uniformly found that compressive strengths were higher for lower water-to-binder (W/B) ratios, especially that of 0.3, when compared to those for higher W/B ratios. This highlights the significance of maintaining a lower water content in order to achieve superior strength. It is obviously clear from the results that the highest strength would be realised at 40% and 50% substitution levels of GGBS and at the water-to-binder ratio of 0.3. These blends exhibit the superior performance of concrete strength of GGBS. Besides the trends caused by statistics, the benefits of integration of GGBS into concrete are amazing. It increases the ability of withstanding compressive force dramatically, and further aids in sustainability by lessening traditional cement and thereby reducing carbon emissions. In addition, while there is a certain higher first cost related to GGBS, the reduced amount of cement compensates this. On top of this, the concrete with GGBS is of enhanced durability because of the reduced permeability, hence it is less sensitive to chemical attacks and its long-term structural efficiency is enhanced. To summarise, the use of GGBS in concrete making provides an opportunity of attaining higher performance in structures while being environment responsible at the same time, which makes this option an appealing one for the modern construction methodologies. The higher strength augmentation develops with a higher amount of GGBS substitution, clearly marking the high pozzolanic reactivity of this additive cementitious material. This shows that with the addition of water, GGBS shall react with calcium hydroxide and other substances chemically, a process that can increase hydration while as a result, the microstructure of concrete will be more compact and homogenous. This, in turn, leads to increased compressive strengths at all stages of the curing process. Also, this becomes important to the water-to-binder (W/B) ratio. The result shows that the lower water-to-binder (W/B) ratios, i.e. 0.3, have been constantly effective in the sense of bringing about superior compressive strengths as opposed to the higher ratios of 0.4 and 0.5. Thus, it is for this reason that there is an inclination towards achieving an appropriate balance of water and binder materials that encourage effective hydration without over-dilution. Thus, low water content is an important factor toward attaining optimum strength. The most accurate indications are obvious when the GGBS and water-to-binder (W/B) ratio is at a mix of 40% and 50%, and with that, the resulting W/B ratio is also 0.3. These combinations showed consistent results in having the highest values for compressive strength at different curing ages indicating the most appropriate proportion, Figures 5, 6 and 7 show the trend of the strengths attained with CC with 0.3, 0.4, 0.5 binder ratios of GGBS. It is therefore observed from the results that a 40% and 50% GGBS replacements are the optimum combinations for the mixes where high-strength concrete is required with a W/B ratio of 0.3. Summing up, the wide testing of the supplied data proves the remarkable potential of GGBS in the enhanced compressive strength in various water-to-binder ratios. A maximum 40% and a minimum 50% of replacement in cement by GGBS with a constant water-to-binder ratio of 0.3 give the best compromise between strength, sustainability, economy, and durability. Usage of GGBS in the making of concrete not only serves for the betterment of the quality of a structure but also gives out an environment-friendly outlook—hence an attractive choice for modern-day construction.

Comparison of optimal binder ratio with GGBS

Generally, data are consistent that after 28 days of curing, the water-to-binder ratio (W/B ratio) of 0.3 attains better performance than those at higher water-to-binder ratios (W/B) of 0.4 and 0.5 at all levels of ground granulated blast furnace slag (GGBS) replacement. On the replacement level of GGBS at 30% for 28 days, the compressive strength should be around 54.67 MPa for a water-to-binder ratio of 0.3. However, at the same replacement level, the compressive strengths result as 43.11 MPa and 36.00 MPa with water-to-binder ratios of 0.4 and 0.5, respectively. The same trend of superior strength development continuously was shown with the 0.3 W/B ratio even at 56 days. Significantly, when GGBS reaches a replacement of up to 50% and at 0.3 water-to-binder ratio, the compressive strength tops to 67.56 MPa after 56 days. However, when the same level of replacement was done with the water-to-binder ratio being 0.4 and 0.5, the strengths realised at both these respective water-to-binder ratios are 57.33 MPa and 46.67 MPa, which are lower. This difference in strengths becomes much more evident after 90 days, hence establishing that the 0.3 W/B ratio provides the better mix percentage for maximum compressive strengths consistently at the different curing ages. The results presented indicate the importance of selection of a proper water-to-binder ratio, as the ratio of 0.3 provided better uniformly increased results of compressive strength at the ages of 28, 56, and 90 days. This option not only delivers quicker

