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EFFECT OF RECYCLED GLASS AGGREGATES ON MECHANICAL AND PHYSICAL PROPERTIES OF STRUCTURAL CONCRETE

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The exponential expansion in concrete use has put the environment under immense pressure to supply cement, aggregates, and water. Natural resource consumption impacts the environment and undermines the concrete industry. A swift shift towards sustainable concrete is required considering the emergency triggered by human activity on the climate. Glass concrete (GC) has sparked the curiosity of the construction industry owing to its environmentally friendly approach. The study uses recycled glass aggregates (RGA) to partially replace natural aggregates (NA) to produce sustainable structural concrete with superior mechanical properties. 20 % glass concrete outperformed all others in fresh and hardened concrete. Only 75 % glass blend demonstrated a slight decrease in compressive strength due to drop in density. Glass concrete showed a lower water absorption capacity. However, glass has triggered an alkali-silica (ASR) reaction, reducing the durability of the concrete significantly.

Key words: concrete, recycle glass aggregates, sustainable concrete, natural aggregates.

Introduction

The concrete industry and the Portland cement industry are key participants in environmental policy (Meyer, 2009). The necessity of utilising industrial by-products to reduce the consumption of raw materials appears to be universally acknowledged by various international stakeholders. There are already several conventional materials available on the market that have proven to be effective in enhancing the qualities of concrete. Nonetheless, availability of these resources is only sometimes assured. To decrease economic and environmental constraints, producing locally sourced and environmentally friendly products to substitute conventional materials and prevent their disposal in landfills is essential. Several research on the potential use of glass in concrete has been conducted within the context of the industrial chair on the valorisation of glass as a recyclable resource (Chandru & Chandrashekar, 2015). Above 10 billion tonnes of concrete are produced annually. Aggregates are the essential component of concrete. Aggregates occupy approximately 70–80 % of the volume of structural concrete, with fine aggregate accounting for 25–30 % and coarse aggregate accounting for 40–50 % (Shetty & Jain, 2019). The volume and characteristics of aggregates significantly impact concrete's various characteristics and properties. In the UK, natural aggregates are traditionally utilised as coarse aggregate and river sand as fine aggregate. Due to the rapid expansion of the construction industry, conventional aggregate sources are rapidly decreasing, resulting in a scarcity of resources. These resources should be used judiciously for sustainable development, while alternative materials to replace conventional aggregates should be explored. The construction industry can improve its sustainability by using lower Portland cement content concrete. Several industrial by-products, such as fly ash, crushed, granulated blast furnace slag, and condensed silica fume, possess cementitious properties. The aim of sustainability is to offer a better environment for people to live, socialize, and work in while not depleting natural resources. Environmental issues are regularly covered in the media and are of significant interest to the general people. As a partner in environment, construction industry must recognize that our environment and natural habitat are under threat, and that if nothing is done to reverse this trend, even the future of humanity will be jeopardized. With raising concerns about environmental issues, the building industry can improve its sustainability by using concrete with a lower Portland cement percentage. Cementitious qualities can be found in various industrial byproducts, including fly ash, pulverized, granulated blast furnace slag, and condensed silica fume. The use of recycled materials in concrete has been extensively researched. Glass is one of the most prevalent materials used in everyday life, including condiment containers, windowpanes, glass bulbs, and many more. According to the Glass Recycling Report, the UK recycles 76.5 percent of its glass waste (Wrap, 2019). The UK government's goal is to achieve 90 % by 2030. Furthermore, because glass is a siliceous material, it has nearly the same chemical composition as natural sand. This study focuses on partially substituting natural aggregates with crushed glass to create concretes with the same or better mechanical qualities than conventional concrete.

Materials

Glass is an amorphous material composed primarily of Silicon dioxide. Additionally, it has trace levels of alkalis such K_2O and Na_2O. Glass meets all the characteristics of pozzolanic material, which are a high silica concentration, amorphous and with a large surface area (Neville, 1996). For this study, recycled glass aggregates were sourced from "Specialist Aggregates", a UK-based company which provides recycled glass materials. Industrial and residential glass collections are processed and crushed using either jaw crushers or a hammer mill, and then the glass is sized over conventional screen decks. The glass is relatively soft, and the breaks are often sharp. However, the onward movement of the glass along the conveyors and over the screen decks is sufficient to tumble the glass and remove the sharp edges. This process is simple and energy efficient. Specialist aggregates provide the market with glasses of different colours and sizes. This study utilised a mix of clear crystal and green glass, and the size distribution was matched to that of natural aggregates using BS EN 933-1(1997). Table 1 below indicates the chemical composition and percentage by mass for cement, glass and natural sand.

