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THE EFFECT OF WASTE GLASS POWDER ON THE MECHANICAL AND PERMEABILITY PROPERTIES OF ROLLER-COMPACTED CONCRETE

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ABSTRACT

In the context of endeavours to mitigate the global environmental impact of the construction industry, the utilization of pozzolanic additives derived from waste materials has emerged as a pivotal area of research, particularly in the pursuit of sustainable materials. The present study investigates the use of ground waste glass powder (WGP) as a binder material in roller-compacted concrete (RCC), whilst also examining the effects of different curing regimes on the mechanical performance of RCC. Within the experimental programme, four main mixture groups were designed by replacing CEM I 52.5 N type cement with WGP at ratios of 0%, 10%, 20%, and 30%. The production process was conducted for each group at five distinct water contents. The optimum water content was determined on the basis of the maximum dry density. The consistency of the fresh mixtures was determined using the modified Vebe test. The mechanical and permeability performance of the samples that had been cured for 28 days was evaluated using a range of testing methods, including compressive strength, flexural strength, water absorption, and sorptivity tests. Furthermore, chemical curing, membrane and wet burlap methods were employed on specimens produced with a 10% WGP replacement rate, and the impact of the curing method was examined. The findings indicate that a 10% replacement of WGP results in optimal performance with regard to both compressive and flexural strength. Conversely, the incorporation of 20% WGP has been demonstrated to enhance permeability properties. The highest strength values were obtained from RCC samples cured wet burlap. The findings of this study demonstrate that WGP can be regarded as an effective binder with a low carbon footprint, and that it offers contributions to RCC in terms of both environmental sustainability and technical performance.

Keywords: Roller-compacted concrete, Waste glass powder, Optimum water content, Curing methods.

1 INTRODUCTION

In the contemporary context, sustainable construction practices are acquiring mounting significance due to a range of factors, including the imperative to curtail environmental degradation, conserve natural resources, and enhance waste management. In this context, the research of new materials aimed at reducing environmental impacts in cement-based materials and the reuse of industrial waste has become a fundamental focus in both academic and applied studies in the field of construction materials. The production of cement, the most widely used binder in the construction industry, is directly linked to high energy consumption and carbon emissions. In particular, it has been reported that Portland cement production accounts for approximately 7% of global carbon dioxide (CO_2) emissions [1-3]. This has prompted research into reducing cement consumption or replacing it with environmentally friendly alternative materials. Consequently, the development of environmentally sensitive, durable, and economically viable binding systems is imperative for achieving sustainability goals in the field of concrete technology. In this context, new-generation concretes produced using alternative materials that can partially or completely replace Portland cement contribute to both reducing carbon emissions and utilising industrial waste.

Waste glass powder (WGP) is regarded as a prospective pozzolanic material that can be integrated into cement matrices due to its elevated silica (SiO_2) content and amorphous structure. This material, which is obtained by grinding waste glass, can be used as a partial substitute for cement in the production of concrete. It has been demonstrated that finely ground glass dust reacts with calcium hydroxide ($Ca(OH)_2$) released during cement hydration, thereby promoting the formation of secondary C-S-H phases [4-6]. The reactivity of amorphous silica in glass powder plays a pivotal role in this process, and the resulting secondary phases increase the amount of C–S–H gel, thereby enhancing the mechanical strength and permeability resistance of concrete [5-6]. Furthermore, the fine-grained structure of WGP has been demonstrated to fill the voids in the concrete's microstructure, thereby reducing permeability and enhancing durability [7]. The utilisation of WGP as a pozzolanic additive in concrete production has been demonstrated to reduce the consumption of natural resources and contribute to a reduction in the carbon footprint [8].

The impact of WGP on conventional concrete has been extensively examined in numerous studies in the extant literature. Uzun et al. (2018) [9] reported that replacing 0–20% of cement with WGP reduces workability but increases compressive strength. This phenomenon

is attributed to the increased water demand resulting from the high specific surface area of glass powder and its micro-filling effect. In the study conducted by Aliabdo et al. (2016) [10], the production of concrete with target compressive strengths of 33 MPa and 45 MPa was achieved through the incorporation of 5–20% WGP replacement [10]. This outcome serves to demonstrate the efficacy of the method in achieving high compressive strengths at low replacement ratios. Orhan and Esen (2017) [11] stated that the pozzolanic activity of WGP is approximately 80%, and that it complies with Turkish standards. The optimum outcomes in terms of tensile strength were achieved with a 10% WGP replacement. In a recent study, Muhedin and Ibrahim (2023) [12] observed an increase in compressive strength of 32% at seven days and 14% at 28 days with a 5% WGP replacement. However, as the replacement ratio increased, the strength increases remained limited or decreased. Ibrahim (2021) [13] reported an increase in compressive strength of 7.5% and a further increase in tensile strength of 13.15% with a 5% WGP replacement, but a decrease in strength was observed after a 15% replacement ratio. Sakale et al. (2016) [14] reported that the optimal substitution ratio is 20%, at which flexural and tensile strength reach their highest values, but mechanical strength decreases at ratios above 20%. It was also noted that elevated substitution ratios have a detrimental effect on workability. In their study, Mahmoud et al. (2019) [15] examined the impact of partial replacement of cement with 10–25% WGP, observing substantial increases in compressive strength at replacement ratios of 15–20%. The highest observed strength was recorded at a 20% replacement ratio, which resulted in a 53% increase. Conversely, a decrease in strength was observed at a 25% replacement ratio.

Roller compacted concrete (RCC) is a type of concrete characterised by a low water-to-cement ratio and dry consistency, with placement and compaction typically carried out using vibrating rollers. Its primary applications include large-scale infrastructure projects such as roads, dams, and airports [16]. Although it shares similar components with traditional concrete, RCC offers cost-effectiveness due to its ability to be applied without formwork, its lack of reinforcement requirements, and its rapid placement [17-19]. However, due to its low water-to-cement ratio, RCC's performance is highly sensitive to curing conditions. The large surface area and rapid production increase moisture loss in fresh concrete, which negatively affects hydration and strength development [20-22]. Therefore, curing conditions are as critical as mix design in RCC production.

