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Research article

Effect of binder-aggregate ratio and glass powder on the performance of concrete cured in different media

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Abstract: The current approach to producing concrete is believed to be unsustainable because of its significant consumption of cement and aggregate, thereby causing environmental risks and improper curing of concrete, which could lead to lower durability and increased permeability. This study investigated the use of glass powder as a partial replacement for cement by testing the output concrete with three different curing methods. The percentage replacement of glass powder in cement varied from 0%, 10%, and 20% for varying binder/aggregate ratios of 0.35, 0.46, and 0.57, respectively. Results show that the concrete mix with a binder/aggregate ratio of 0.46 had the highest slump value. The samples cured in liquid coatings of lime solution had the highest mean density of 2575 kg/m^3, which makes lime curing the most appropriate method if permeability is a desired concrete property. Water curing produced the highest compressive strength of 17.27 N/mm^2 at an optimum binder/aggregate ratio of 0.46. The findings show that increasing the aggregate content of concrete mix with subsequent wet curing will most likely decrease concrete permeability. The use of waste glass as a partial replacement for cement is recommended as it improves the structural performance of concrete.

Keywords: binder-aggregate ratio; concrete; curing methods; glass powder

1. Introduction

Concrete is widely utilized as a construction material owing to its robustness and capacity to withstand compressive forces. However, this material accounts for anthropogenic CO_2 emissions ranging between 5% and 8% [1]. Approximately half is emitted due to the de-carbonation of limestone to produce cement; the other half is emitted from the fossil fuel required for the production process since much energy is required to heat the material to a temperature above 1000 °C. In [2], it was reported that the CO_2 emissions of cement production range from 10% to 15%. Emerging nations such as China and India are the top concrete consumers, with a significant demand for cement for construction work due to economic growth, urbanization, and infrastructure development [3]. It is, therefore, necessary to reduce carbon dioxide emissions attributed to concrete construction with cement as the sole binder. Using recycled waste materials as supplementary cementitious material is an interesting solution that needs to be continuously encouraged [4]. For instance, waste glass as a residue can be further processed to powder and used as a supplementary cementitious material in concrete [5,6]. This eliminates cement as a sole binder for concrete aggregates. Waste glass has no regular storage areas, and continuous urban transformation will generate more of this waste [7]. Therefore, it is necessary to reutilize waste glass to reduce the chances of soil and water pollution due to its oxidation effect [4]. Due to the depletion of natural resources and changes in climatic conditions, researchers have found waste glass powder to have economic and mechanical benefits when used in concrete by enhancing its pozzolanic activity and improving durability and compressive strength [8–10]. Recent studies recommend between 15% and 25% replacement of cement with glass powder for increased mechanical properties [11]. This is because glass provides a pozzolanic effect, which improves and increases the cementitious properties of concrete [12]. Also, alkali-activated recycled cement achieves significant mechanical performance improvements when optimized for alkali content and activation parameters, providing a low-carbon alternative to traditional binders [13].

Nano-silica significantly enhances hydration processes in recycled cement, increasing its mechanical strength and promoting sustainability through reduced CO_2 emissions and energy use [14]. A review of the utilization of glass powder in ultra-high-performance glass concrete was presented in [15]. The authors summarized the advantages of using milled waste glass to replace cement, quartz powder (QP), silica fume (SF), and sand in ultra high performance concrete (UHPC) mixtures. Another study [16] investigated the incorporation of waste glass and limestone in geopolymer concrete deep beams, aiming to recycle these materials and assess their mechanical properties. The authors showed that using waste glass aggregate results in less than a 15% reduction in strength compared to geopolymer concrete with limestone. In [17], the addition of glass powder, combined with kaolin and sisal fibers, was investigated in pervious concrete. The authors showed that kaolin is more beneficial than glass powder at 10% replacement of cement for the pervious concrete. Another study incorporating glass powder in concrete subjected to freezing and thawing showed an improvement in resistance and durability when compared to conventional concrete [18]. Glass powder was also utilized as a cement replacement among other waste materials [19]. The authors showed that the compressive strength of concrete mixtures was reduced while highlighting their pozzolanic properties. On the other hand, in [20], glass powder was shown to benefit the mechanical properties of reactive powder concrete. Similarly, in [21], the addition of supplementary cementitious materials was shown to enhance the mechanical properties of concrete in structures subjected to dynamic and cyclic loads.