Table 1

The chemical composition of cement and glass aggregates

Chemical composition	Percentage (%) By mass			
	Cement	Crushed glass	Glass powder	Sand
CaO	61.9	11.7	11.42	7.11
Al_2O_3	4.7	1.38	1.54	2.55
SiO_2	20.2	72.34	72.2	78.6
K_2O	0.82	0.38	0.43	0.64
Na_2O	0.19	12.92	12.85	0.42
Fe_2O_3	3	0.48	0.48	2.47
MgO	2.6	0.56	0.79	0.46
TiO_2	n/d	n/d	n/d	0.15
SO_3	3.9	0.09	0.09	n/d
Loss on ignition	2.69	0.15	0.2	7.6

Experimental Methods

Five concrete mixes were produced containing varying amounts of glass aggregates. The constituents utilised were natural fine and coarse aggregates, recycled glass fine and coarse aggregate, and a fix water-cement ratio in all the mixes. The control concrete had no glass aggregate. BS EN 197-1:2011-compliant CEM I 52.5N Portland cement was utilised throughout the study. Tap water was utilised throughout the study. Glass replacement ratios in concrete mixtures were 0 %, 10 %, 20 %, 50 %, and 75 %. However, to obtain more detailed data for the shrinkage test 100 % replacement ratios were also used. The mix design was done following the Building Research Establishment's mix design standards. The sieve analysis of percentage fine aggregates passing 600 µm sieve determined the proportion of fine aggregates. The mix proportions of concretes studied are given in Table 2, which were designed to have an average slump between 100–150 mm under BS EN 206-1:2006 for S3 concrete workability class. Parts 1 and 2 of BS EN 12350:2000 were followed for concrete preparation and testing of fresh concrete. After casting moulds, an initial slump was observed, and the fresh concrete properties were noted. The mix was formulated to achieve a compressive strength of 35 MPa. Table 2 presents the volume of fine and coarse aggregates replaced for each mixture.

Table 2

Composition of the different mixtures

Mix Reference	Mix Nomenclature	Cement (kg/m³)	Water (kg/m³)	Aggregates (kg/m³)				W/C Ratio
				FA	CA	FG	CG	
1	MC	350	180	540	1270	–	–	0.51
2	M10	350	180	485	1140	55	130	0.51
3	M20	350	180	430	1030	110	260	0.51
4	M50	350	180	270	635	270	635	0.51
5	M75	350	180	138	322	414	966	0.51

A sieve analysis was performed to evaluate the grading of fine and coarse aggregates for both GA and NA to determine their suitability for use in concrete mixtures. Two series of sieves built in a column pattern were employed for coarse and fine aggregates. The test sieves utilized in this investigation met the specifications outlined in BS EN 933-2 (1996). The grade was calculated as the cumulative percentage of weight passing through the sieves, as defined in BS EN 933 Part 1 (1997). Fig. 1 presents the particle size distribution of fine glass aggregate.

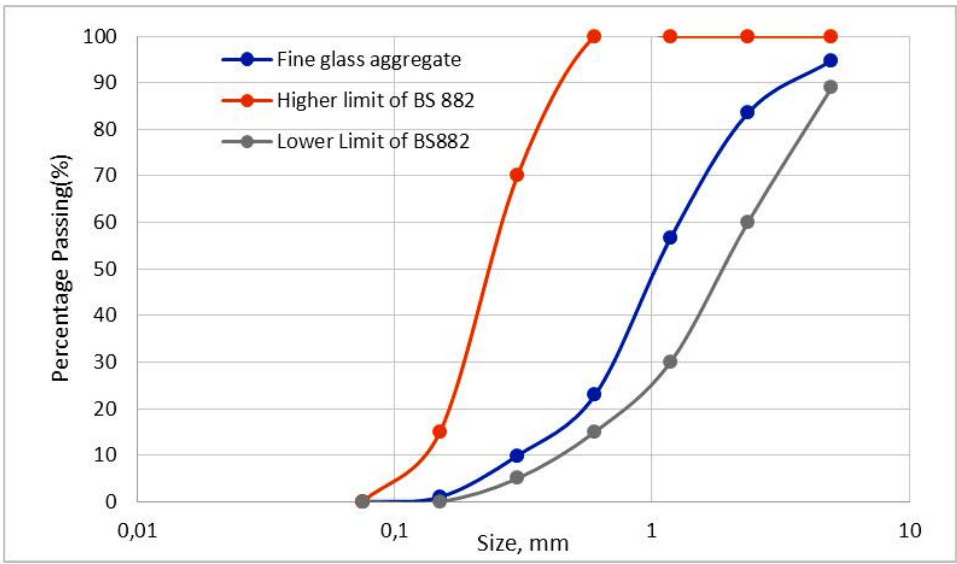

Fig. 1. Particle size distribution of fine glass aggregate in line with BS EN 933-1(1997)