In recent years, there has been an increase in the utilisation of alternative binders in the production of RCC. This approach is significant in terms of both reducing environmental impact

and offering cost advantages. Pozzolanic additives, such as fly ash, granulated blast furnace slag, and silica fume, have been extensively researched [23-28]. Conversely, alternative pozzolans, such as glass powder, have been the focus of only a limited number of studies. The extant literature pertaining to the effects of WGP on RCC is relatively limited, with existing studies primarily focusing on strength development. For instance, Faubert et al. (2013) [29] reported that RCC mixtures produced with 10–25% WGP replacement achieved the highest compressive and flexural strengths at 91 days at a 20% replacement ratio. Omran et al. (2017) [30] observed that RCC containing 20% WGP demonstrated compressive and flexural strengths that were 5% and 15% higher, respectively, at 91 days. Furthermore, SEM analyses revealed a more dense microstructure.

The efficacy of curing methods is a critical factor in the development of mechanical strength, particularly in RCC mixtures with low water-to-cement ratios. As outlined in the ASTM C171 [31] and ASTM C309 [32] standards, the implementation of curing methods must be executed in a manner that ensures moisture retention, thereby facilitating continuous hydration in RCC. In the study conducted by Keleş (2019) [22], the application of chemical curing, membrane, and wet burlap methods with delays ranging from 0 to 60 minutes was investigated, and it was demonstrated that the optimal results were obtained with water curing, while wet burlap emerged as an economical and feasible alternative.

The objective of this study is to systematically evaluate the effects of WGP content and different curing methods on the fresh and hardened properties of RCC. RCC mixtures were produced with varying optimum water contents for various WGP replacement ratios. The fresh concrete properties were evaluated using the modified Vebe test, while the hardened concrete properties were assessed through compressive strength, flexural strength, water absorption, and sorptivity tests. Furthermore, three distinct curing methodologies (chemical, membrane, and wet burlap) were employed on mixtures comprising 10% WGP, and their impact on mechanical performance was evaluated.

This study makes significant contributions to the literature in terms of both the utilization of environmental waste in construction materials and the optimization of the performance of alternative binding material. The partial replacement of cement with WGP in RCC mixtures not only reduces cement consumption and contributes to lowering carbon emissions but also enables the use of more sustainable materials in the construction industry. Furthermore, the study emphasizes that curing conditions represent a critical technical parameter that must be carefully selected in RCC applications, by highlighting the significant

effects of different curing methods on mechanical strength development. In this regard, the study makes a significant contribution to the objectives of sustainable material development and to engineering requirements related to application safety and performance.

2 MATERIAL AND METHOD

2.1 Materials

In experimental studies, Portland cement of type CEM I 52.5 N, with a specific gravity of 3.16 g/cm³, a Blaine specific surface area of 3123 cm²/g, and compliant with the EN 197-1 (2011) [33] standard, was used as the binding material. The chemical analysis results for the cement are presented in Table 1.

Table 1. Chemical composition of Portland cement

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O
62.94	19.03	5.13	3.04	1.62	2.66	0.65	0.14

The mechanical and durability performance of RCC is directly influenced by fundamental parameters, including aggregate type and granulometry. In particular, aggregate size, gradation range, and mix design play a decisive role in the compactness, workability, and final density of the mixture in RCC mixtures. The ACI 211.3R-02 (2009) [34] guideline specifies the maximum particle size recommended for road-type RCC applications, along with the lower and upper limit gradation curves to achieve optimal granulometry. In this study, marble dust and basalt aggregate with a maximum particle size of 19 mm were utilized, in accordance with the aforementioned guideline. The particle size distribution ratios of each aggregate are presented in Table 2, while the specific gravity values and water absorption capacity are shown in Table 3. As demonstrated in Figure 1, the gradation curve obtained for the aggregate mixture is observed to fall within the recommended limit gradation curves by ACI 211.3R-02 (2009) [34], thereby meeting the optimal granulometry conditions. This finding suggests that the prepared aggregates are adequate for supporting the formation of a compact structure and meet the strength and durability criteria targeted for RCC mixtures.

Table 2. Results of aggregate sieve analysis

Sieve size (mm)	Marble dust	Basalt Aggregate		
		0.075-4.75 mm	2.36-12.5 mm	4.75-19 mm
25	100	100	100	100
19	100	100	100	100
12.5	100	100	100	39.24
9.5	100	100	87.87	1.18
4.75	100	99.70	15.79	0.22
2.36	99.61	76.85	1.49	0.22
1.18	96.60	57.74	1.21	0.22
0.6	84.20	42.94	1.21	0.22
0.3	54.70	29.59	1.21	0.22
0.15	34.57	18.36	1.21	0.22
0.075	21.97	11.96	1.21	0.22

Table 3. Physical properties of aggregates used

Aggregate		Specific gravity	Water absorption (%)
Basalt aggregate	4.75-19 mm	2.76	1.47
	2.36-12.5 mm	2.70	2.83
	0.075-4.75 mm	2.65	2.51
Marble dust		2.66	7.36

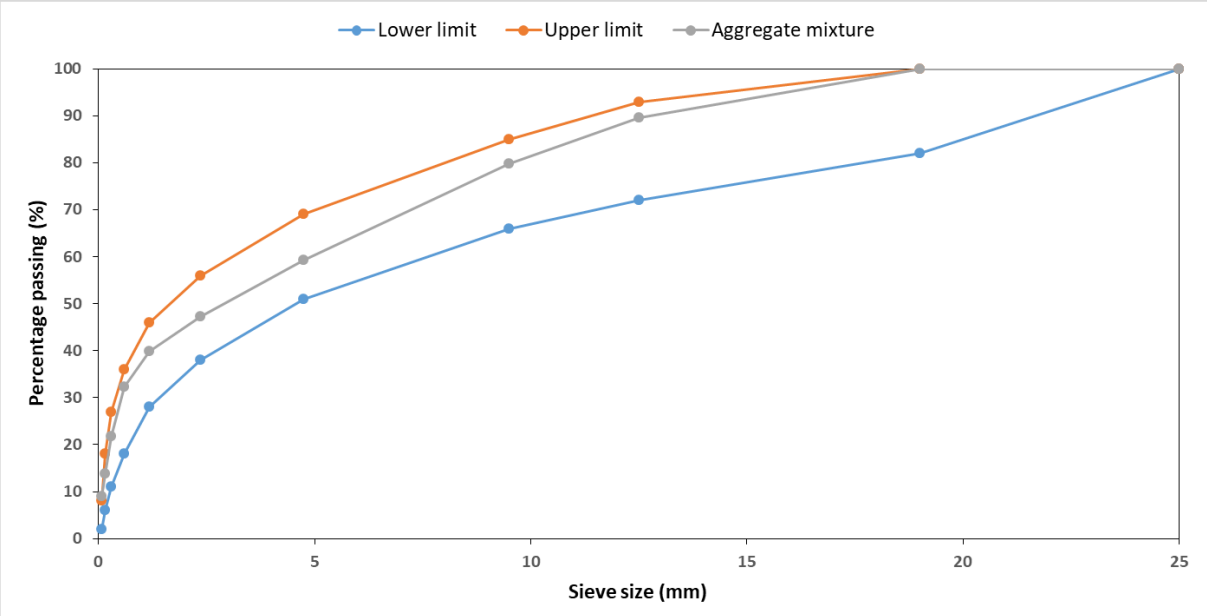


Figure 1. Gradation curve of the aggregate mixture and the limit curves recommended in the ACI guideline

In this experimental study, WGP shown in Figure 2 with a specific gravity of 2.58 g/cm³ and water absorption ratio of 0.02% was used. The WGP used in this study was obtained from Akcihan Glass Industry and Trade Ltd. The particle size distribution percentages of WGP are presented in Figure 3, and its chemical composition is given in Table 4.

