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LONG-TERM EFFECT OF DIFFERENT PARTICLE SIZE DISTRIBUTIONS OF WASTE GLASS POWDER ON THE MECHANICAL PROPERTIES OF CONCRETE

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Abstract
In this paper, a comprehensive experimental investigation was conducted into the effect of the particle size distributions (PSDs) and percentages of waste powdered glass as a partial replacement of cement on the long-term mechanical behavior of concrete produced at two different cement levels. For this purpose, two different mixtures of concrete were used as reference mixtures; the first has a relatively low cement content (331 kg/m^3), and the second has a relatively high cement content (490 kg/m^3). Two different PSDs of glass powder (GP) labeled GP-A and GP-B ((55 µm < GP-A < 135 µm) and (55 µm > GP-B) were used, and the considered GP content for the low cement content mixture (LCCM) and the high cement content mixture (HCCM) were (0%, 5%, and 10%) and (0%, 5%, 10%, and 15%) by weight of cement, respectively. The mechanical performance of all concrete mixtures at 180 days was investigated and evaluated in related tests as compressive strength and toughness, splitting and flexural tensile strength, elastic modulus, and compressive stress-strain behavior. The experimental results generally indicated that the compressive strength of GP-modified concrete improved significantly over the long-term age (180-days) compared to the early age (28-days). The contribution of PSDs of GP to enhancing the mechanical properties of concrete is insignificant compared to its replacement amount. Finally, independent of the PSDs, the incorporation of 10% GP for LCCM and 15% of GP for HCCM has a positive effect on the long-term mechanical properties of concrete, indicating that GP can be used as a replacement for cement.

Keywords: **Long-term mechanical properties; Particle size; Stress-strain curves; Supplementary cementitious material; Waste glass powder.**

1. INTRODUCTION

According to the Global Cement Report, the total annual cement consumption in 2016 was 4.13 gigatonne (Gt), and by 2050 it is anticipated to expand to 4.68 Gt /year [1]. This means that demand for cement production has not decreased. The cement manufacturing process is the most energy-intensive sector, inevitably accompanied by high CO_2 emissions, which cannot be averted even if the overall production process is optimized to the fullest extent possible. According to Worrell et al. (as cited in Sonebi et al. [2]), the estimated reduction of CO_2 emissions of cement by at least 5% and possibly up to 20% could be achieved once the construction industry is committed to using supplementary cementitious materials (SCMs). Federico [3] has defined SCMs as those which react either hydraulically or pozzolanically in the pore solution of hydrating cement. Silica fume, ground granulated blast-furnace slag, and fly ash are such materials considered as the most widely used waste-based SCMs [2]. The use of SCMs to partially replace cement could reduce cement production and thus reduce the consumption of fossil fuels and greenhouse gas emissions [4].

The restricted availability or even unavailability of traditional SCMs in some regions of the world makes researchers develop new and locally available sources to be used as an alternative SCMs. Due to the amorphous nature, the relatively large quantities of silica and calcium content, and high surface area, considerable attention has been paid to the feasibility of using waste powdered glass as an alternative SCM in mortar and concrete production. In this respect, many attempts have been made to examine the physical, mechanical, and durability characteristics of mortar and concrete modified with waste GP [5–14]. Studies have shown that the above properties are affected by the GP pozzolanic behavior, which, in turn, depends mainly on the fineness of the particles, chemical compositions, and the substitution rate of GP.

The main concern for the use of waste glass (WG) in the production of concrete is the Alkali-Silica Reaction (ASR), which has a negative impact on the strength and durability of concrete [48, 50, 51, 52]. ASR occurs in concrete, in the presence of sufficient moisture, between highly alkaline cement paste and reactive amorphous (non-crystalline) silica present in the WG. The ASR produces alkali-silica hygroscopic gel, which negatively affects the concrete matrix. It can absorb water and expand to create a pressure that, over time, causes distress in the concrete matrix, such as cracking, spalling, and loss of concrete strength, ultimately leading to a concrete failure [53]. Previous studies have pointed out that WG with good pozzolanic characteristics can mitigate ASR and reduce efflorescence by consuming lime (calcium hydroxide) and producing calcium silicate [9, 49].

The pozzolanic characteristics of GP have been investigated in several studies [16–18, 45]. Generally, no definite conclusions have been drawn concerning the optimum particle size in which glass acts as a pozzolana. However, most studies confirming pozzolanic reactivity below 125 μm, and the degree of reactivity increases as the size of the GP particle decreases, thereby prohibiting destructive alkali-silica reaction (ASR) [6, 10, 15, 19, 20, 21].