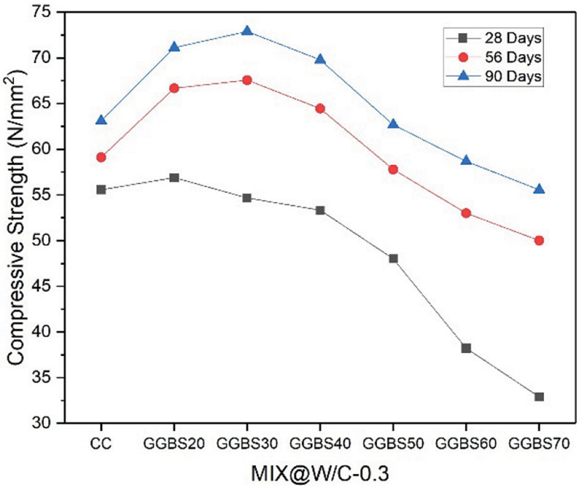

Figure 5. CC and W/B (0.3) with GGBS

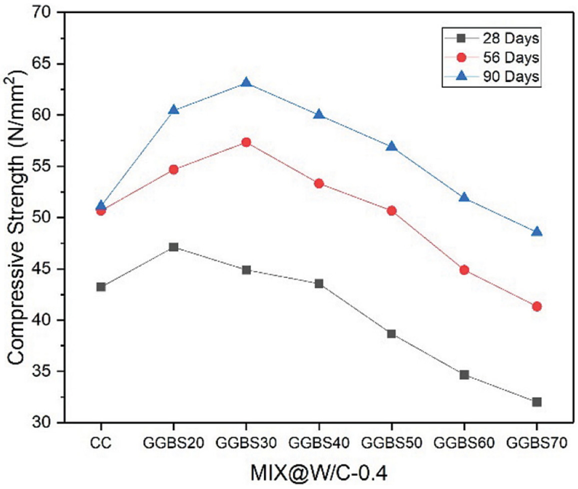

Figure 6. CC and W/B (0.4) with GGBS

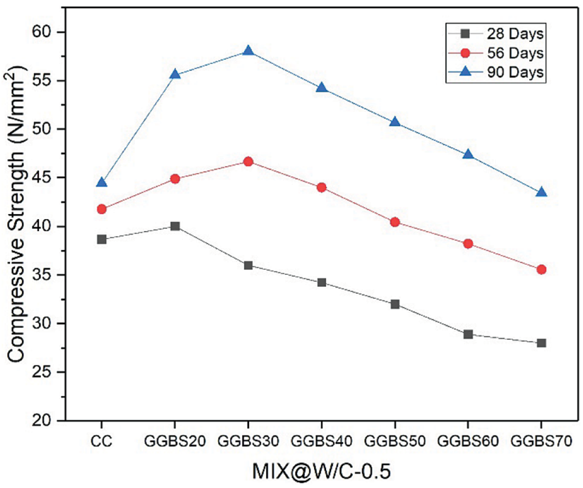

Figure 7. CC and W/B (0.5) with GGBS

development of strength but also yields long-term benefit in terms of durability. Therefore, this combination mix of the two materials is promising for use in high-strength concrete applications with GGBS, considering the 0.3 water-to-binder ratio, to ensure superior performance through ages.

SEM and XRD analysis of the samples

This study examined ordinary concrete specimens with binder ratios of 0.3, 0.4, and 0.5 using scanning electron microscopy (SEM) XRD analysis. The scanning electron microscopy (SEM) examination of the concrete microstructure exposed its essential components, such as the pore network, quartz aggregates, ettringite crystals, and cement hydration products. The constituents showed signs of well-structured and well-hydrated concrete matrices at all binder ratios. Various degrees of interlocking and bonding were observed at the aggregate-cement paste interface, and quartz aggregates were found evenly distributed throughout the cementitious matrix. Ettringite crystals were found, indicating early cement hydration and stable hydration products. Figures 8, 9, and 10 show conventional concrete microstructure images at various binder ratios (0.3, 0.4, and 0.5). Furthermore, scanning electron microscopy (SEM) images and XRD analysis revealed the existence of a compact and interrelated system of hydration products, such as calcium hydroxide (portlandite) and calcium silicate hydrate (C-S-H) gel, which enhanced the toughness and lifespan of the concrete. Due to its low porosity and well-distributed pore network, the pore structure was ideal for reducing permeability as well as resisting freezing-thawing, and chemical ingress. The SEM results and XRD analysis promote the hypothesis that the ratio of binder significantly affects microstructural characteristics as well as properties of conventional concrete, which can be used to optimise concrete mix designs and improve durability in engineering applications [48, 49].

SEM and XRD analysis of conventional concrete with fly ash

According to SEM analysis and XRD analysis, there are many important differences and similarities between regular concrete and fly ash partial substitute concrete. Although both types of concrete had similar parts like quartz aggregates, ettringite crystals, and hydrated cementitious phases, fly ash partial replacement concrete had different microstructure features that showed it was a different