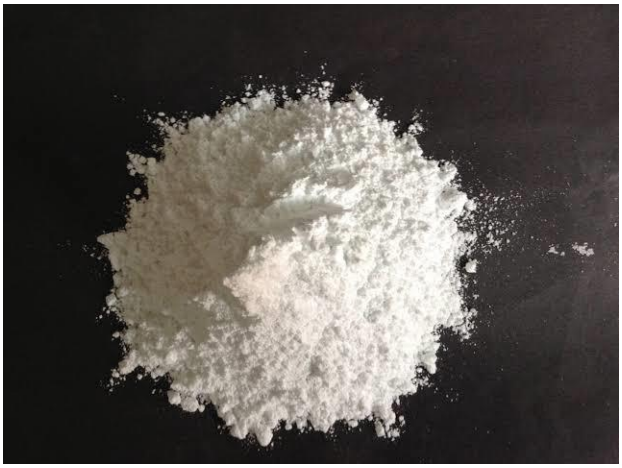


Figure 2. Photograph of WGP used

Table 4. Chemical composition of WGP

SiO_2	Fe_2O_3	CaO	Al_2O_3	MgO	Na_2O	LOI
69.42	0.4	8.27	1.09	4.25	12.31	16.18

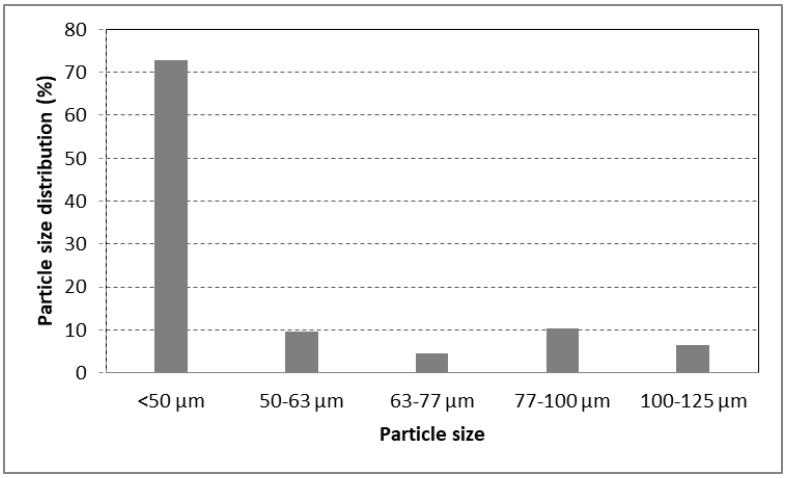


Figure 3. Particles distribution percentage of WGP

For this study, a paraffin-based curing chemical that complies with ASTM C309 (2017) [32] was used in the curing process. The physical properties of this chemical are presented in Table 5.

Table 5. Physical properties of paraffin-based curing chemical

Parameter	Value
Density	0.95-1.00 kg/lt
Colour	White
Consistency	Liquid
Appearance of the final film layer	opaque layer
Consumption	0.15-0.2 kg/m^2

In the process of wet burlap curing, jute fabric that complies with the ASTM C171 (2016) [31] standard was utilised. The material exhibits a surface density of 230 g/m² and a porosity of approximately 2 mm. Furthermore, a 1.5 mm-thick black plastic cover, which complies with the ASTM C171 [31] standard, was utilised as a membrane coating material in the curing process.

2.2 Detail of Mixes and Preparation

In this study, RCC mixtures with varying binder compositions were prepared by replacing cement with WGP at ratios of 0%, 10%, 20%, and 30% by weight. In the initial phase of the experimental programme, the objective was to ascertain the optimal water content for each WGP replacement ratio. In all mixtures, the binder content was maintained at a constant 14% of the total dry aggregate weight. A total of 20 mixtures were designed by testing five different water contents for each WGP level.

The optimum water content was determined based on the principle of maximum density within the framework of the relationship between wet and dry density. For the purpose of this study, each mixture was placed in cylindrical moulds measuring 150×300 mm in three layers. Each layer was then compacted using a vibrating rammer in accordance with the ASTM C1435 (2014) [35] standard (see Figure 4). The total weight of the fresh concrete placed in the mould was measured, and the wet unit volume weights (γ_{wet}) were calculated using Equation 1. Subsequently, random samples were obtained from each layer of the RCC samples extracted from the mould, and their mass (m_{wet}) was determined. The samples were then dried in an oven at 105 ± 5 °C for a period of 24 hours, after which their dry weights (m_{dry}) were determined. The water contents and dry densities of the specimens were calculated using Equation 2 and Equation 3, respectively. Following the creation of point distribution graphs utilizing the water content values corresponding to the dry density obtained, a second-degree polynomial trend line was derived through the implementation of the least squares method. The optimum water contents corresponding to the maximum dry density were identified for each RCC mixture.

$$\gamma_{wet} = \frac{m}{v} \tag{1}$$

$$w = \frac{(m_{wet} - m_{dry})}{m_{dry}} x100 \tag{2}$$

$$\gamma_{dry} = \frac{\gamma_{wet}}{1 + w} \tag{3}$$



Figure 4. Stages of determining the optimum water content of RCC mixtures

The RCC mixture ratios utilized in this study were determined in accordance with the ACI 211.3R-02 [34] guideline, which encompasses the mixture principles advocated for concrete with zero slump values. Following the determination of the optimal water content for each WGP replacement ratio (0%, 10%, 20%, and 30%), four distinct RCC mixtures were produced. The material quantities utilized in the prepared RCC mixtures are presented in Table 6.