Studies on the durability properties of GP modified concrete have generally shown improved performance against chloride permeability, freeze-thaw resistance, and water permeability. Islam et al. [5] reported that the durability of GP-concrete showed better long-term performance against chloride permeability than free-GP concrete. A study by Schwarz et al. [14] found that concrete containing 10% GP with particle sizes of 72% finer than 45 μm showed preferred performance against chloride permeability, indicating a certain amount of pore refinement in GP-modified concrete specimens. The results of the experimental durability tests presented by Omran et al. [15] on roller compacted concrete containing 20% GP indicate that the use of GP improves concrete resistance to freeze-thaw cycles. Nassar and Soroushian [22] observed an increase in concrete resistance to chloride ion permeation by incorporating 20% of waste GP with an average particle size of 13 μm. This improvement was related to the positive effect of GP on concrete pore refinement and pore blockage. The authors also found that using GP as a cement substitute improves the water absorption in mixtures with low and high water to cement ratios. The review study conducted by Jiang et al. [24] indicated that chloride ion penetration into concrete could be reduced by 40%–90% by incorporating 20–30% GP as cement replacement. The incorporation of GP up to 25% with particulate finer than 75 μm showed a negligible impact on setting time and cement expansion [12]. Shayan and Xu [16] reported a satisfactory GP-containing concrete performance up to 30% with a nominal particle size of fewer than 10 μm for drying shrinkage and alkali reactivity.

On the other hand, an apparent contradiction can be observed in the literature on the fresh properties of concrete incorporating GP. It has been found that the content and physical characteristics of GP, such as particle size, water absorption, and morphology, have contributed significantly to the fresh properties of concrete [24]. Kumarappan [25] found that replacing cement by up to 40% of GP with a particle size of less than 300 μm leads to a systematic increase in the concrete slump. Khatib et al. [26] showed a systematic increase in the concrete slump with an increase in the GP mixture content of up to 40%. Nassar and Soroushian [22] observed a slight increase in the concrete slump when the GP content was 20%. Kalakada and Doh [11] investigated the workability properties of concrete containing four different percentages of GP (20%, 40%, 60%, and 80%) with two different particle sizes of less than 75 μm (GP1) and 150 μm (GP2). The slump was found to increase with an increase in GP1 and GP2 of up to 40% and 60%, respectively. They also indicated that GP could be used as a cement substitute in concrete mixtures where there is a higher demand for workability. Conversely, the use of GP in some other studies showed a negative effect on concrete workability [16, 27, 28].

In terms of the mechanical properties of concrete, test results have shown that there is no consensus on the optimum content of GP to improve the strength of hardened concrete [47]. This was mainly due to the different chemical compositions, amorphous phases, and particle sizes of GP. Kumarappan and Khatib et al. [25, 26] have observed that the use of up to 10% GP as a cement replacement improves concrete compressive strength. The test results of Vandhiyan et al. [27] showed that the use of GP by up to 10% improves the mechanical properties of concrete at 28 days (compressive, tensile, and flexural). Kalakada and Doh [11] experimentally investigated the impact of two-particle sizes (75 µm and 150 µm) of GP to replace cement up to 80% by weight on workability, density, compressive and splitting tensile strength of concrete. The results showed that the density, compressive, and splitting tensile strength is decreased with the increased use of GP. They also reported the possibility of using GP as a partial cement replacement for low strength and lightweight applications. Naaamandadin et al. [29] studied the effect of partially replaced cement by GP on the compressive and splitting tensile strength. They found that the use of 4% of GP increased both the compressive and the splitting tensile strength by approximately 34.65% and 21.27%, respectively.

The review of previous studies revealed that a limited number of publications [4, 16, 30, 31] have examined the long-term mechanical behavior of GP modified concrete in field projects. Also, the laboratory study of the mechanical properties of GP modified concrete is still limited to 90-days of testing. Therefore, in this study, an experimental investigation was conducted to fully understand the long-term (180-day) effect of GP content with different PSDs on the mechanical behavior of concrete produced with different cement contents.

2. EXPERIMENTAL STUDY

2.1. Material descriptions

In this research, the employed cement was ordinary Portland cement (OPC) with a strength grade of (42.5 R) produced locally following the Iraqi standard (IQS/5/1984) [54]. The GP used was obtained from locally collected waste-broken glass windows, commonly known as soda-lime glass. To meet the fundamental demands of the pozzolanic behavior of GP and to prevent adverse effects of alkali-silica reactions, the waste glass was ground and then sieved to less than 135 µm of particle size. In order to examine the impact of particle sizes of GP of the same type, two PSDs were used: labeled GP-A, particle sizes ranging from 55 µm to 135 µm (55 µm < GP-A < 135 µm) and labeled GP-B, particle sizes less than 55 µm (55 µm > GP-B). The chemical and mineralogical analysis of the cement and GP used are given in Table 1. Compared to the chemical composition of natural pozzolans of ASTM C618-2015a [32], the combination of the three oxides ($SiO_2 + Al_2O_3 + Fe_2O_3$) in GP is about 75.16%, which surpasses the 70% requirement for Class N raw and calcined natural pozzolans requirement. GP is, therefore, expected to be capable of producing high-quality pozzolans. The X-ray diffraction (XRD) for GP was performed as shown in Fig 1. From this figure, the amorphous nature of the GP can be seen as there were

Table 1.
Chemical composition for ordinary Portland cement and glass powder with requirements of ASTM C618 for pozzolans used in the study