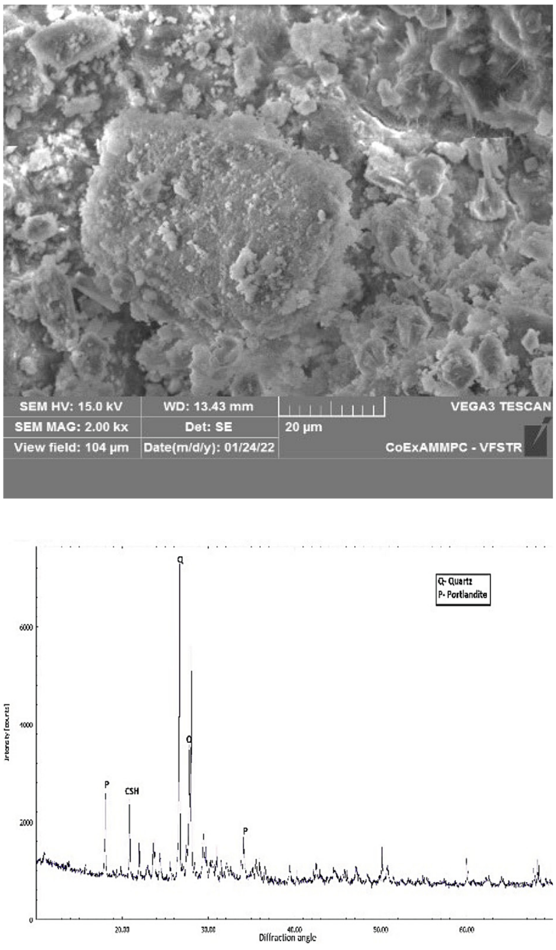

Figure 8. CC with 0.3 W/B (SEM and XRD)

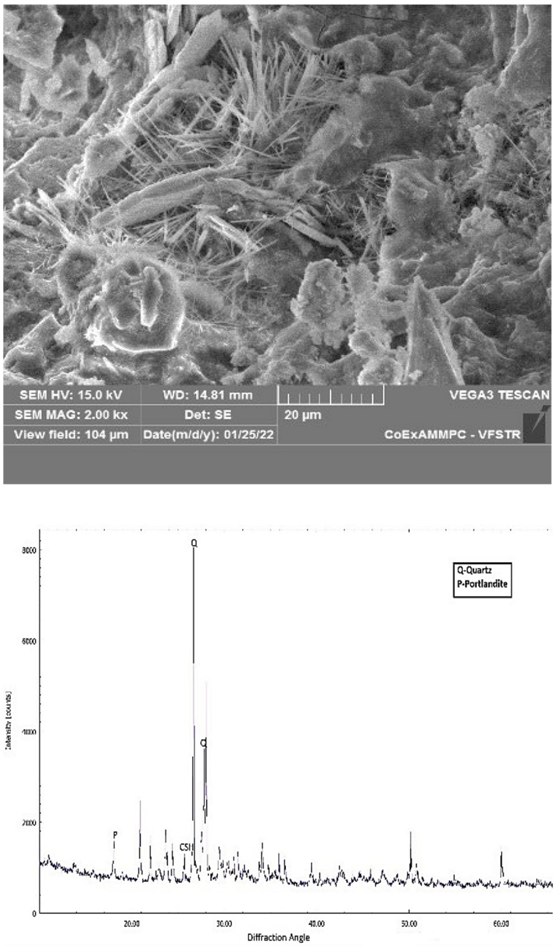

Figure 9. CC with 0.4 W/B (SEM and XRD)

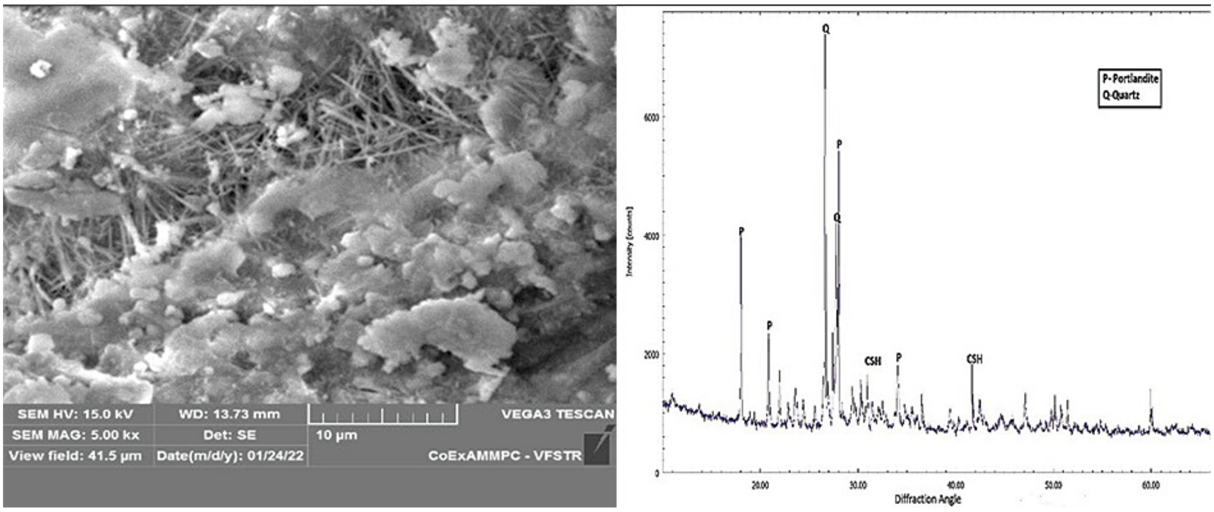

Figure 10. CC with 0.5 W/B (SEM and XRD)