Table 6: Quantities of materials used in 1 m³ of RCC mixtures

Mix ID	Cement (kg)	Aggregate		WGP (kg)	Water (kg)
		0-4.75 mm (kg)	4.75-16 mm (kg)		
%0 WGP	276.7	1086.9	889.3	0.00	162.6
%10 WGP	247.8	1081.5	884.9	27.5	164.8
%20 WGP	218.3	1072.1	877.2	54.6	170.0
%30 WGP	189.5	1063.4	870.1	81.2	174.6

As demonstrated in Figure 5, the RCC samples were produced by compaction using vibrating hammer in accordance with the ASTM C1435 (2014) [35] standard. During the production process, fresh concrete mixtures were placed in moulds in three stages, with compaction applied for approximately 20 seconds for each stage. Subsequent to the completion of the compaction process, the samples were left in the moulds for a period of 24 hours, after which they were removed from the moulds and subjected to water curing until the day of testing.



Figure 5. Production of RCC samples

2.3 Testing

The present study employed the modified Vebe test to ascertain the consistency of the RCC mixtures produced. Water absorption, sorptivity, compressive strength, and flexural strength tests were conducted to ascertain the properties of hardened concrete.

In order to ascertain the consistency of RCC mixtures, a modified-Vebe test was conducted in accordance with the ASTM C1170 (2014) [36] standard. In this test, 12.5 kilograms of fresh RCC mixture was loosely placed in the cylindrical chamber of the Vebe device, and a standard load of 22.7 kilograms was applied on top. The stopwatch was initiated when the load came into contact with the mixture, and the device was activated to compress the mixture. The stopwatch was halted when a continuous and distinct ring formed between the surface of the plate exposed to the load and the surface of the test device mould. The measured time was recorded as the modified-Vebe time for the mixture and used as the basis for evaluating the mixture's consistency.

The sorptivity test was conducted on RCC samples measuring 100x100x100 mm in accordance with the ASTM C1585 (2013) [37] standard. The samples were dried in an oven at a temperature of 105 ± 5 °C until they reached a constant mass. The lateral surfaces of the samples were coated with a waterproof adhesive membrane measuring approximately 2–3 cm in width, thereby ensuring that only the inferior surfaces were in contact with water. Subsequent to the membrane application, the dry weight of each sample was measured. The samples were positioned within a capillary water apparatus, characterized by a constant water level, such that only their bottom surfaces were in contact with water. At predetermined time intervals, the samples were retrieved, the excess water on their surfaces was dried using a towel, and they were weighed again. Consequently, the water absorption quantities of the samples were determined as a function of time. The water absorption quantities were calculated by dividing the water absorption quantities by the base area of the sample in contact with water. A graph was then plotted using these values and the square root of the corresponding time intervals. The slope of the best fit line obtained from this graph was defined as the sorption coefficient for each sample. The experiment was conducted on three samples for each mixture, and the sorptivity coefficient was calculated by taking the average.

The water absorption test was conducted in accordance with the ASTM C642 (2013) [38] standard, utilizing RCC samples measuring 100×100×100 mm. The samples were initially dried in an oven at a temperature of 105 ± 5 °C until a constant mass was achieved. Thereafter, the dry masses obtained in this state were recorded. Subsequent to the drying process, the samples were immersed in water for a period of 24 hours, with the objective of achieving a state of saturated surface dry. Subsequently, the residual water present on the surfaces of the samples was removed, and the samples were weighed. The weights obtained from this measurement were recorded as saturated surface dry mass. The water absorption ratio was calculated for each sample, and the arithmetic average of the results obtained from three samples for each mixture was taken.

The flexural strength was conducted in accordance with the ASTM C293 (2016) [39] standard, employing prismatic RCC specimens with dimensions of 100×100×400 mm. The test was conducted based on the three-point loading principle, and three specimens were tested for each mixture. The arithmetic means of the obtained results were calculated.

The compressive strength test was conducted in accordance with the ASTM C39 (2012) [40] standard, on RCC specimens with dimensions of 100×100x100 mm. Three samples were prepared for each mixture and loaded under uniaxial load until failure to determine the

compressive strength. The mean value of the three measurements obtained for each mixture was accepted as the compressive strength of the corresponding mixture.

The workflow diagram, which summarises the stages of the research conducted within the scope of the study, is presented in Figure 6.