In line with BS EN regulations, several major physical parameters of NA and coarse GA were tested to assess the suitability of aggregates used in this study for use in concrete. All aggregate samples were produced in line with BS EN 932 Part 1 (1997) utilising the riffling technique for the reduction phases, followed by separation into representative sections. The major parameters for coarse and fine GA and NA were compared. Table 3 below present a list of tests carried out on both types of aggregates. It also presents the results of the different tests. The fresh concrete tests were conducted according to the BS EN 12350-part 2(2002). Results of the slump test (Abrams cone) is presented in Table 4. These tests aimed to investigate the effect of altering the amount of glass aggregates to natural aggregates on engineering parameters of concrete, specifically compressive and flexural strength. The density of the hardened concrete was also investigated and compared with the control concrete. These properties play a significant role in the structural role of reinforced concrete. The results determine recycled glass concrete's short- and long-term attributes. Furthermore, drying shrinkage is investigated since the presence of cracks induced by moisture loss might worsen cracks induced by the probable ASR reaction generated by the alkali-silica gel, which increases internal pressure, expands, and splits the concrete further.

Results and Discussion

Aggregates Characteristics

Table 3

Physical characteristics of aggregates tested in this study

Physical Test	Unit	Natural Sand	Glass Sand	Coarse Natural Aggregate	Coarse Glass
Apparent particle density	kg/dm^3	2.64	2.6	2.78	2.57
Oven dried particle density	kg/dm^3	2.21	NA	2.49	NA
Saturated surface dry particle density	kg/dm^3	2.1	2.58	2.75	2.25
Water absorption	%	2.1	0.1	2.81	0.1
Aggregate Impact Value	%	NA	NA	26.44	26.78
Aggregate Crushing Value	%	14.3	18.6	27.31	29.45
Fine Modulus	%	2.62	2.24	NA	NA
Moisture content	%	3.81	2.15	1.12	0.21

As seen in Table 3 the particle density values of the GA are lower than those of the NA. In terms of water absorption, the hydrophobic behaviour of the GA is evident, leading to almost zero absorption for glass aggregates. The crushing value results revealed expected higher values for glass. This result highlights the brittle nature of glass relative to the impact and crushing process. Glass sand has a finer modulus than natural sand. The results also observed that natural aggregates tend to capture more moisture than glass aggregates. Conclusions drawn from Table 4 indicate that the decreased water requirement from RGA is the cause of the high flowability in the 10 % RGA concrete mixes. Because glass particles do not absorb water rapidly, there is more free water to improve fluidity. It was found that workability with a higher glass content in the concrete and a 0.5 Water/cement ratio. Whereas higher replacements significantly decrease the workability. An increase in RGA to 20 % reduces the slump value. The decrease could be attributed to the angular shape of the glass particles, which may cause an interlocking effect and reduced flexibility of movement in the concrete mixture compared to rounded natural fine aggregate, which provides more workability. As the RGA mixing ratio increases, more cement paste adheres to the surface of the waste glass, resulting in less accessible cement paste required for concrete flowability, as demonstrated

Table 4

Slump values for all concrete mixes

Mix	Glass Replacement (%)	Slump (mm)			Average Slump (mm)	Slump Category
		Test 1	Test 2	Test 3	Mean	
MC	0	102	105	99	102	High
M10	10	94	95	91	93	High
M20	20	83	85	83	84	Medium
M50	50	60	57	60	59	Low
M75	75	52	48	45	48	Low

Density

Density values measured after varying curing periods showed consistency, validating the appropriate experimental methodology. The mean density results indicated that density gradually increases throughout the first 28 days of curing. The density results obtained are tabulated and presented in Fig. 2 and Fig. 3. The density of the control concrete at 28 days was 2300 kg/m^3. The density of glass concrete decreases as the glass content increases (Abdallah. S and Fan. M., 2014).