Chemical Composition	Chemical Formula	OPC (%)	GP (%)	ASTM C618
Lime	Cao	61.66	9.868	
Silica	SiO_2	19.83	74.03	
Alumina	Al_2O_3	4.48	1.023	
Ferrite	Fe_2O_3	2.32	0.108	
Magnesia	MgO	3.14	4.739	
Sulfur trioxide	SO_3	2.57	0.13	
Potassium oxide	K_2O	0.68	0.198	
Sodium oxide	Na_2O	0.19	8.024	
Loss on Ignition	LOI	1.5	1.83	
Tricalcium silicate	Ca_3SiO_5	59.50		
Dicalcium silicate	Ca_2SiO_4	11.98		
Aluminate Tricalcium	$Ca_3Al_2O_6$	7.95		
Tetracalcium Aluminoferrite	$Ca_4Al_2Fe_2O_{10}$	7.05		
$SiO_2 + Al_2O_3 + Fe_2O_3$, min. %			75.16	70
SO_3, max. %			0.13	4
Moisture content, max. %			-	3
Loss on ignition, max. %			1.83	10

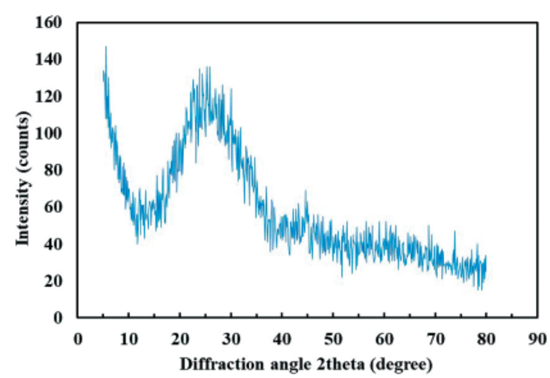

Figure 1.
XRD patterns for GP used in the study

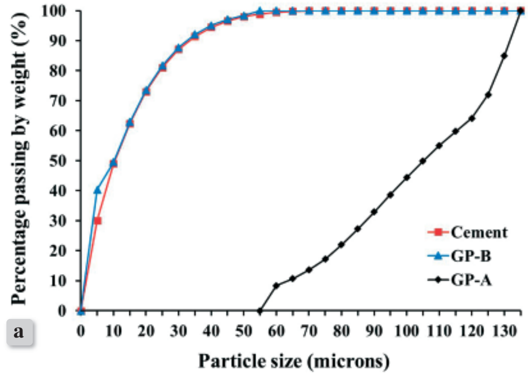

Table 2.
Physical properties of sand and gravel

Physical Properties	Sand	Gravel	ASTM-Designation	
			Sand	Gravel
Bulk specific gravity, Dry	2.65	2.47	ASTM C128	ASTM C127
Bulk specific gravity, (SSD)	2.69	2.49		
Apparent specific gravity	2.77	2.52		
% Absorption	1.68	0.94		
Dense-dry density, (kg/m³)	1875	1600	ASTM-C29	
Loose-dry density, (kg/m³)	1716	1462		
Fineness Modulus, (unitless)	3.20	2.30	ASTM C 125	

Figure 2.
(a) Particle size distribution curves of cement, GP-A, and GP-B, (b) waste glass powder after milling and cement used in the study

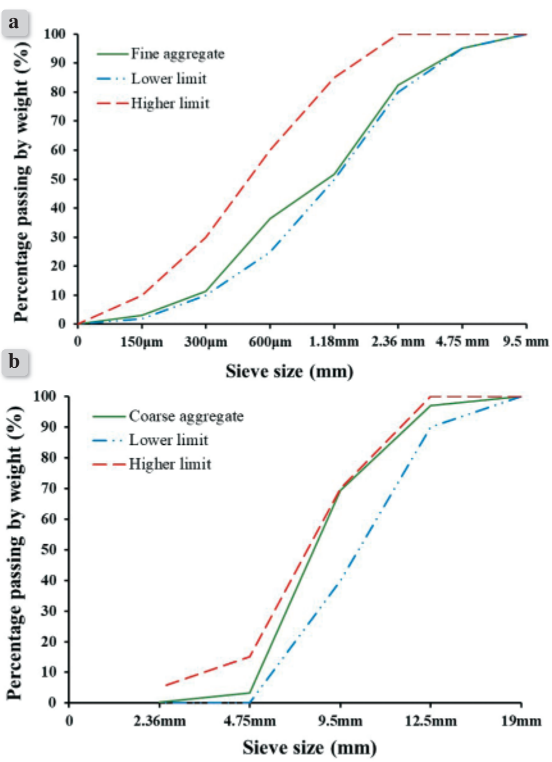

Figure 3.
Grain size distribution for aggregates according to ASTM C33 limits. (a) sand and (b) gravel

no clear crystalline peaks to be found. A Laser Particle Analyzer was used to determine the grain size distribution curves for cement and GP, and the results are shown in Fig. 2. The specific gravity of cement, GP-A, and GP-B were determined to be 3.15, 2.50, and 2.505, respectively. The coarse aggregate used was crushed gravel with a nominal maximum size of 12.5 mm. Washed river sand with a maximum size of 4.75 mm was used for fine aggregates. Physical tests of aggregates were carried out following the ASTM designations, and the results are shown in Table 2. The gradation test was carried out on aggregates following ASTM C136 [33]. The aggregate used was within the limits of the specification of ASTM C33 [34], as shown in Fig. 3.