The replacement of silica fume with waste glass powder for high-strength concrete (HSC) was investigated by [22]. The experiments and numerical analysis conducted demonstrate that using waste glass powder enhances the loading capacity and ductility of HSC beams, making it a viable alternative to silica fume as a pozzolanic powder. Similarly, the mechanical behavior of HSC with the incorporation of glass powder was investigated under high-temperature conditions [23]. Concrete made with waste glass powder exhibited better strength retention at elevated temperatures compared to concrete incorporating silica fume, highlighting the positive role of waste glass powder as an effective inert material for concrete strength improvement under fire exposure.

Another question related to concrete is the form of curing that will yield the best results. Curing represents the concluding phase and is deemed one of the most critical factors in concrete-related operations [24]. It denotes the process of regulating the temperature and humidity levels, which govern the ingress and egress of water in concrete, intending to promote cement hydration [25]. The hydration of cement largely influences the short- and long-term performance of concrete. It stops when the relative humidity drops below 80%, which is why specimens are conventionally kept in water to keep the relative humidity above this value. The cessation in the hydration of cement may lead to the concrete not possessing the required properties such as strength or impermeability because not enough calcium silicate hydrate (C-S-H) can be formed from the reaction of cement compounds with water [25,26]. The C-S-H gel is the primary strengthening product of the cement hydration reaction, reducing porosity by producing a dense microstructure in concrete. Since concrete is prone to drying, pore structures may form on the near surface, which may allow the ingress of potentially debilitating materials that are responsible for weakening the durability properties of concrete. Curing helps concrete maintain the required water content in its early stages to gain design properties, thereby improving the long-term performance of the concrete [27]. However, inadequate or improper concrete curing can result in reduced strength and durability and an overall decrease in the quality of the final product.

Different methods of curing are available, depending on climate conditions and the nature of the work [24]: water curing, membrane curing, and heat application. The duration of a sufficient curing time also depends on various factors such as mixture proportions, weather conditions, or specified strength [25]. In [28], authors studied the impact of curing conditions on the performance of concrete and noted that curing temperature had no effect on the permeability of concrete; however, chloride infiltration and the compressive strength of the samples were greatly influenced. In [29], cubes were cured in different proportions of water-lime solution; lime curing was reported to help the concrete gain high early strength due to the exothermic reaction between lime and water [30]. Higher temperatures accelerate exothermic hydration reactions and gain strength over time [31]. In [32], curing methods and the time effect were studied on the compressive strength of plain concrete. It was reported that samples cured in lime gained more compressive strength than those covered with a wet rug and air dried. In [33], the effect of curing on the behavior of self-compacting concrete at ambient temperature and 110 °C was studied. Early strength was shown to be highly impacted by curing temperature. In [2], authors investigated the mechanical and durability properties of high calcium fly ash-based one-part geopolymer concrete with varying paste/aggregate ratios of 0.57, 0.45, and 0.35. Specimens were cured at ambient temperature in a solar chamber and water. It was reported that the mechanical properties increased at a lower paste/aggregate ratio for all curing media considered. Also, the paste/aggregate ratio had minimal impact on the permeability of matrices.

Sustainability in construction involves the consideration of resource efficiency and ecology in the creation of a built environment [34]. Cement production has posed many challenges regarding CO_2

emission and depletion of natural resources, among others. Supplementary cementitious materials (SCMs) have been adopted to alleviate these challenges [32]. The non-biodegradable nature of glass waste makes its disposal in landfills an environmental nuisance [35]. Research has shown that glass has a chemical composition and phase similar to traditional SCMs [36,37]. Previous research showed that glass-incorporated concrete had a better performance in preventing chloride infiltration in the long term but also raised concerns about alkali-silica reaction (ASR) [35]. The influx of deleterious materials into the concrete increases the risk of ASR, but a good pozzolan mitigates such a reaction and reduces efflorescence by consuming lime [38]. Waste glass has been used as a partial replacement in cement mortar and concrete or as fine aggregate, and it can provide more durability and strength, reduce air content, pack pore spaces, and enhance resistance to acid, salt, and alkali [39].