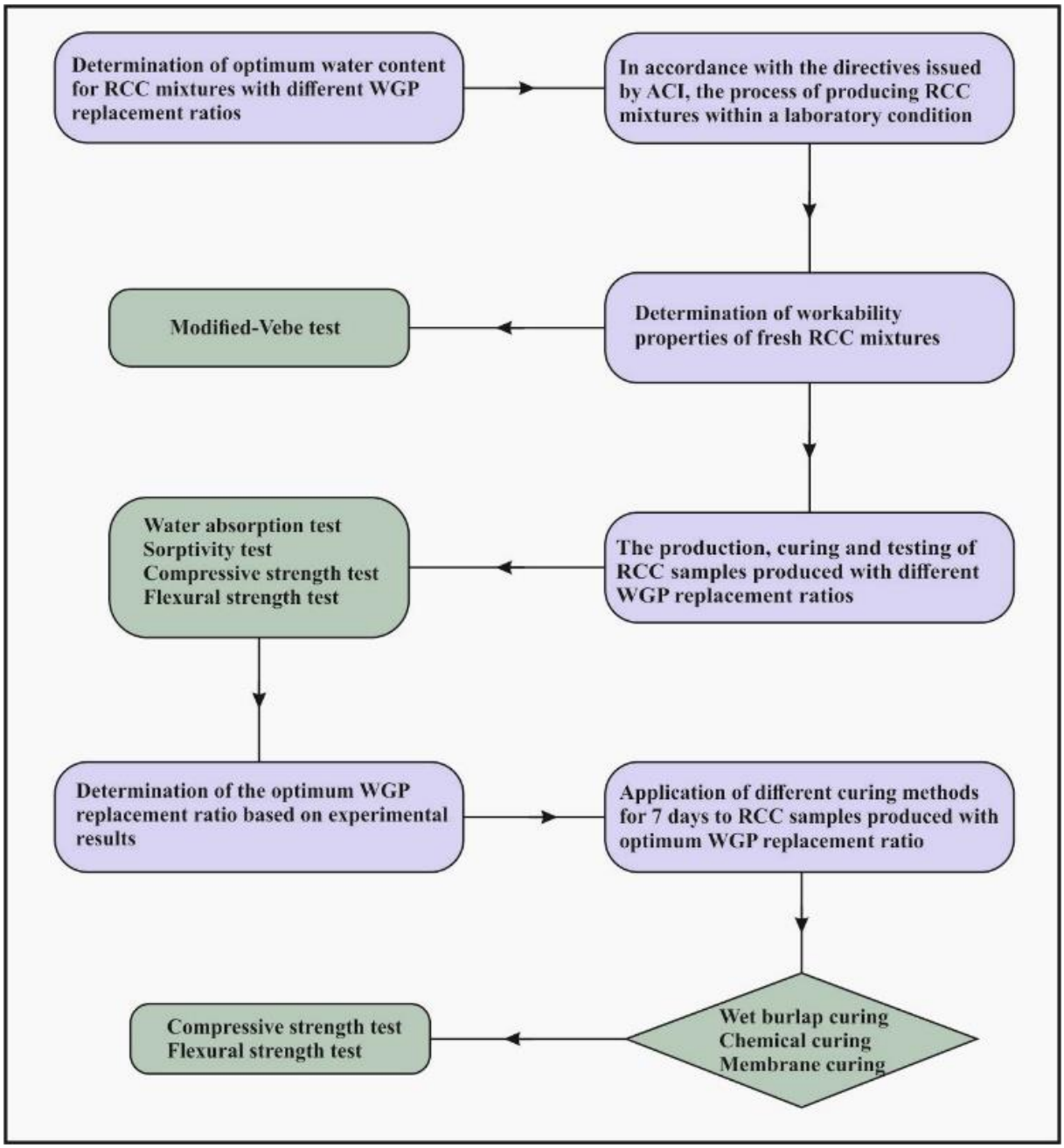


Figure 6. Workflow diagram

3 RESULTS AND DISCUSSION

3.1 Optimum Water Content and Dry Density

Figure 7 shows the relationship between the water content and dry density of RCC mixtures prepared by replacing WGP at different ratios. Experimental studies conducted for each mixture revealed that the optimum water content values corresponding to the maximum dry density for mixtures containing 0%, 10%, 20%, and 30% WGP were 8.23%, 8.38%, 8.72%, and 9.03%, respectively. The results clearly demonstrate that the optimum water requirement of the mixture increases gradually with the increase in the WGP replacement ratio. This phenomenon can be explained by WGP having the finer particle size and higher specific surface area compared to cement. Furthermore, the maximum dry density results corresponding to the optimum water content values obtained for each WGP replacement ratio are also shown in Figure 7. The dry density values thus determined for mixtures containing 0%, 10%, 20%, and 30% WGP were measured as 2291 kg/m³, 2272 kg/m³, 2244 kg/m³, and 2230 kg/m³, respectively. The findings indicate a decreasing trend in the density values of the mixtures as the WGP content increases. This phenomenon can be attributed to the lower specific gravity of WGP in comparison to cement, resulting in a reduction in the total mass per unit volume of the mixture.

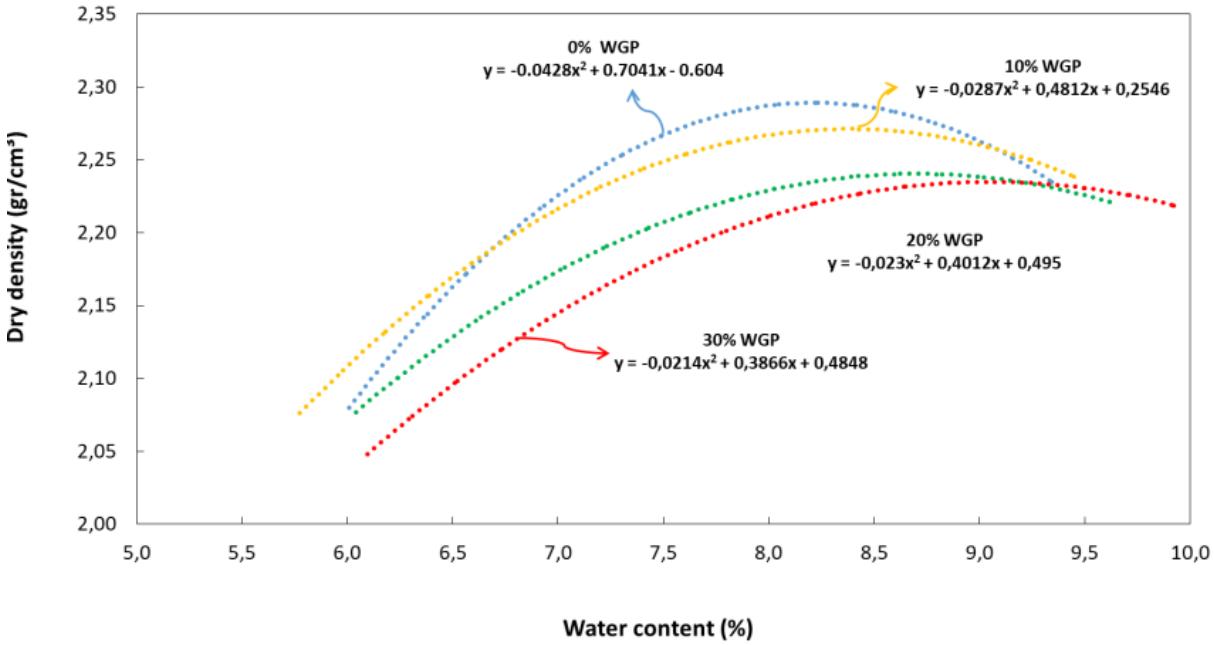


Figure 7. Relationship between water content and dry density of RCC mixtures

3.2 Modified-Vebe Time

In this study, the consistency of RCC mixtures was determined using a modified Vebe test apparatus in accordance with the ASTM C1170 (2014) [36] standard. The Vebe times obtained for mixtures containing 0%, 10%, 20%, and 30% RCC, prepared using the optimum water content, were measured as 34, 35, 37, and 40 seconds, respectively. The results indicate that the Vebe time increases with an increase in the RCC replacement ratio. According to ACI 325.10R (2001) [41] standard, the recommended suitable Vebe time range for RCC mixtures is specified as 30 to 40 seconds. Within this scope, it was determined that all Vebe time values obtained in the study fall within the aforementioned range and thus meet the RCC production criteria. Similarly, in the literature, it is stated that the replacement of cement with WGP in both conventional concrete and RCC increases the water requirement of the mixture and negatively affects workability [9-11].