kind of cementitious material. Fly ash-based partially substituted concrete has pores that are smaller and more spread out, as shown in SEM images and XRD analysis in Figures 11, 12, and 13. This is because fly ash and calcium hydroxide react in a pozzolanic way. This refined pore structure improves durability, including chloride ingress and sulphate attack, rendering fly ash substitute concrete a good choice for aggressive infrastructure applications. Fly ash particles in the cementitious matrix densify and reduce permeability, improving durability and environmental sustainability [50, 51].

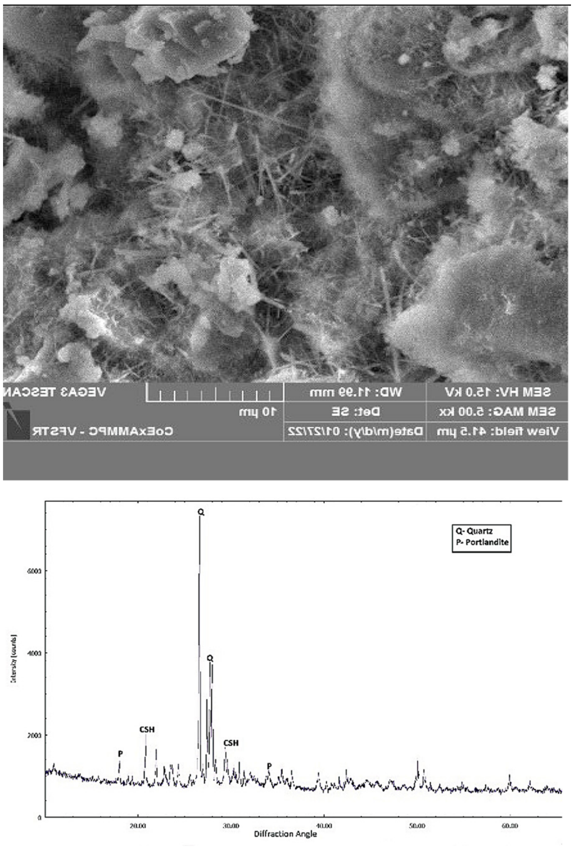

Figure 11. Fly ash (30%) with 0.3 W/B (SEM and XRD)

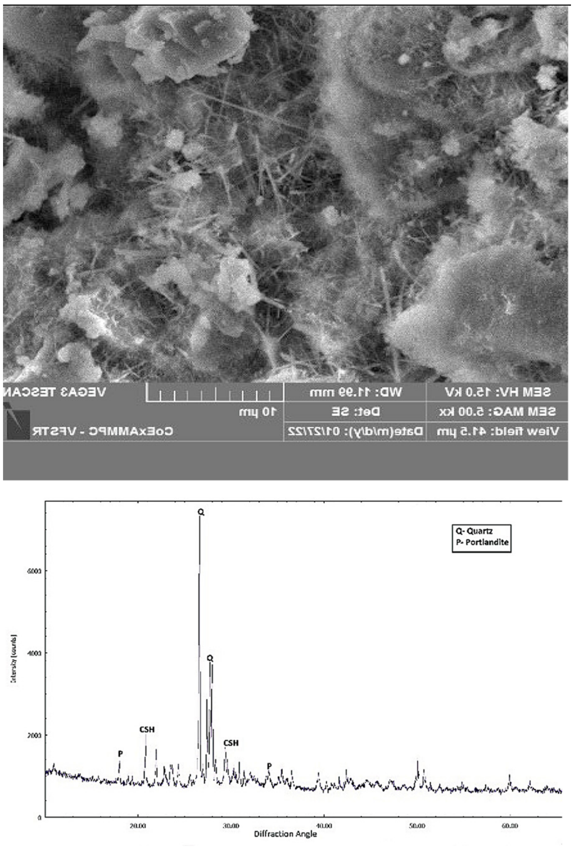

Figure 12. Fly ash (30%) with 0.4 W/B (SEM and XRD)

SEM and XRD analysis of conventional concrete with GGBS

On the other hand, structural examination using SEM and XRD analysis of GGBS partially substituted concrete unveiled discernible microstructural attributes in contrast to conventional concrete. GGBS partial replacement concrete had finer and more uniform hydration products due to its pozzolanic and latent, hydraulic properties, despite having quartz aggregates, ettringite crystals, and hydrated cementitious phases. The refined pore structure that decreased pore connection in SEM images and XRD analysis 14, 15, and 16 resists chloride penetration and alkali-silica reaction. GGBS also increases calcium silicate hydrate (C-S-H) gel, which strengthens and lasts longer. Due to its microstructural refinement and densification, GGBS partial replacement concrete is ideal for sustainable construction applications due to its exceptional durability and environmental benefits [52, 53].