2.2. Experimental program

To fully understand the long-term performance of using GP content with different particle sizes on the mechanical behavior of concrete produced with different cement amounts, two sets of concrete mixes were made. The control mix of the first set (LCCM) had a cement content and a water-cement ratio of 331 kg/m^3 and 0.54, while the cement content and

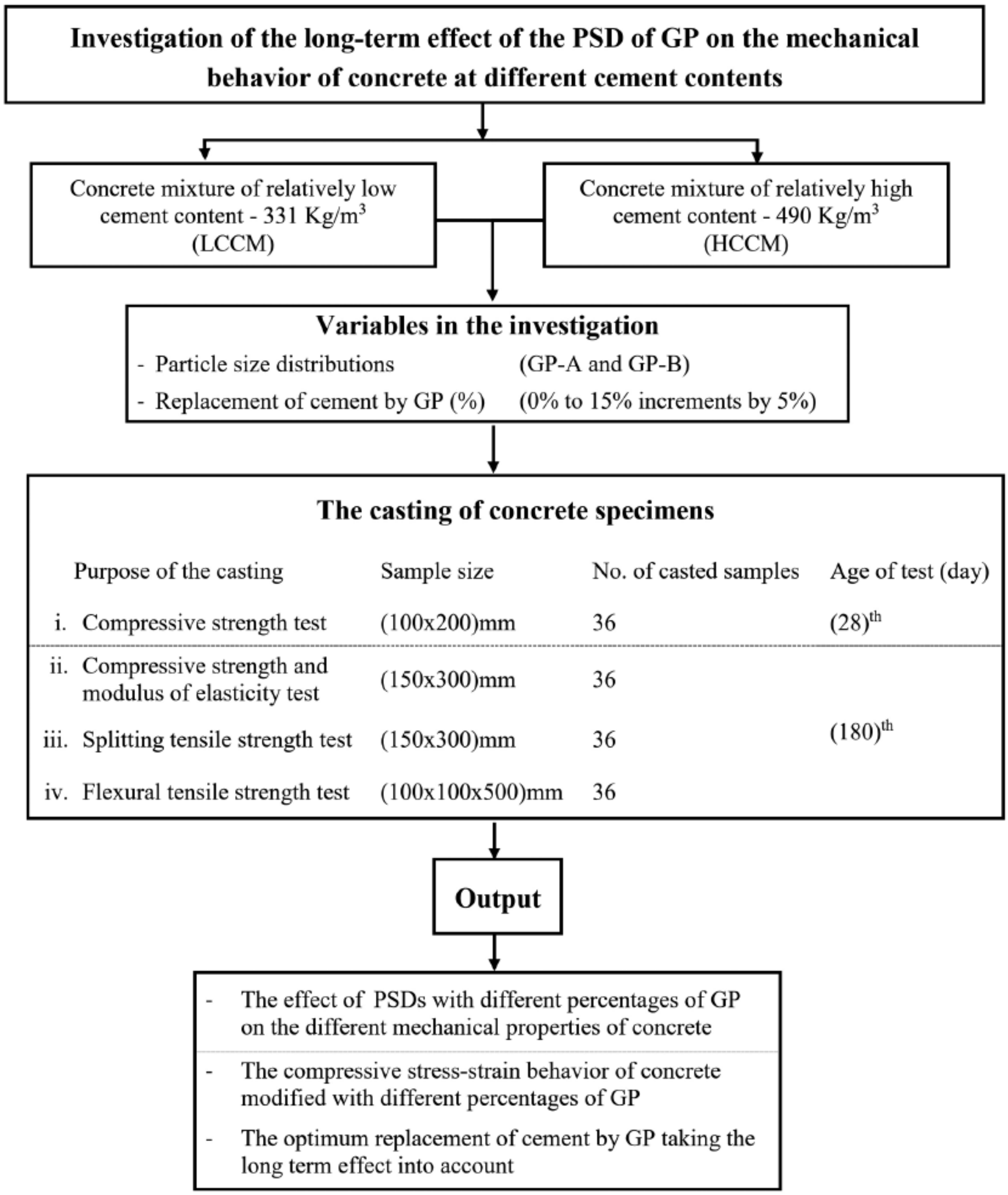

Figure 4.
Flowchart of the experimental program

water-cement ratio of the control mix of the second set (HCCM) were 490 kg/m^3 and 0.41, respectively. In comparison to the first, the cement content of the second set is high. The ratios of GP for each of GP-A and GP-B used as cement replacement in the first and second sets were (0%, 5%, and 10%) and (0%, 5%, 10%, and 15%), respectively. Slump test and different mechanical behavior for the mixes mentioned above have been achieved and compared to each other. Further details on the experimental parameters and the tests carried out in this study are provided in Fig. 4.