3.3 Sorptivity

Figure 8 presents the sorptivity coefficients obtained for RCC mixtures with different WGP replacement ratios. The sorptivity coefficients determined for mixtures containing 0%, 10%, 20%, and 30% WGP were measured as 0.0585, 0.0584, 0.0567, and 0.0965 mm/min$^{1/2}$, respectively. These results indicate that the use of WGP at low concentrations positively affects the capillary water absorption of RCC. When compared to the control sample, the sorptivity coefficients of mixtures with 10% and 20% WGP replacement ratios were found to be 0.2% and 3.1% lower, respectively. This improvement is attributed to the fine structure of glass powder, which fills the porous matrix regions and restricts the capillary pore network. However, the sorptivity coefficient of the mixture produced with a 30% WGP replacement ratio showed a 65% increase compared to the control sample. This significant increase can be attributed to the mixture having a higher optimal water content and water/binder ratio.

In line with previous studies, this research found that using glass powder decreases the sorptivity value of concrete, especially at low ratios. A study conducted by Du and Tan (2017) [42] found that using glass powder in concrete significantly improves its sorptivity capacity. Concrete prepared with a 15% glass powder replacement exhibited the highest sorptivity resistance, with only 9% water absorption compared to the reference concrete. This improvement was attributed to the refinement of the pore structure in the cement paste, the reduction of pore connections and densification of the microstructure in the transition zone. Meanwhile, Schwarz et al. (2008) [43] reported that concrete containing 10% glass powder

exhibited lower sorptivity after 14 days, though this effect was reversed after 90 days, with higher sorptivity observed compared to the reference concrete. Matos and Sousa-Coutinho (2012) [44] found that there was no significant change in sorptivity in mixtures containing 10% or 20% glass powder.

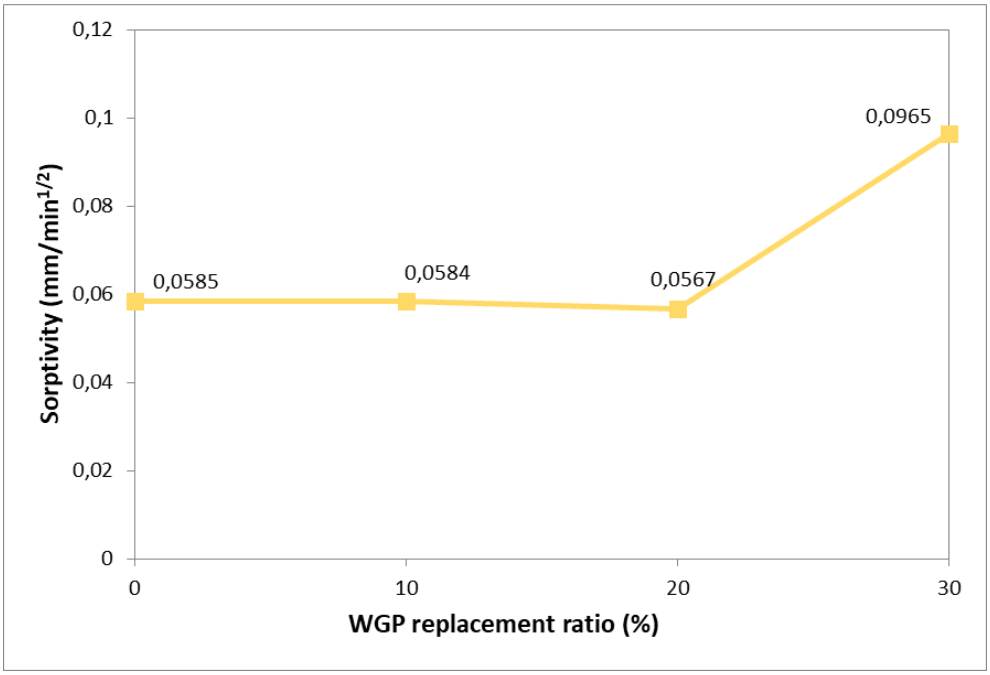


Figure 8. Sorptivity coefficients of RCC samples with different WGP ratios

3.4 Water Absorption Ratio

Figure 9 shows the change in water absorption values of RCC mixtures depending on WGP replacement ratios. The water absorption values measured in RCC samples with 0%, 10%, 20%, and 30% WGP content were determined as 3.72%, 3.67%, 3.61%, and 3.87%, respectively. The results obtained indicate that the use of WGP at low replacement ratios improves the permeability properties of concrete. Compared to the control mixture, the water absorption ratios of mixtures containing 10% and 20% WGP were found to be 1.4% and 3% lower, respectively. This can be explained by the micro-filling effect of glass powder, which partially fills capillary voids and reduces the concrete's permeability to water. However, when the WGP replacement ratio was increased to 30%, the water absorption ratio increased by 4.04% compared to the control mixture.