At 28 days, the density of the concrete dropped by 0.4 % when the glass percentage in the mix was 10 %. At 20 % glass aggregate substitution, the density drops by 1.7 %, respectively. A 2.17 % drop was noted when the GA equals the NA. The density reduction is enhanced by a 75 % replacement, resulting in a density of 2220 kg/m^3 for a drop of 3.4 %. This tendency is consistent with the findings of other researchers (Castro & Brito, 2013; Topçu & Canbaz, 2004), who claimed that crushed glass reduces concrete density.

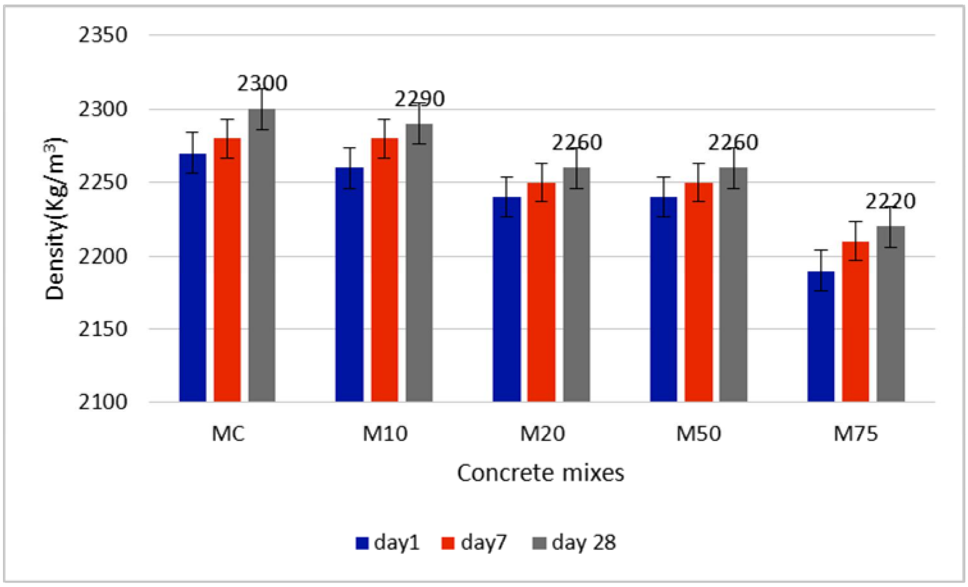

Fig. 2. Density of Hardened concrete with different glass replacement percentages