Despite ongoing research on utilizing waste glass as a partial replacement for concrete, a review article suggests that investigations in this area still need to be expanded and validated. In [15], a review on the behavioral impact of recycled glass waste as a replacement for cement was performed; a reduced water absorption of glass-incorporated concrete in comparison to normal cement concrete was reported. Authors in [40] recommend further research to examine the properties of concrete when waste glass is incorporated into its composition. Preceding studies on using glass powder as a replacement for cement have considered different percentage replacement levels for a constant binder content. This study will consider different percentage levels for varying binder contents expressed in the form of the binder/aggregate ratio; we aim to investigate the effect of binder/aggregate ratios and curing methods on the performance of concrete containing glass powder at different percentage replacement levels. The glass powder was used as a partial replacement for cement at 0%, 10%, and 20% levels. The binder/aggregate ratio varied for the different mixes at 0.35, 0.46, and 0.57, respectively. This study investigated the effect of a glass-blended concrete matrix cured in a solar chamber, water, and lime powder solution. The objectives of this study were to evaluate the fresh and hardened properties, i.e., compressive strength, density, and durability performance, of glass-blended concrete cured in these various media. Hence, this study seeks to investigate the effects of different binder/aggregate ratios and glass powder on the performance of concrete when cured in different media.

2. Materials and methods

2.1. Materials

Glass powder: glass powder was made from ground glass into fine particles, as shown in Figure 1. The specific gravity of the glass powder was 2.51. The glass powder was used as a partial replacement for cement at 0%, 10%, and 20%. Glass powder presented a chemical composition of 77.46% of SiO_2, 0.04% of CaO, 3.74% of Al_2O_3, 1.51% of Fe_2O_3, 0.00% of MgO, 0.16% of K_2O, and 0.35% of SO_3.

Figure 1. Glass powder.

For this study, Dangote cement's grade 42.5, specifically their Portland limestone Cement (PLC) under the Dangote brand, as depicted in Figure 2, was acquired from a local market in Ado-Ekiti, Ekiti State.

Figure 2. Dangote cement.

Fine aggregate: the fine aggregate was sharp sand purchased in Ado Ekiti. The specific gravity of the river sand was 2.67.

Coarse aggregate: the coarse aggregate used was the locally available crushed granite stones of a nominal size of 20 mm. It was obtained from a local quarry in Ado-Ekiti, Ekiti State. Figure 3 presents the sieve analysis for both fine and coarse aggregate.

Water: potable water supplied within ABUAD was used for mixing and curing.

Superplasticizer (SP): the COSTAMIX 200, manufactured by Costar Building Product Systems Ikeja, Lagos, Nigeria, was used to improve the workability of the concrete.

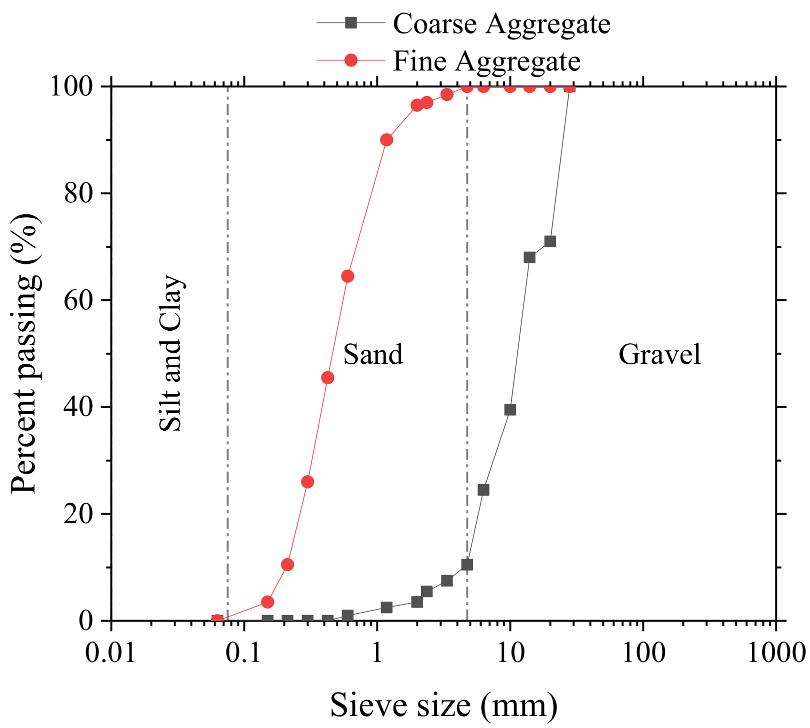

Figure 3. Sieve analysis for the aggregates.