Figure 5.
Pictures showing the sides of the tests carried out on hardened concrete modified with and without GP. (a) Samples being prepared and tested for their compressive strength; (b) splitting tensile strength test; (c) flexural tensile strength test; (d) test configuration for modulus of elasticity

Table 3.
Mixture proportions for 1m^3 of concrete

Mix. type	Specimen Details		Cement (kg)	Sand (SSD) (kg)		Gravel (SSD) (kg)	Water (kg)	GP		Water/binder W/C+GP
				GP-A	GP-B			%	(kg)	
LCCM	CR-2		331.0	956.64		848.0	178.74	-		0.54
	A5-2	B5-2	314.5	953.01	952.97	848.0	178.74	5	16.55	0.54
	A10-2	B10-2	297.9	949.43	949.36	848.0	178.74	10	33.10	0.54
HCCM	CR-3		490.0	838.67		776.31	200.9	-		
	A5-3	B5-3	465.5	833.33	833.28	776.31	200.9	5	24.5	0.41
	A10-3	B10-3	441.0	828.0	827.89	776.31	200.9	10	49.0	0.41
	A15-3	B15-3	416.5	822.66	822.51	776.31	200.9	15	73.5	0.41

2.3. Mixture proportion and casting

To meet the research objectives, twelve mixtures were prepared and cast. The composition and labeling of the concrete mixtures used in this study are presented in Table 3. The mixtures were made using a 0.08 m^3 electric tilting mixer following the procedures in ASTM C192 [35] standard.

2.4. Curing, preparation, and testing samples

The cylinders and prisms were prepared and cured under laboratory conditions in the structural laboratory of the Department of Civil Engineering, College of Engineering, University of Sulaimani-Iraqi Kurdistan. After 24 hours of casting, the specimens were demolded and submerged in a water-curing tank at 23 ± 2°C, as recommended by ASTM C192 [35] until the time of the test.

In general, four sets of specimens were prepared for each mixture, and each set of specimens consisted of three individual specimens. The first set was used for the 28-day compressive strength test. The other three sets were used to test the 180-day Compressive strength and elastic modulus, splitting tensile, and flexural strength. The test result for each set was obtained by averaging the specimens' values of that set. Additional details on the tests, the total number, and the size of the specimens used in this study are provided in Fig. 4. Figure 5 shows the experimental work and tests performed on hardened concrete specimens with and without GP.

The samples were tested using a universal testing machine (CONTROLS type) with a maximum capacity of 4000 kN. The loading rate used for testing compressive and elastic modulus, flexural strength, and splitting tensile strength was 0.275 MPa/s, 0.02 MPa/s, and 0.023 MPa/s, respectively. The flexural tensile strength was conducted using a third-point loading test.

Two electrical resistance strain gauges of type (BX 120-80 AA) were used to obtain strain measurements for each cylindrical specimen used to test the elastic modulus. The strain gauges were symmetrically fixed at the center of the concrete cylinder's height using a high-performance adhesive. Stress and the corresponding strain values were measured using the data acquisition system (Microlink 851). Graphic displays were obtained using the data acquisition software "Windmill Software". Elastic modulus was then determined following ASTM C469 specification [36].

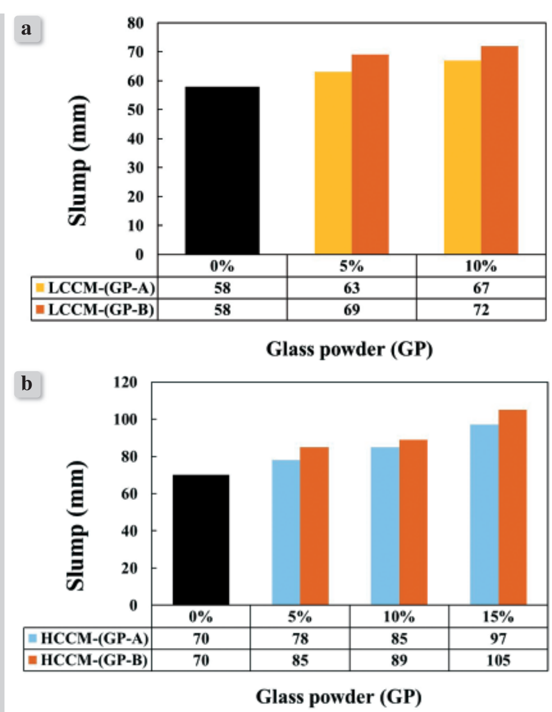

Figure 6.
Effect of particle size of GP with various percentages on the workability of concrete made of: (a) relatively low cement content (LCCM), (b) relatively high cement content (HCCM)

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1. Sump test (ASTM C143 [46])

The slump test results for all mixtures containing GP-A and GP-B and compared with the control mixture are shown in Fig. 6. The test results showed that, regardless of the GP particles' size, there is a systematic increase in workability with an increase in GP replacement. Both GP particle sizes have the same increasing trend. The non-absorbent nature and glassy surface of GP can be considered significant factors in increasing concrete workability [28, 43, 44].