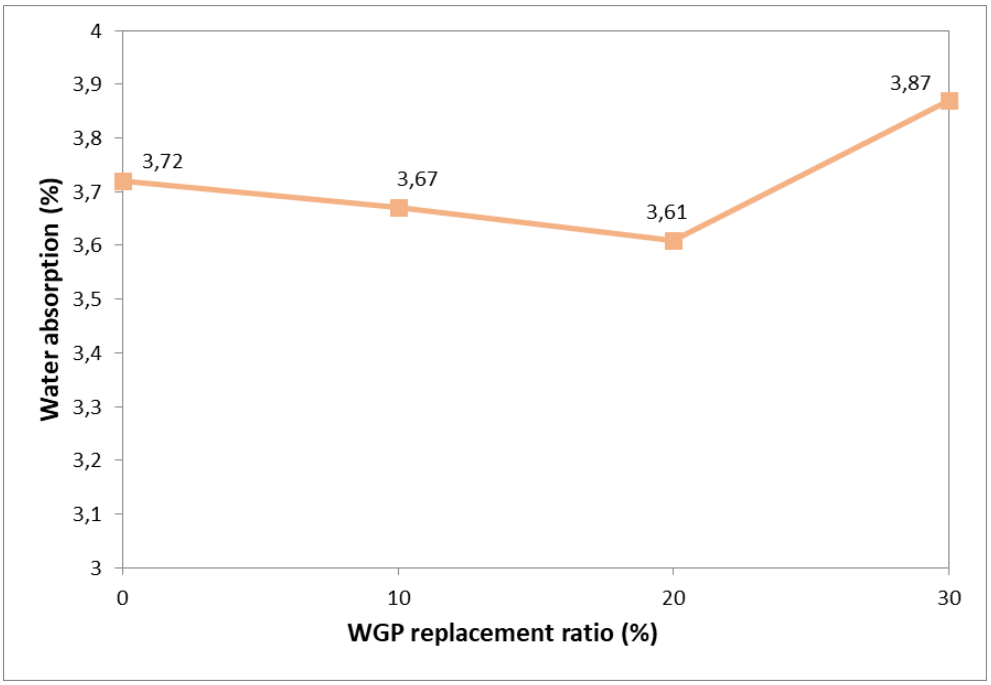


Figure 9. Water absorption ratios of RCC samples with different WGP ratios

The enhancement of concrete permeability properties through the utilization of WGP, up to a specific ratio, is predominantly associated with the chemical composition and the size of the material's particles. Fine-grained WGP reacts with calcium hydroxide ($Ca(OH)_2$) released during cement hydration, forming secondary calcium silicate hydrate (C-S-H) gels. These gels contribute to the formation of a denser and more impermeable structure by filling voids in the concrete matrix. Furthermore, the physical filling effect and fine structure of WGP increase the microstructural integrity in the ITZ region between the cement paste and aggregate, and reduce the void ratio in this region. Consequently, regions of weakness, which play an instrumental role in permeability, are fortified, thereby restricting capillary water movement. Omran et al. (2017) [7] also reported that finely ground glass powder reduces permeability due to both its pozzolanic reactivity and microstructural improvement effect.

3.5 Compressive and Flexural Strength

Figure 10 presents the 28-day compressive and flexural strength values of RCC mixtures produced using the optimum water content, depending on different WGP replacement ratios. According to the results obtained, the highest compressive and flexural strength values were achieved in mixtures containing 10% WGP. The 28-day flexural strength values of RCC mixtures with WGP replacement ratios of 0% (control), 10%, 20%, and 30% were 7.28, 7.41, 5.69, and 4.94 MPa, respectively; while the compressive strength values were determined as 55.98, 58.65, 50.30, and 36.00 MPa, respectively. Compared to the control mixture, a 10%

WGP replacement resulted in a 1.79% increase in flexural strength and a 4.77% increase in compressive strength. Conversely, increasing the WGP replacement ratio to 20% and 30% resulted in significant decreases in both flexural and compressive strength values. The decrease in flexural strength was determined to be 21.85% and 32.15% compared to the control mixture, while the compressive strength decrease occurred at levels of 10.15% and 35.70%. These results indicate that the use of WGP at low ratios improves the strength properties of RCC, but this effect decreases and even becomes negative as the replacement ratio increases. This improving effect is attributed to the pozzolanic reaction capacity of ground glass powder, which is associated with its high amorphous silica content. WGP reacts with calcium hydroxide ($Ca(OH)_2$), which is formed as a result of cement hydration and is weak in terms of strength, to form secondary C–S–H gel phases. This mechanism contributes to the densification of the matrix's internal structure and improves the ITZ region between the cement paste and aggregate, thereby limiting crack propagation.

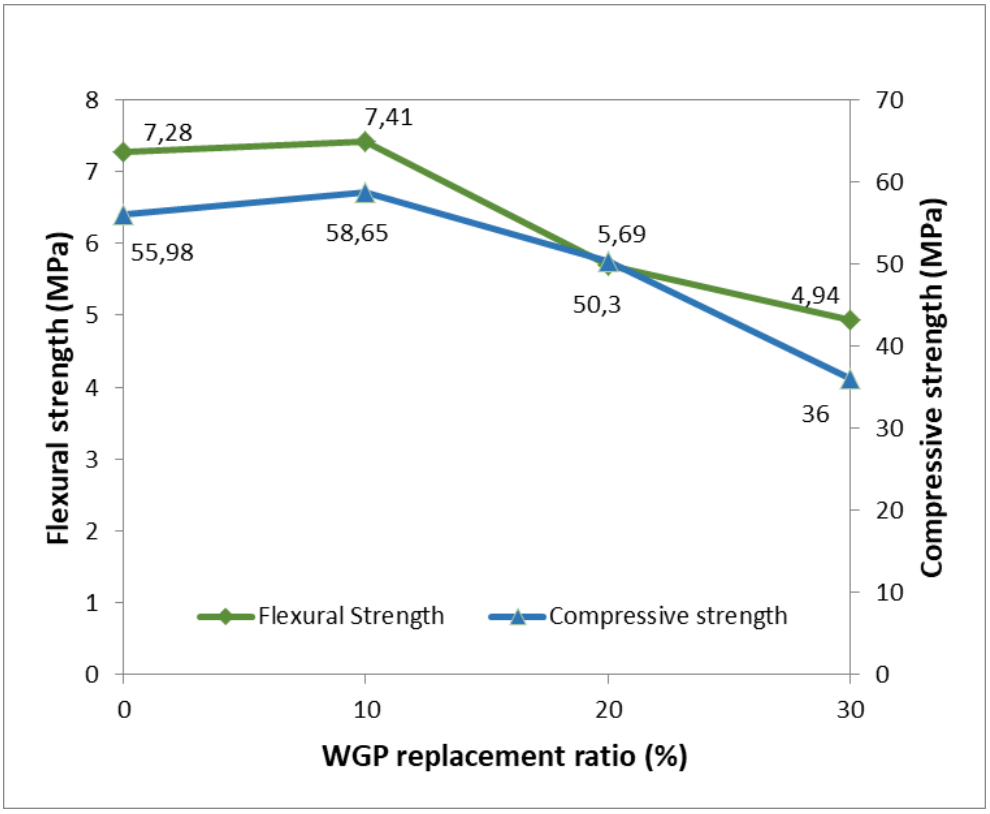


Figure 10. Compressive and flexural strength test results of RCC samples with different WGP ratios

The flexural and compressive strength results obtained are consistent with some studies in the literature. In this study, it was determined that a 10% WGP replacement ratio provides the best performance in terms of both compressive and flexural strength. Similarly, studies conducted on conventional concrete and RCC have reported that the use of low WGP ratios (especially 10%) improves mechanical performance, but strength decreases when the replacement ratio exceeds 20%. Indeed, in the study conducted by Omran et al. (2017) [30], it was observed that the flexural strength of RCC mixtures containing 20% WGP decreased after 28 days; this finding aligns with the low flexural strength values observed in the current study for WGP ratios of 20% and 30%.