2.2. Concrete mix proportion

The required material constituents for nine different concrete mixes are shown in Table 1. The required quantity of fine and coarse aggregates was mixed. After that, the binder was added to the mixture (the binding agent was a mixture of PLC and glass powder, as presented in Table 1). The mixing process continued until a homogenous mixture was observed, after which the required quantity of water mixed with superplasticizer was added, and mixing continued until a workable concrete was derived. Upon completion of the mixing process, concrete samples were placed into already cleaned and lubricated 100 × 100 × 100 mm molds. Compaction was done in two layers using a tamping rod. Tamping was done to ensure an even distribution of the freshly prepared concrete over the cross-section of the mold. Each concrete cube received 25 strokes of tamping per layer (as specified by BS 1881-108: 1983). After compacting, the surface was properly leveled and then smoothened with a hand trowel. The specimens were de-molded after 24 h and allowed to cure at ambient temperature until the required test.

Table 1. Concrete mix proportion.

Mix proportion	Glass powder (%)	Binder/aggregate ratio	Binder (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)
M1	0	0.35	500	532.5	1243	165	7.5
M2	10	0.35	500	532.5	1243	165	7.5
M3	20	0.35	500	532.5	1243	165	7.5
M4	0	0.46	600	495	1155	198	9
M5	10	0.46	600	495	1155	198	9
M6	20	0.46	600	495	1155	198	9
M7	0	0.57	700	457.5	1068	231	10.5
M8	10	0.57	700	457.5	1068	231	10.5
M9	20	0.57	700	457.5	1068	231	10.5

2.3. Curing methods

The study considered three different curing methods. The first set of specimens was immersed in water (Figure 4a), and the second and third sets were immersed in a solar chamber and a lime powder solution, respectively, until the test. Curing in the solar chamber was done intermittently by taking full advantage of the sunlight, as illustrated in Figure 4b. The internal temperature of the solar chamber varied with the intensity of the sun. Lime curing was done by diluting lime powder into water. The dilution was done using a ratio of 50 kg of water to 25 kg of lime powder (Figure 4c). The concrete cubes were cured for 28 days.

(a) (b) (c)

Figure 4. (a) Water curing; (b) solar curing; and (c) lime curing.

2.4. Test procedures

2.4.1. Slump test

The workability of the fresh concrete per mix was evaluated using a slump cone in accordance with BS 1881-108 (1983). The cone had a height of 300 mm with top and bottom diameters of 200 and 300 mm, respectively, as shown in Figure 5. The average of three samples for each experimental run was calculated.

Figure 5. Slump cone on concrete sample.

2.4.2. Density test

The density of each sample was computed by taking the average weight of three cubes. The weight was measured using the weighing balance; the dimension of the cubes used was 100 × 100 × 100 mm. Density was determined using Eq 1.

$$Density\ (kg/m^3) = \frac{Weight}{Volume} \tag{1}$$

2.4.3. Water absorption

The water absorption test was carried out on hardened concrete in accordance with BS 1881-122:1983. The required specimens were removed from the water after the required curing period had elapsed. The specimens were wiped with a towel and oven-dried at 105 °C for 24 h, after which they were allowed to cool before weighing. The weight obtained was identified as W_1. The oven-dried specimens were immersed in water for 24 h and weighed to obtain W_2. The results reported were the average of three specimens for each run. The water absorption was determined using Eq 2.

$$Water\ absorption\ (\%) = \frac{W2 - W1}{W1} \times 100 \tag{2}$$

2.4.4. Compressive strength test

The compressive strength test was carried out at 28 days on 100 mm cubes. The strength was determined using an ELE compression machine with a load capacity of 2000 kN. Results were the average of three specimens per run. Compressive strength was calculated in accordance with BS 1881-116:1983 using Eq 3.