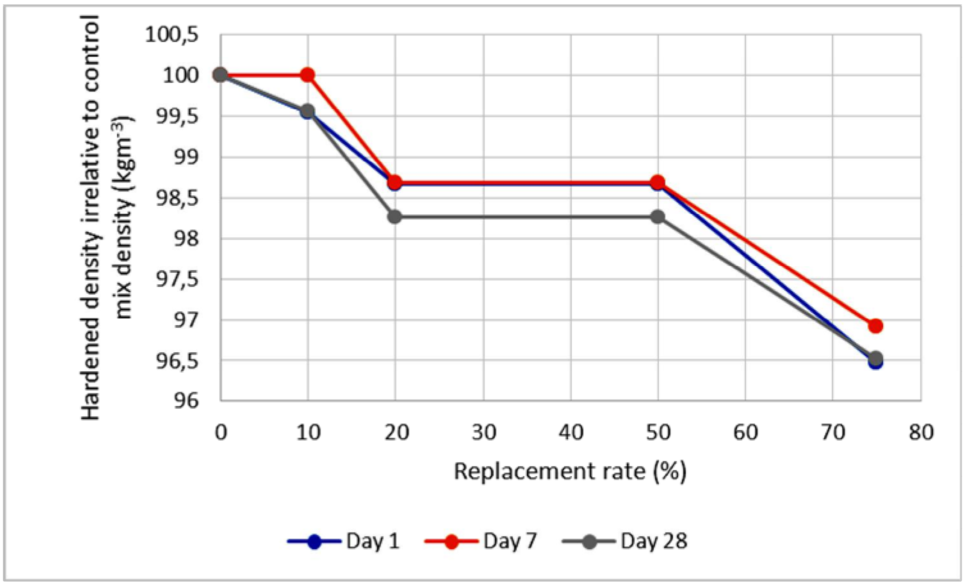

Fig. 3. Density of concrete mixes relative to the reference concrete

Compressive strength

The lower specific gravity of glass aggregate compared to natural aggregate explains the general decline in concrete density when the proportion of glass increases in the concrete matrix. The variations in the mixtures for which various-sized aggregates are replaced are related to changes in the replacement volume. Previous studies have demonstrated that adding glass aggregate reduces density or has almost no effect (Camileri, Montesin, & Sammut, 2004; Shayan & Xu, 2004; Taha & Nounu, 2009). All found density decreases of up to 2 %. This study, however, demonstrates that the decay in density value is in the range of 3 to 3.5 %. This result is consistent with (Tan & Du, 2013), who observed a density decline of 3 % to 4 %. 20 % substitution of conventional aggregate with glass increases the compressive strength of the concrete mix (Corinaldesi et al., 2005). However, when the replacement rate exceeds 20 %, the strength drops; the more glass aggregate present in the concrete, the more significant is the decline in strength. From Table 5 below, at the 7 day testing, 50 % and 75 % of specimens showed a considerable strength loss compared to the control concrete. The drop-in strength was most likely not caused by the tiny volume changes when the concrete hardened. Instead, air pockets trapped in sharp-sided “cracks” on the surface of glass particles caused the bonding between the cement paste and glass aggregate to be less effective (Chon, 2014). Thus, there appears to be a strength benefit to incorporating glass at 20 % replacement levels, resulting in concrete with a near-strength development. Nevertheless, even though M50 and M75 had a lower initial strength value, they continued to gain strength over time under wet curing conditions and approached the strength of the control mixture.

Table 5

Compressive strength of concrete mixtures

Mix	Compressive Strength (MPa)				
	1 day	3 days	7 days	28 days	56 days
MC	15.07	21.19	32.13	37.2	37.64
MC10	14.21	19.18	31.33	41.3	42.25
MC20	16.3	22.23	34.36	42.1	44.33
MC50	15.19	20.73	29.85	38.25	40.73
MC75	14.79	19.87	26.47	37.11	39.93

Flexural Strength

Fig. 4 shows the findings of the experimental investigation of the compressive and flexural strength of concrete at 28 days with 0 %, 10 %, and 20 % glass replacement levels, as well as 50 % and 75 % glass replacement levels. In contrast to compressive strength, flexural strength decreases as the quantity of glass in the concrete increases and confirm (Park and Lee, 2004; Topçu and Canbaz, 2004). The flexural strength-to-compressive strength ratio (f_t/f_{cu}) for all five categories of concrete utilised in the study. The highest achieved f_t/f_{cu} ratio is 15 %, and the lowest is 8 %. According to the test findings, the range of the f_t/f_{cu} ratio for M10 and M20 is consistent with the usual assumption that the flexural strength of concrete is 10–15 % of its compressive strength. The results suggest that the 10–15 % rule of thumb may be used to estimate flexural strength from the compressive strength of recycled glass concrete at a maximum replacement level of 20 %. Flexural results, on the other hand, appear to be contradictory with the 10–15 % rule for concrete with glass percentage higher than 20 %. Moreover, the strength development for M75 was slow compared to control concrete. Minimum and maximum differences between specimens were 0.14 N/mm^2 between MC and M10 while the maximum difference was noted to be between MC and M75 to be 2.2 N/mm^2. This is graphically represented in Fig. 4. As evidenced by the ft/fcu ratio results, the increase in flexural strength is less than the equivalent rise in compressive strength for each ratio of glass replacement. The results also show that control concrete has the most significant flexural strength values (60 % greater) on average. It has been suggested that aggregate shape and texture impact concrete’s flexural strength. (Neville & Brooks, 1987) explained this behaviour by the existence of a stress gradient, which slows the cracking process and ultimately results in failure.