It was also found that, at the same percentage of substitution, the finer-GP (GP-B) yields a relatively higher slump value than the coarse-GP (GP-A).

3.2. Compression strength (ASTM C39 [37])

Figures 7 through 10 illustrate the short-term (28-day) and long-term (180-day) effects of the use of GP-A and GP-B for cement substitution on the compressive strength of concrete with relatively low and high cement content. From Fig. 7, at 28 days of testing and no matter the size of the GP particle, the use of GP in the relatively low cement content mixtures (LCCM) results in a reduction in compressive strength, and the reduction is proportional to the replacement percentage. However, for the relatively high cement content mixtures (HCCM), the compressive strength of mixtures containing 5% of GP-B and GP-A was found to increase by 5.5% and 1.2% compared to the control mix, respectively, as shown in Fig. 8. It was also found that the use of more than 5% GP, independent of the particle size of GP, reduces the compressive strength at 28 days.

From the long-term test results (180-days) (Fig. 9), as the curing ages increased, the compressive strength development of LCCM modified with GP-B increases more evidently compared to the control mix. The compressive strength of the mixture modified with 5% of GP-B is almost equal to that of the control mix. However, the compressive strength of mixtures containing 10% of GP-B exceeds the control mixture by 3.04%. In contrast to GP-B, the 180-day compressive strength values of the mixtures modified with 5% and 10% GP-A remain below the control mix value by approximately 5%.

Referring to Fig. 10, For HCCM, using GP-A and GP-B as cement replacement improves the 180-day compressive strength other than a mixture containing 5% of GP-A, where the compressive strength decreased slightly by 1.95% compared to the control mixture.

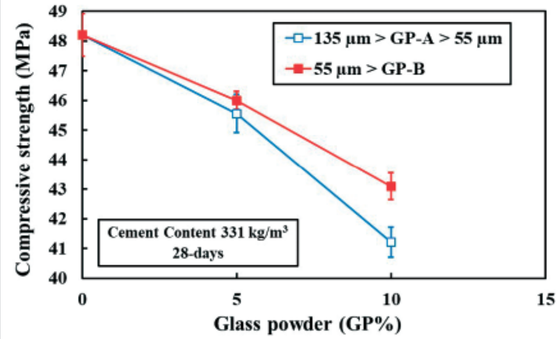

Figure 7.
Short-term effect of GP-A and GP-B with various replacements on compressive strength development when cement content is relatively low (331 kg/m^3)

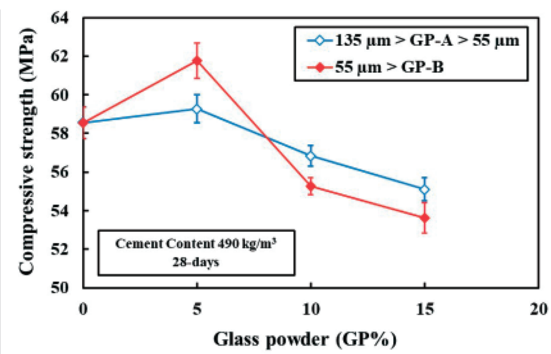

Figure 8.
Short-term effect of GP-A and GP-B with various replacements on compressive strength development when cement content is relatively high (490 kg/m^3)

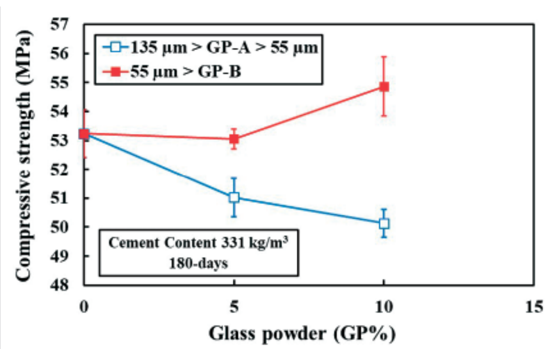

Figure 9.
Long-term effect of GP-A and GP-B with various replacements on compressive strength development when cement content is relatively low (331 kg/m^3)

From the results (Table 4), Both GP-A and GP-B were found to have approximately similar strengths and performance at 28 and 180 days. Considering HCCM and 180-days, the acceptable dosage of GP to be used as a cement replacement independent of the GP particle size is 15%. In terms of LCCM and

Table 4.
Mechanical properties of GP cement replacement mixtures

Mix. type	Specimen Details	Strengths (MPa)			
		Compressive (28 days)	Compressive (180 days)	Splitting (180 days)	Flexural (180 days)
LCCM	CR-2	48.21	53.24	4.59	8.00
	A5-2	45.56	51.02	4.61	8.08
	A10-2	41.22	50.13	4.60	7.80
	B5-2	46.00	53.06	4.68	8.15
	B10-2	43.09	54.86	4.74	8.18
HCCM	CR-3	58.56	64.61	4.45	7.60
	A5-3	59.27	63.35	4.49	7.63
	A10-3	56.84	67.56	4.75	7.65
	A15-3	55.10	65.92	4.65	7.60
	B5-3	61.78	64.98	4.56	7.68
	B10-3	55.26	66.38	4.72	7.63
	B15-3	53.62	65.61	4.61	7.55