$$Compressive\ strength\ (N/mm^2) = \frac{Crushing\ load}{Area} \tag{3}$$

3. Results and discussion

3.1. Workability of the concrete

The ease at which concrete can be mixed and placed is defined by its workability. The workability of the concrete mix of different binder/aggregate ratios and varying percentages of glass powder was evaluated by a slump test. The results are presented in Figure 6 It was observed that M1 with a binder/aggregate ratio of 0.35 and 0% glass powder had the most negligible slump value of 60 mm. This low slump value can solely be attributed to the low binder content in the mixture. This indicates that the combination in this concrete mix is stiff. For the other mixes (M4 and M7) with 0% glass powder and a binder/aggregate ratio of 0.46 and 0.57, the slump values were 75 and 80 mm, respectively. This result indicates that the slump value increases with an increase in the binder. These findings corroborate a previous study [2]. The incorporation of glass powder at 10% with binder/aggregate ratios of 0.35, 0.46, and 0.57 leads to slump increases from 73 to 90 mm and then reduced to 85 mm, respectively. The results indicate an optimum slump value of 90 mm with a binder/aggregate ratio of 0.46. A change in the trend of workability was observed when the percentage of glass powder increased from 10% to 20%. According to [41], a decrease in workability with an increase in glass powder content can be attributed to the high surface tension of glass powder. The result indicates that the presence of glass powder at 10% increased workability; however, when 20% of glass powder was incorporated, a reduction in the slump value was observed. Therefore, considering 0% and 10% replacement levels at a binder/aggregate ratio of 0.35, slump values of 60 and 73 mm, respectively, were observed. According to [42], reducing binder to total aggregate in a concrete mix makes it insufficient as the aggregate limits concrete mobility. The highest slump of 90 mm was obtained with a binder/aggregate ratio of 0.46. At this ratio, the total aggregate content in the concrete mix is about 60%, and the binder volume is about 40%. This indicates that the presence of 10% glass powder combined with 90% PLC can help improve workability, thereby enhancing the mixing and placement of the concrete.

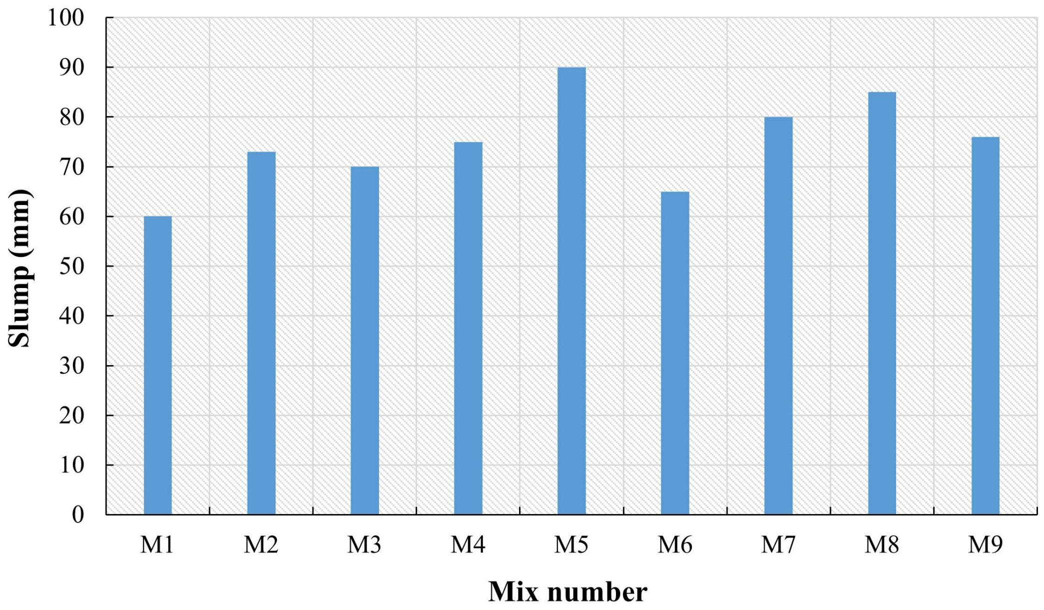

Figure 6. Slump test for concrete mix.