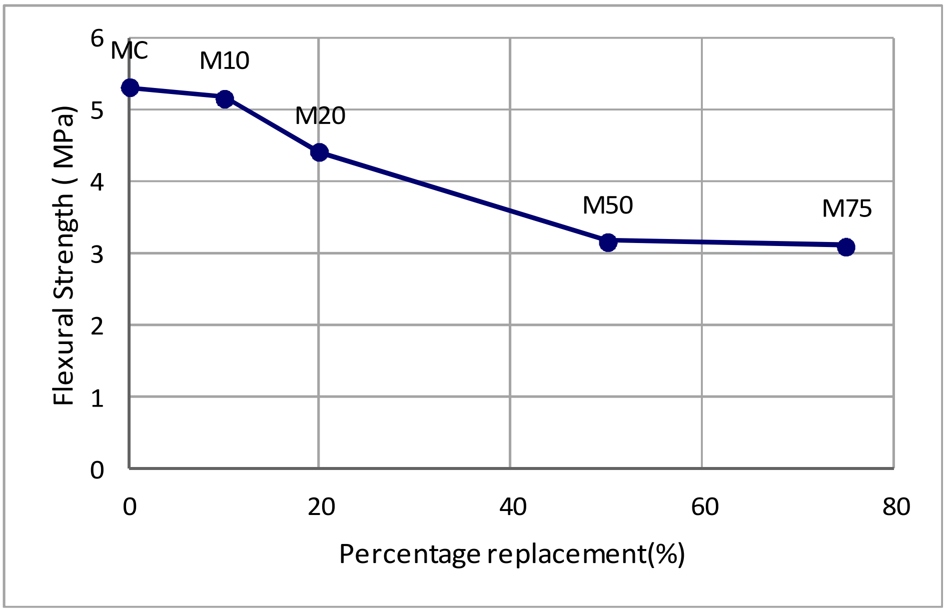

Fig. 4. Flexural strength of the concretes

Ultrasonic pulse velocity

All mixes showed an increase in UPV compared to the control concrete. Fig. 5 shows a graph of mean ultrasonic velocity vs curing time for concrete containing partly glass aggregate. Glass consistently provided the lowest UPV value for day one and day three curing time. However, the pattern reverses at day 7, and by day 28, glass concrete has greater UPV values. Glass concrete results were very similar to conventional concrete results. The UPV value of all the different concrete mixes continuously increased over time. Compressive strength and UPV exhibited comparable tendencies. With glass aggregates, higher pulse velocities indicate higher-quality concrete. M75 showed a higher UPV value for all the curing periods than the control mix. This supports (Dhir, Limbachiya & Dyer, 2001) study conclusion that glass in concrete serves as pozzolan; therefore, at 75 % replacement, glass powder mixes with cement to generate a more significant pozzolanic effect, causing the concrete to set and develop higher strength faster than the control mix.

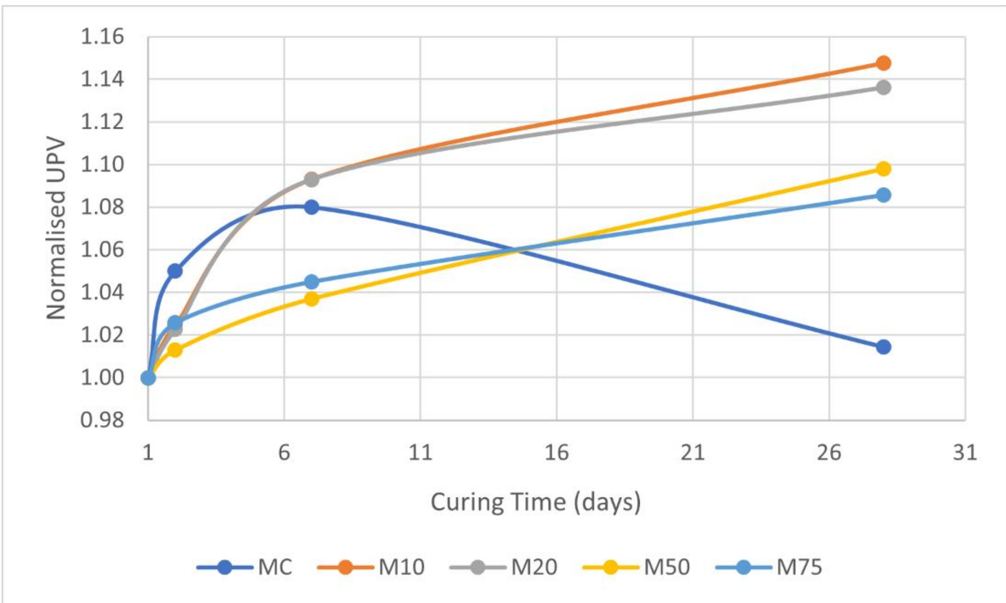

Fig. 5. Normalised Pulse velocity (Km/s) vs Curing time (days)

Drying Shrinkage

Fig. 6 shows the drying shrinkage of control concrete and concrete mixes made of 10 %, 20 %, 50 %, 75 % and 100 % glass. According to the results, shrinkage values initially increased up to the 28-day age before steadily stabilising. For prisms of M100, the minimum shrinkage values recorded after seven days were 206, 210, and 212 με. However, the highest strain values for MC at 28 days of curing were recorded as 692, 695, and 698 με. Results showed that applying 10 % glass to the concrete mix reduces by 15 % the shrinkage while a 100 % glass addition reduces the shrinkage by 62 %. As previously stated, adding glass to the concrete mix decreases the drying shrinkage value. When 100 % glass aggregate was utilised to make concrete, the drying shrinkage was the lowest. The primary factor for the decrease in shrinkage was that glass aggregate has a significantly lower water absorption rate than natural aggregate. Consequently, less moisture was left in the concrete when drying began, which led to less shrinkage of the concrete that contained it.