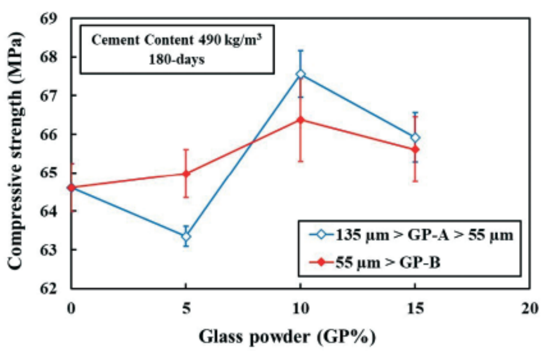

Figure 10.
Long-term effect of GP-A and GP-B with various replacements on compressive strength development when cement content is relatively high (490 kg/m^3)

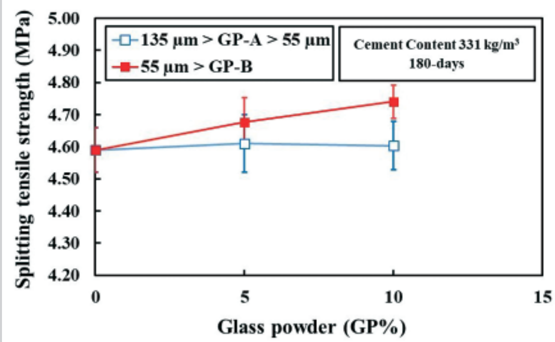

Figure 11.
Long-term effect of GP-A and GP-B with various replacements on splitting tensile strength development when cement content is relatively low (331 kg/m^3)

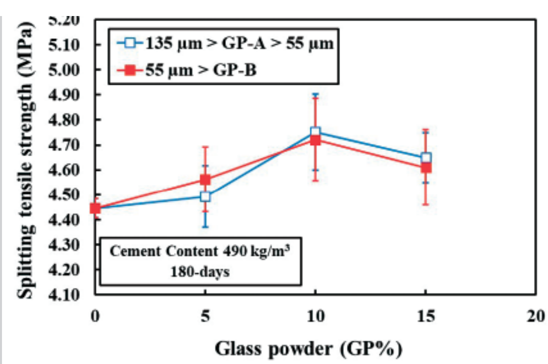

Figure 12.
Long-term effect of GP-A and GP-B with various replacements on splitting tensile strength development when cement content is relatively high (490 kg/m^3)

180-day testing age, the optimal dosage of GP to replace cement regardless of GP particle size is 10%. Although GP-A and GP-B had approximately similar strengths at 28 days, the improved performance of the finer GP (GP-B) compared to GP-A can be seen at 180 days of testing.

In general, the enhanced compressive strength of GP-modified concrete after 28 days is mainly due to the secondary pozzolanic reaction and micro filler effect of GP particles, whereby they contribute to the densification of the matrix and interface zone, which reduces porosity and improves concrete performance [23]. However, GP's pozzolanic response at 28 days is low, showing only the inert filler effect of GP particles before the progression of the pozzolanic reaction of GP occurs at a later age.

3.3. Splitting tensile strength (ASTM C496 [38])

The cracking and deflection behavior of the concrete members can be indicated by understanding their tensile strength. Therefore, the splitting and flexural tensile strength of the concrete are essential parameters for the flexural and shear members' design. Figures 11 and 12 show the results of the effect of the use of GP-A and GP-B with different levels of

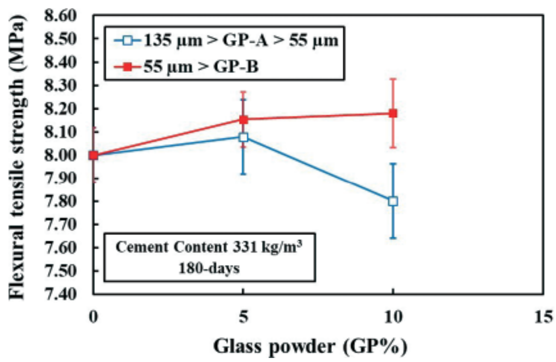

Figure 13.
Long-term effect of GP-A and GP-B with various replacements on flexural tensile strength development when cement content is relatively low (331 kg/m^3)

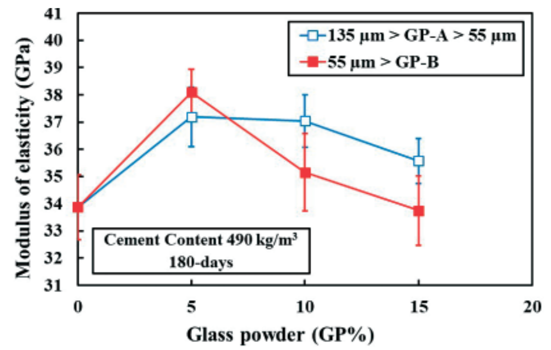

Figure 16.
Long-term effect of GP-A and GP-B with various replacements on elastic modulus when cement content is relatively high (490 kg/m^3)