RCPT RESULTS WITH CONVENTIONAL CONCRETE WITH BINARY REPLACEMENT

Fly ash induced concrete

The rapid chloride permeability test (RCPT) assesses the chloride ion penetration resistance of concrete blends, ensuring their durability and integrity under extreme conditions [54, 55]. It is important to make concrete more resistant to chloride so that it doesn't break down as quickly from corrosion caused by chloride. Careful material selection and concrete mix design can achieve this. Figures 17, 18 and 19 show the results of the tests performed in this study. It is observed that fly ash can increase concrete chloride resistance, according to studies. With greater precision, resistance is significantly increased when the proportion of fly ash is increased from 30% to 50%. The enhanced performance can be ascribed to the pozzolanic reaction that takes place in the concrete among fly ash and calcium hydroxide. This reaction generates an additional layer of calcium

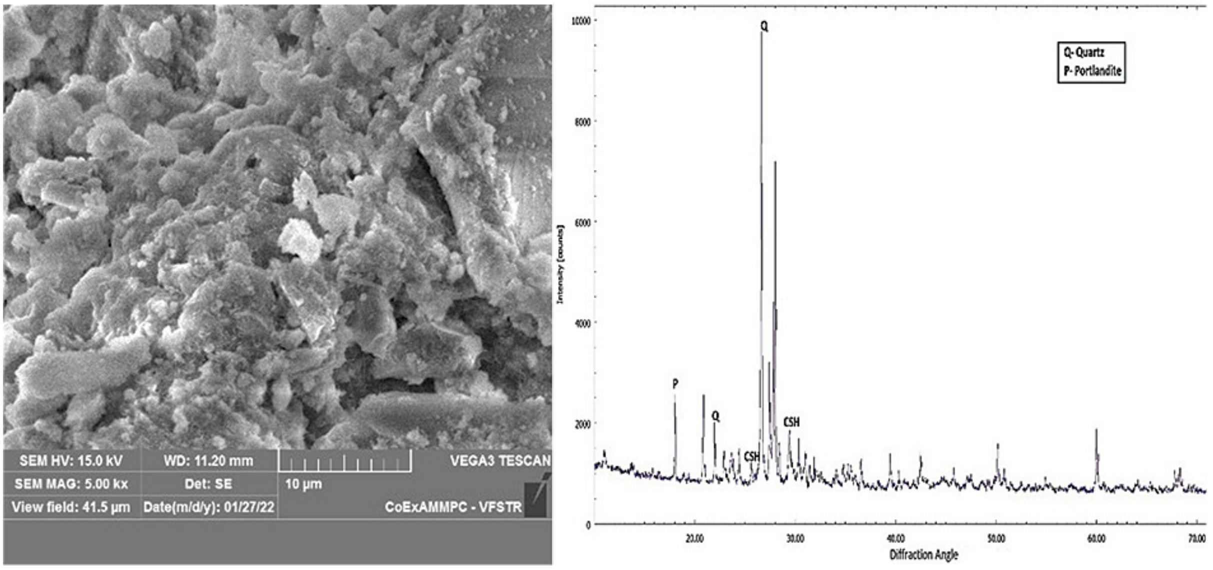

Figure 13. Fly ash (30%) with 0.5 W/B (SEM and XRD)

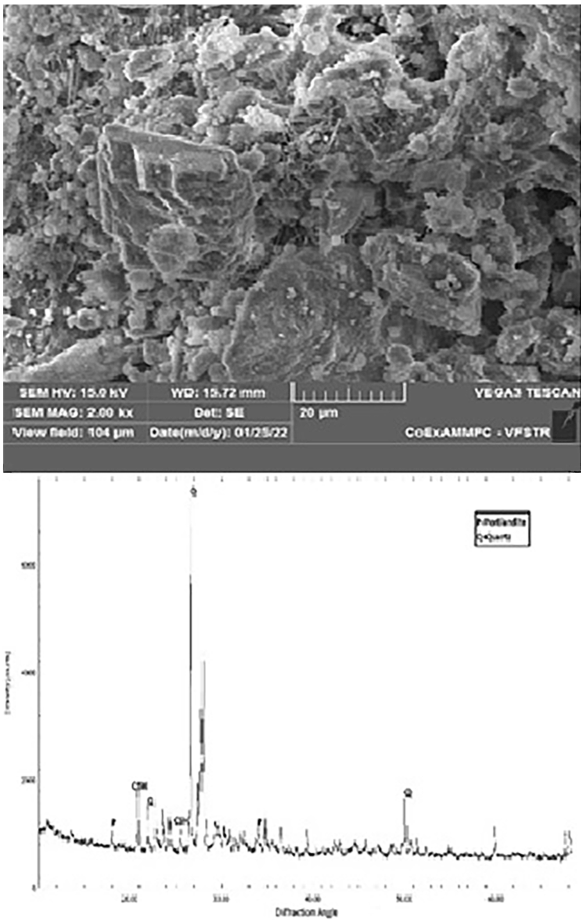

Figure 14. GGBS (30%) with 0.3 W/B (SEM and XRD)