3.2. Density

The mean average density obtained for each of the curing media ranged from 2501 to 2330 kg/m^3, 2529 to 2403 kg/m^3, and 2574 to 2362 kg/m^3 for solar curing, water curing, and lime curing, respectively, as presented in Figure 7. Density values obtained for all specimens can be classified as normal-weight concrete even with the presence of glass powder incorporated at different percentage levels of replacement for cement. From the results, it was observed that concrete cubes cured in lime water had the highest mean density; this may be attributed to the calcium carbonate ($CaCO_3$) present in the lime water solution. Carbonation can have positive consequences since $CaCO_3$ replaces $Ca(OH)_2$, occupying a greater volume. This reduces the concrete permeability, and water released by $Ca(OH)_2$ during carbonation may aid the hydration of erstwhile dry cement. These reactions help improve surface hardness, strength, and resistance to attacks caused by permeability [43,44]. Water-cured concrete was next in line with the highest density of 2529 kg/m^3; the process of immersion in water at ambient temperature is usually the most common method of curing. According to [45], this method of curing provides sufficient moisture and suitable vapor pressure, which maintains the continued hydration of cement.

Furthermore, the results indicate a decrease in concrete density with an increase in the percentage of glass powder content in the concrete mix regardless of binder/aggregate ratios. According to [46], the specific gravity of a homogenous material is constant, irrespective of the testing performed. This implies that when composite material is produced with an additive material (glass powder) with a lower specific gravity than the parent material (PLC), the resulting matrix reduces accordingly in relation to the additive content. In general, it can be observed that dense concrete can still be achieved by incorporating glass powder as an alternative binder to promote sustainability in the construction industry.

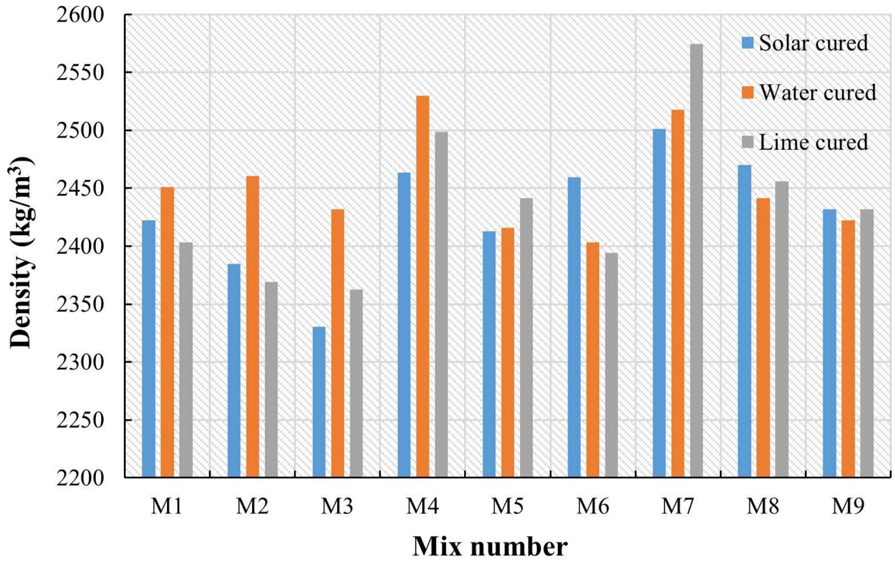

Figure 7. Density of concrete for different curing media.

3.3. Compressive strength

The compressive strength results obtained for the various curing media under consideration are presented in Figure 8. These values ranged from 16.85 to 11.58 MPa, 17.27 to 10.46 MPa, and 16.56 to 11.95 MPa for solar curing, water curing, and lime curing, respectively. The effect of the binder/aggregate ratio on compressive strength was evaluated using mixes M1, M4, and M5. It was observed that an increase in binder/aggregate ratio from 0.35 to 0.46 increased compressive strength by 8.3%, 23%, and 16% for solar curing, water curing, and lime curing, respectively. However, a 14%, 7%, and 2% decrease was observed when the binder/aggregate increased from 0.46 to 0.57. An earlier study by [2] reported a reduction in compressive strength with an increase in binder/aggregate ratios. Based on the results obtained, it could be inferred that an optimum binder/aggregate ratio was achieved at 0.46. This may be attributed to the adequate binding between the binder and the total aggregate ratio.