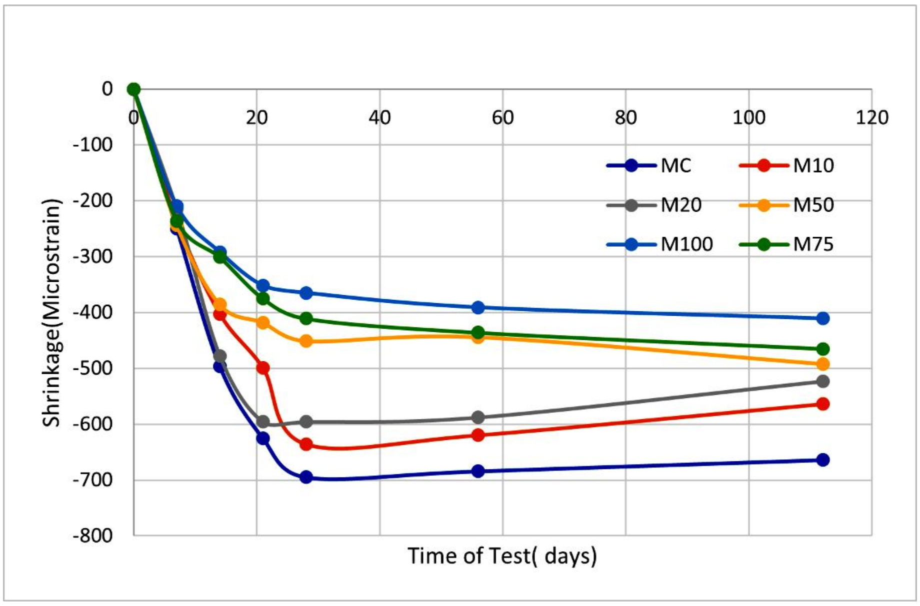

Fig. 6. Shrinkage rate with respect to time in days

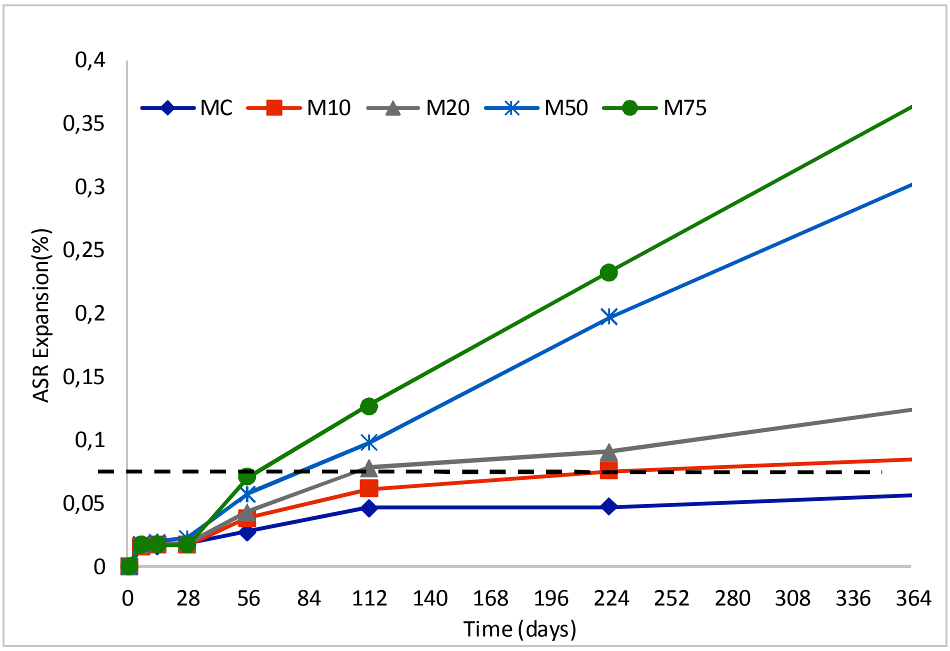

Fig. 7. ASR expansion vs time

Alkali – Silica Reaction

The results of the ASR of percentage length change tests carried out on prisms of the concrete cast and treated following the relevant British Standards are presented in Fig. 7. The control concrete showed an expansion of 0.055 % after one year. This value is below the limits for typical reactivity set by BRE Digest 330, Part 2 (2004), which is 0.2 % at 365 days and 0.1 % at 28 days. However, the ASR expansion increased significantly with increased glass content. Concrete with 20 % glass content showed negligible expansion, while concrete with a higher percentage of glass showed a high expansion rate. Therefore, mixes with a glass content higher than 20 % were all above the limit set by the BRE (BRE, 2004).

Conclusion

This study evaluated concrete's structural and long-term performance using glass aggregates. The experimental results allowed the relevant conclusions to be drawn:

1. Particle size, shape, and texture significantly impact the workability of concrete with glass. Loss of workability is attributable to the angular shape of the glass particles, which may result in an interlocking effect and decreased mobility in the concrete mixture.
2. As a result of the lower particle density of the glass, concrete with a higher proportion of glass has a noticeable reduction in density. The lower specific gravity of glass aggregate compared to natural aggregate explains the general decrease in concrete density as the percentage of glass in the concrete matrix increases.
3. Concrete with up to 20 % glass has a higher compressive value than control concrete. However, beyond 20 % replacement, compressive strength decreases. Meanwhile, an increase in strength is noted over time.
4. Concrete containing GA absorbs less water than concrete without GA. This is due to the hydrophobic nature of glass and the denser microstructure of concrete containing finer glass particles.
5. Natural aggregate concrete's pulse velocity increases over time. In contrast, the initial pulse value for glass concrete was lower, but the pattern changed after day 7. UPV and compressive strength exhibit similar trends. This is due to the pozzolanic qualities of fine glass particles, which enable concrete to set faster.