Similarly, studies conducted by Shao et al. (2000) [45] and Elaqra et al. (2019) [46] have also indicated that the use of WGP at a 30% ratio negatively affects the flexural strength of conventional concrete. However, some studies have reported that the optimal replacement ratio for WGP is 20% [9,10,29, 47-49]. However, other studies have shown that a replacement ratio of 10% yields more effective results in terms of both compressive and flexural strength [11,50,51]. These differences can be attributed to various factors such as the type of binder used, aggregate characteristics, mixture ratios, particle size distribution, and curing conditions.

3.6 The Effect of Curing Methods on Compressive and Flexural Strength

To evaluate the effects of different curing methods on the mechanical performance of RCC, RCC samples containing 10% WGP were produced. The produced samples were subjected to three different curing methods—burlap, membrane, and chemical curing—for the first 7 days. Following the curing process, the samples were stored in a laboratory environment until they reached 28 days of age and were then subjected to compressive and flexural strength tests. The relevant mechanical strength results are presented in Figure 11. The highest flexural and compressive strength values were obtained in the samples cured with wet burlap. As shown in Figure 11, the flexural strength of RCC samples cured with wet burlap, chemical curing, and membrane curing methods at 28 days was determined to be 6.15 MPa, 5.68 MPa, and 5.61 MPa, respectively. These values correspond to 83%, 77%, and 76% of the characteristic flexural strength of the sample cured under standard conditions with the same composition, which is 7.41 MPa. A similar trend was observed in the compressive strength results. The 28-day compressive strength of the samples treated with wet burlap, chemical curing, and membrane curing was determined to be 55.62 MPa, 51.82 MPa, and 50.57 MPa, respectively. These values represent 95%, 89%, and 86% of the 28-day characteristic compressive strength of the sample with the same composition.

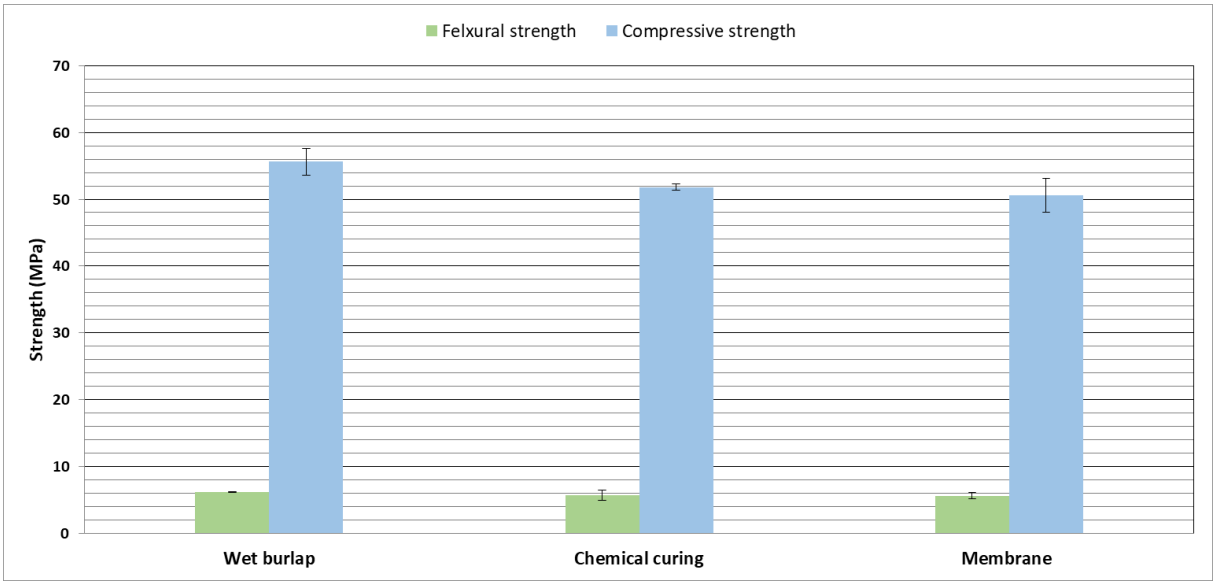


Figure 11. Compressive and flexural strength results of RCC samples under different curing conditions

4 CONCLUSION AND SUGGESTIONS

As a consequence of the experimental studies undertaken in this investigation, the effects of varying ratios of WGP replacement on the fresh and hardened concrete properties of RCC were evaluated, and the findings are summarized below.

- The optimal water content values of RCC mixtures containing different ratios of WGP were found to increase with an increase in the WGP content.
- When compared to the control mixture, it was determined that the maximum dry density value decreased with an increase in the WGP replacement ratio in RCC mixtures containing WGP.
- The modified Vebe time of RCC mixtures increased with increasing WGP replacement ratio. According to ACI 325.10R, the suitable Vebe time range for RCC is 30 to 40 seconds, and it was determined that the Vebe times of all RCC mixtures produced in this study were within the standard range.
- As the WGP replacement ratio increased up to 20%, the sorptivity coefficient and water absorption ratio decreased. However, it was observed that the sorptivity coefficient and water absorption ratio of RCC samples produced at a 30% WGP replacement ratio were higher than those of the control sample.
- The best results in terms of compressive and flexural strength were obtained from RCC samples with a 10% WGP replacement ratio.

- It was determined that the curing method is a decisive parameter affecting the mechanical performance of RCC, and that the curing application performed with wet burlap, in particular, significantly contributes to the development of compressive and flexural strength by more effectively supporting the hydration process.
- From an environmental perspective, the use of WGP as a cement substitute facilitates the recycling of waste glass while reducing cement usage and, consequently, contributing to the reduction of CO_2 emissions from cement production. In this regard, WGP emerges as one of the sustainable and environmentally friendly binding materials alternatives.
- In this study, WGP obtained from a single source was used. In subsequent research, the impact of material diversity should be examined by utilising diverse categories of glass waste.
- All experiments were conducted within a controlled laboratory environment. In order to evaluate the role of environmental effects on performance, it is recommended that future studies be conducted on field applications.
- The present study concentrated on the partial replacement of cement with WGP. In future studies, the synergistic effects of combinations of WGP with other pozzolanic materials, such as fly ash, silica fume, and blast furnace slag, should be investigated.
- Further studies are required to evaluate the long-term durability performance of the materials. It is imperative that these studies comprehensively address resistance to environmental effects such as freeze-thaw, sulphate attack and wetting-drying cycles.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

Artificial intelligence-supported language editing tools were employed to improve the clarity and coherence of the final manuscript.

Contributions of the Authors

First author: Conceptualization, Methodology, Validation, Investigation, Writing—review and editing. Second author: Formal analysis, Investigation, Data curation, Writing—original draft preparation, Visualization.

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