Water curing was the most effective method of curing since it gave the highest compressive strength of 17.27 MPa. This may be attributed to improved pore structure and lower porosity, influenced by a better cement hydration reaction without moisture loss from the concrete specimens [24]. Considering mixes M2, M5, and M6 with 10% glass powder and binder aggregate of 0.35, 0.46, and 0.57, respectively, there was a slight reduction in compressive strength with an increase in binder/aggregate ratio for all curing media. However, it is interesting to note that the effect of glass powder at a 10% cement replacement at a binder/aggregate ratio of 0.46 was minimal on compressive strength. The reduction in strength was less than 4%, 3%, and 2% for solar curing, water curing, and lime curing, respectively. This implies a proper binding of 10% glass powder in the concrete mix at a binder/aggregate ratio of 0.46. Furthermore, incorporating 20% glass powder into the concrete mix further reduced its compressive strength.

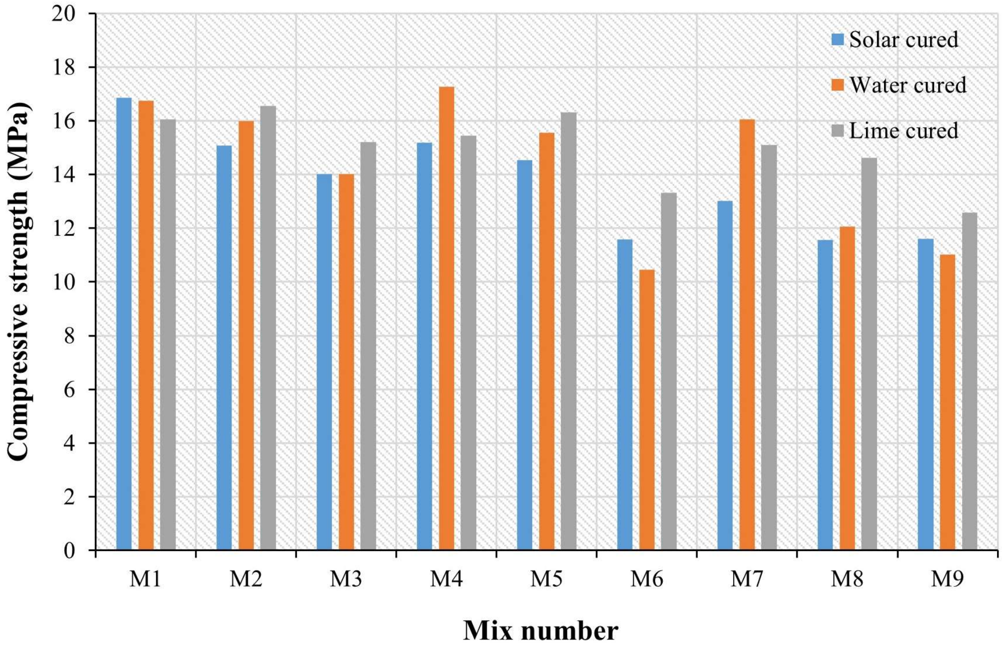

Figure 8. Compressive strength of concrete for different curing media.

3.4. Water absorption

The water absorption test was carried out to assess the durability performance of the concrete. It is generally accepted that the durability of concrete is closely related to the characteristics of its pore structure. The degradation mechanisms of concrete are often dependent on the way that potentially aggressive substances can penetrate the concrete, possibly causing damage. This allows the ingression of external fluid in the concrete, which can produce irreversible damage. The water absorption results for concrete cubes cured in water are presented in Figure 9. Since all mixtures had the same water-to-binder ratio, a common open porosity was expected for all curing media. A comparison of M1, M4, and M7 containing 0% glass powder and binder/aggregate ratios of 0.35, 0.46, and 0.57, respectively, indicates that water absorption increases with an increase in binder/aggregate ratio. This implies that an increase in the aggregate content of a concrete mix is most likely to reduce the resistance of concrete to water penetration. In [2], a similar trend irrespective of the curing media was observed. The water absorption of concrete made with a binder/aggregate ratio of 0.57, corresponding to a total aggregate content of 60%, was higher than that of a binder/aggregate ratio of 0.46 and 0.35 by 21.38% and 164%, respectively. The high water absorption could be attributed to the high binder content within the mix.