6. With increased GA, recycled glass concretes' volumetric change or drying shrinkage reduces. The main reason for the reduction in shrinkage is that the glass aggregate absorbs water at a lower than natural aggregate. As a result, less moisture was present in the concrete before drying got underway, which prevented it from shrinking.
7. ASR expansion increased significantly as glass content increased. The expansion rate of concrete containing 20 % glass was minimal, whereas concrete with a higher proportion of glass expanded rapidly above the minimal limit set by BRE Digest 330.

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ВПЛИВ ЗАПОВНЮВАЧІВ РЕЦИКЛІНГУ СКЛА НА МЕХАНІЧНІ ТА ФІЗИЧНІ ВЛАСТИВОСТІ КОНСТРУКЦІЙНОГО БЕТОНУ

Суттєве збільшення використання бетону у сучасному будівництві спричиняє зростання його шкідливого впливу на навколишнє середовище, що зумовлено значною потребою у цементі, природних заповнювачах та воді. У будівельній галузі необхідний швидкий перехід до сталого мислення, враховуючи надзвичайну ситуацію, спричинену впливом людини на клімат. Бетон, що містить заповнювачі на основі відходів та переробки, викликає інтерес завдяки своєму екологічному підходу. Досліджено заповнювачі рециклінгу скла, які використовуються для часткової заміни природних заповнювачів у бетонній суміші, для виробництва стійкого конструкційного бетону з підвищеними механічними властивостями. Встановлено, що заміна 20 % природних заповнювачів на заповнювачі рециклінгу скла мала позитивний вплив на властивості як бетонної суміші, так і затверділого бетону. Заміна природного заповнювача на заповнювачі рециклінгу скла у кількості понад 20 % спричиняла зменшення рухомості бетонних сумішей. Введення 75 % заповнювачів рециклінгу скла продемонструвало незначне зниження міцності на стиск унаслідок зниження середньої густини. Водопоглинання бетону з збільшенням частки заміни природного заповнювача на заповнювачі рециклінгу скла знижується. Введення скляного заповнювача зумовлює лужно-кремнеземну реакцію, що значно знижує довговічність бетону. Результати випробувань щодо лужно-кремнеземної реакції показали, що заміна 10–20 % заповнювачів рециклінгу скла не викликала небезпечного розширення внаслідок лужно-кремнеземної реакції. Однак зразки, що містили понад 20 % скла, розширювались вище мінімальної межі, встановленої BRE Digest 330.

Ключові слова: бетон, заповнювачі рециклінгу скла, стійкий бетон, природні заповнювачі.