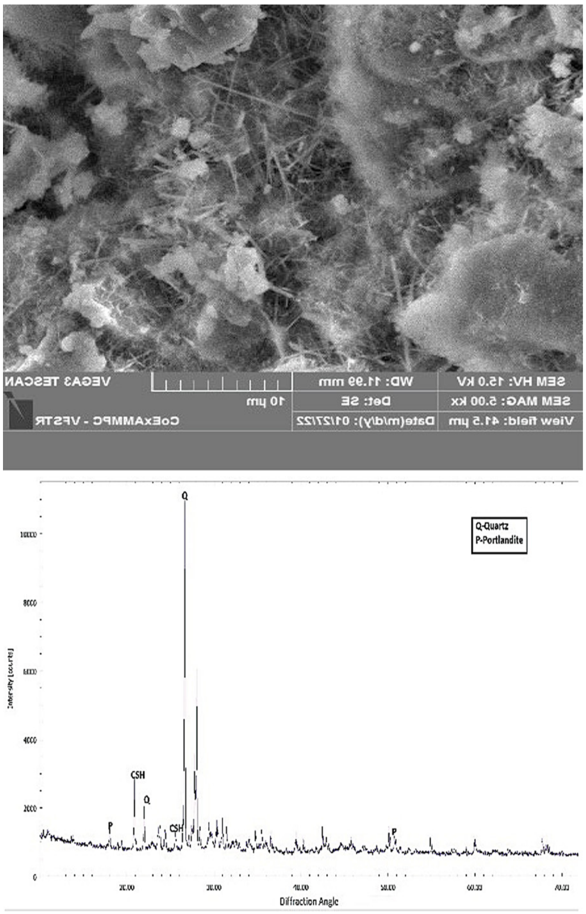

Figure 15. GGBS (30%) with 0.4 W/B (SEM and XRD)

silicate hydrate gel. This gel reduces concrete permeability, preventing chloride ion ingress. For instance, concrete mixes with 30% fly ash have an RCPT value of 1044 Coulombs at 28 days, but 50% fly ash reduces it to 846. The durability resulting from fly ash incorporation is shown by its increased resistance at 56 and 90 days.

In addition, the water-to-binder (w/b) ratio affects concrete chloride resistance. Denser, less capillary-filled concrete is chloride-resistant at lower

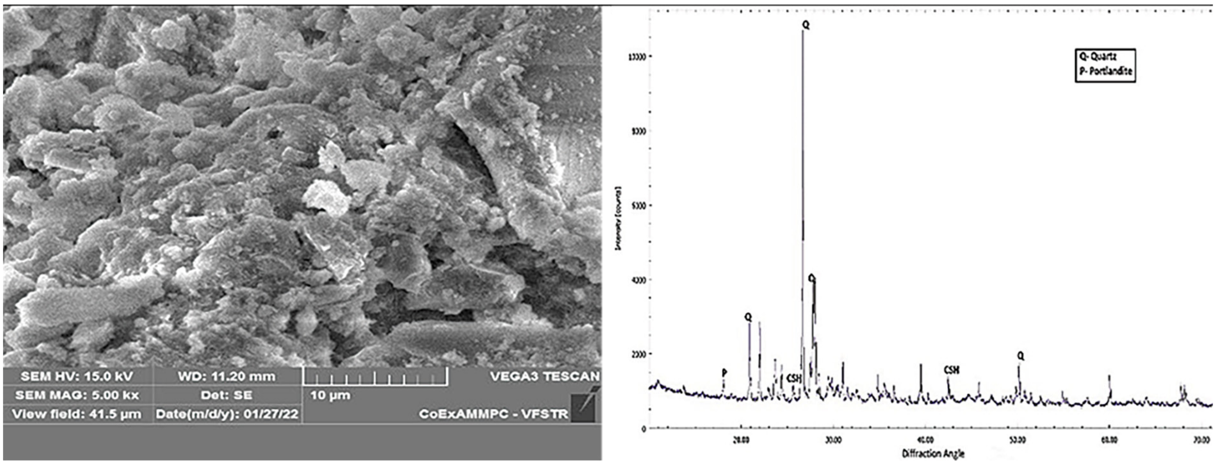

Figure 16. GGBS (30%) with 0.5 W/B (SEM and XRD)