A comparison between M2, M5, and M8, each containing 10% glass powder and binder/aggregate ratios of 0.35, 0.45, and 0.57, respectively, indicates an 11% increase in water absorption when the binder/aggregate ratio increased from 0.35 to 0.45. However, at a binder/aggregate ratio of 0.57, the water absorption was reduced by 60%. A similar trend was observed when the percentage of cement replacement with glass powder increased from 10% to 20%. The decrease in water absorption can be attributed to the decrease in porosity in the hardened concrete with the incorporation of glass powder. This corroborates previous reports that low-volume fly ash concrete demonstrates superior water absorption characteristics and durability under immersion conditions [47]. Incorporating glass powder at a higher percentage in the concrete mix reduces the expected multiple micro-cracks on the concrete surface, which is associated with a dry shrinkage mechanism at higher binder content. However, excessive replacement percentages may reduce the strength of concrete.

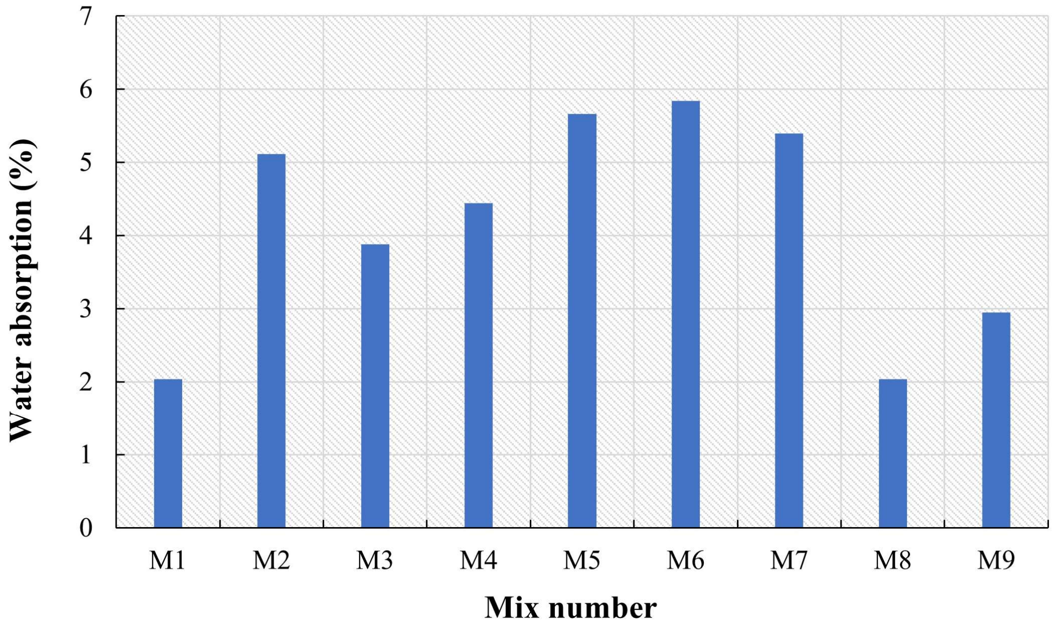

Figure 9. Water absorption for concrete cured in water.

4. Conclusions

The study evaluated the effects of varying binder/aggregate ratios and the use of waste glass powder as a partial replacement for cement in concrete production. The workability, density, water absorption, and compressive strength of the resulting concrete were tested using various curing methods, and the following conclusions were drawn based on experimental results:

1. The workability of all concrete mixes was directly proportional to the binder-aggregate ratio, as evidenced in the slump test results.
2. There was a reduction in concrete density with an increase in the percentage of glass powder content, regardless of the variation in the binder/aggregate ratio. However, the density values obtained for all specimens can be classified as normal-weight concrete.
3. The concrete cubes cured in lime water had the highest mean density, making lime curing the most appropriate method when reduced surface permeability is desired.
4. Based on the results obtained, it could be inferred that optimum binder/aggregate ratio and glass powder replacement were achieved at 0.46% and 10%, respectively.
5. Water curing is the most effective method of curing for strength purposes.
6. An increase in the aggregate content of concrete mix has the highest likelihood of increasing the resistance of concrete to water penetration.
7. This study promotes the use of industrial wastes as possible complements to cement in concrete. The microstructure and interfacial transition zone of concrete containing glass powder can be explored in future research.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Authors contributions

Original draft: writing—review & editing: Awolusi, Marc; methodology: Awolusi and Ajayi; formal analysis: Awolusi, Accouche and Azab; data curation: Awolusi, Nnochiri and Azab; conceptualization & supervision: Awolusi.

Conflict of interest

The authors declare no conflict of interest.

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