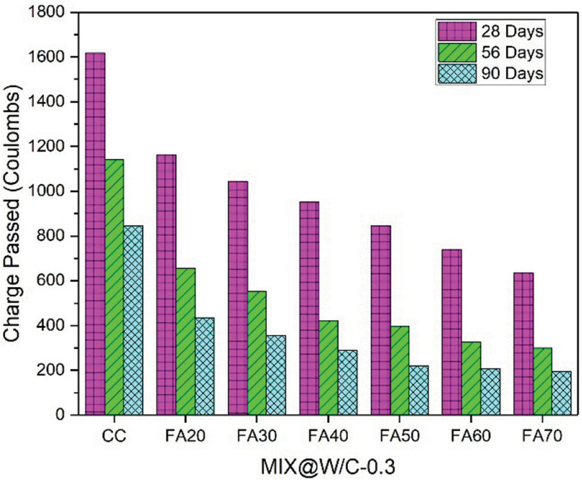

Figure 17. RCPT - CC and W/B (0.3) with fly ash

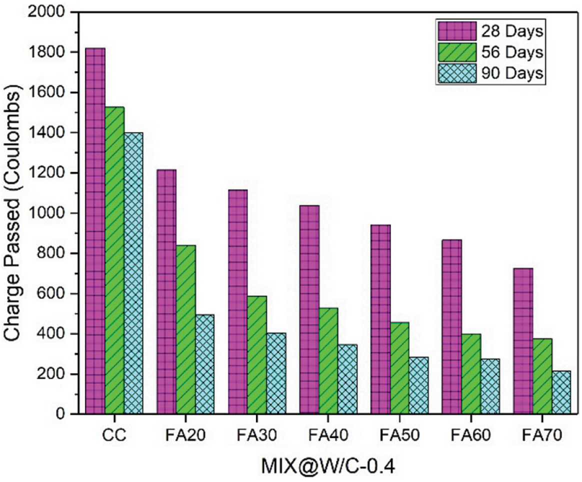

Figure 18. RCPT - CC and W/B (0.4) with fly ash

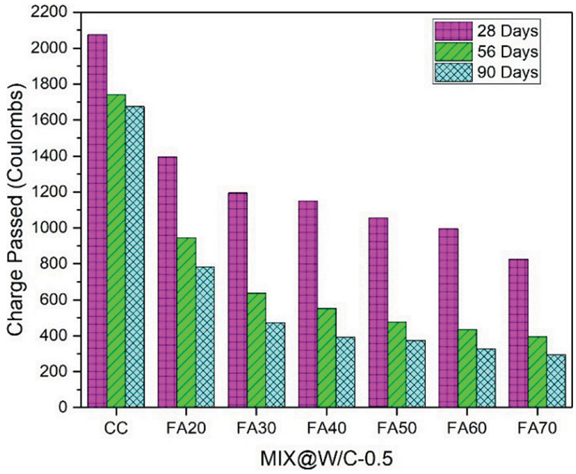

Figure 19. RCPT - CC & W/B (0.5) with fly ash

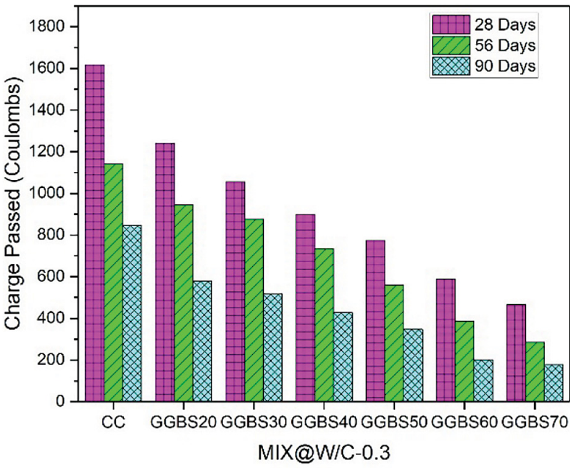

Figure 20. RCPT - CC & W/B (0.3) with GGBS

w/b ratios. The research that compared various weight-to-volume relationships of fly ash in blends with 50% fly ash showed that an RCPT value of 0.3 is much lower than ratios with higher weights to 50% GGBS mix from 0.3 to 0.5 increased RCPT values from 774 to 1445 Coulombs at 28 days, highlighting the importance of optimizing the ratio to maximise chloride resistance and the role

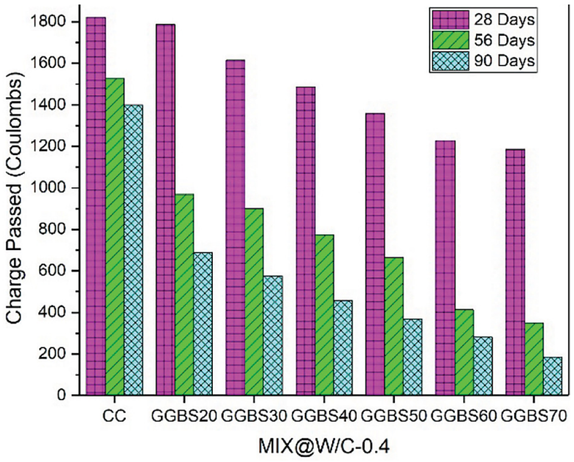

Figure 21. RCPT - CC and W/B (0.4) with GGBS

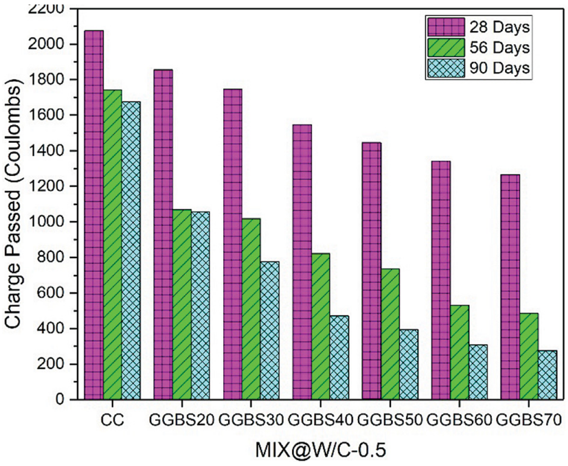

Figure 22. RCPT - CC and W/B (0.5) with GGBS

volumes. This suggests optimising fly ash content and w/b ratio for chloride resistance. Using 50% fly ash and 0.3 w/b achieves the best results. This chloride-resistant mix promotes sustainability. Fly ash-based concrete reduces waste and greenhouse gases. The buildings that are exposed to chlorides need less upkeep and last longer because this mix is strong and does not let water through easily.

RCPT analysis with GGBS

Concrete with GGBS can withstand chloride ion penetration, a key indicator of durability and sustainability in harsh, chloride-rich environments, according to the RCPT [56, 57]. The resistance of concrete to chloride-induced corrosion is greatly improved by GGBS, which extends its lifespan and maintenance. Chloride penetration resistance is positively correlated with concrete GGBS content. GGBS content from 20% to 50% increases chloride resistance uniformly across testing stages. It was found that the enhancement can be attributed to the pozzolanic and latent hydraulic properties of GGBS, which limit the movement of chloride ions and lower the permeability of concrete [58, 59]. For example, concrete with 20% GGBS had 1240 Coulombs in RCPT values at 28 days, while mixes with 50% GGBS at 0.3 water-to-binder (w/b) ratio had 774 Coulombs. Figures 20, 21 and 22 show the results obtained for GGBS replaced with a percentage of 30%. The inclusion of GGBS reduces RCPT values for 56 and 90 days, demonstrating its long-term effects. Data also shows that w/b ratio significantly affects chloride resistance. Different GGBS mix proportions show that lower w/b ratios increase resistance. Changing the w/b ratio of mix design in durable concrete. In all testing periods, the mix with 50% GGBS and a w/b ratio of 0.3 showed the lowest RCPT values and was the most durable against chloride ion penetration. This chloride penetration-resistant mix is the best for environmental sustainability and structural durability.

CONCLUSIONS

The concrete made with fly ash and GGBS reduces construction carbon emissions and improves sustainability. By decreasing portland cement use, coal-derived fly ash reduces waste and carbon emissions. Among the different binder ratios developed and experimented for this study, the goal was to identify the binder ratios that performed better across the mixes. The study identified that the concrete blend containing 30% fly ash and 0.4 water-to-binder ratio achieves 54.22 MPa compressive strength after 28 days, demonstrating its structural integrity and ecological advantages. GGBS from iron and steel production has potent pozzolanic properties that reduce CO_2 emissions from cement production. A 30% cement substitute with GGBS at the identical water-to-binder ratio yields 56.89 MPa compressive strength after 28 days, surpassing the standard strength of concrete and encouraging its use for improved material properties and reduced environmental impact. For durable and sustainable building, engineers and architects should use fly ash and GGBS more. Teaching the building sector about these materials and governmental regulations and subsidies could boost sustainable construction. Such strategies reduce carbon emissions and environmental impact while building durable, affordable buildings, improving sustainable construction.

An in-depth analysis of RCPT results shows that fly ash boosts the chloride resistance of concrete, with a 50% fly ash and 0.3 water-to-binder ratio formula being the best for durable, environmentally friendly, and affordable development in corrosive-exposed settings. This mix performs well structurally and shows a commitment to sustainability in construction. The RCPT data also emphasise the significant impact of GGBS on the chloride resistance of concrete, recommending a 50% GGBS mix with a 0.3 water-binder ratio. This formulation reduces carbon emissions and extends concrete structure durability in corrosive environments, meeting sustainability goals. Its excellent performance shows that GGBS in concrete mixes for construction provides an ecologically sound, durable, yet financially viable solution to modern infrastructure issues.

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