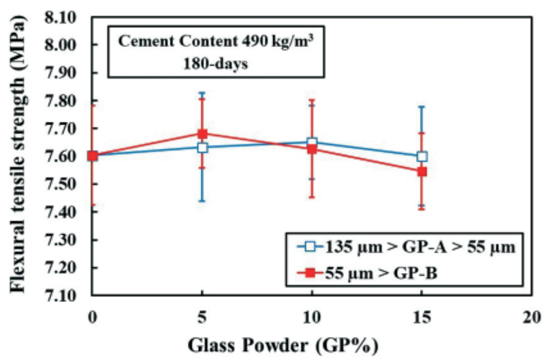

Figure 14.
Long-term effect of GP-A and GP-B with various replacements on flexural tensile strength development when cement content is relatively high (490 kg/m^3)

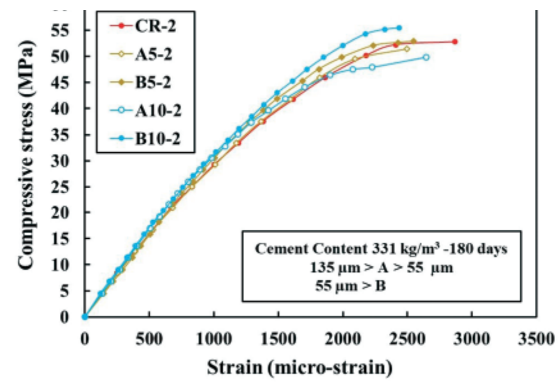

Figure 17.
Effect of GP-A and GP-B with various replacements on non-linear stress-strain curves of concrete with a relatively low cement content (331 kg/m^3)

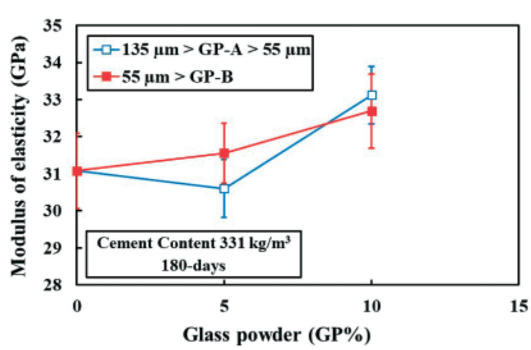

Figure 15.
Long-term effect of GP-A and GP-B with various replacements on elastic modulus when cement content is relatively low (331 kg/m^3)

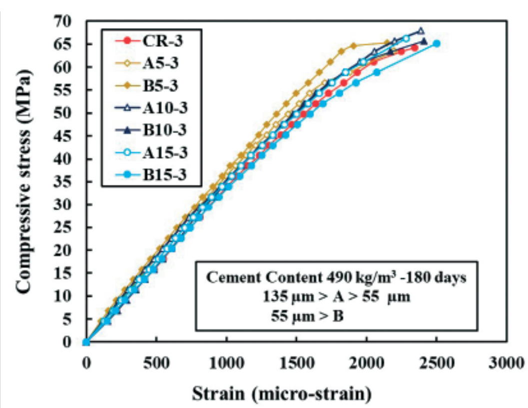

Figure 18.
Effect of GP-A and GP-B with various replacements on non-linear stress-strain curves of concrete with a relatively high cement content (490 kg/m^3)

replacement on the 180-day splitting tensile strength of concrete containing low and high content of cement, respectively. The results generally showed that using GP-A and GP-B for LCCM and HCCM enhanced the splitting tensile strength of concrete. It was observed that the particle size distribution has no significant contribution to the enhancement of the splitting tensile strength compared to the amount of GP replacement. The maximum difference between the splitting tensile strength value of GP-A modified concrete and the corresponding GP-B is 0.14 MPa and 0.07 MPa for LCCM and HCCM.

Considering the maximum splitting tensile strength obtained, the optimum GP-A and GP-B replacement level is 10% for LCCM and HCCM, respectively. However, the optimal GP content for cement replacement was found to be 10% and 15%, respectively, for LCCM and HCCM compared to the reference mix.

Long-term splitting tensile strength results indicate that the use of GP up to 10% for LCCM and 15% for HCCM, regardless of its particle size, tends to improve concrete porosity through its pozzolanic reactivity.

3.4. Flexural tensile strength (ASTM C78 [39])

The results of the 180-day flexural tensile strength of GP-modified concrete with relatively low and high cement contents are shown in Figures 13 and 14. For LCCM, the increase in GP-B levels from 5% to 10% slightly improves the flexural tensile strength by 1.88% and 2.25% compared to the control mixture. In comparison, for GP-A, only a slight improvement was observed at 5% by 1%, and the flexural strength of the concrete mixture containing 10% of GP-A was slightly less than that of the control mixture by 2.5% (Fig. 13). The positive long-term effect of fine GP particles (GP-B) on the flexural strength of concrete can be seen when the use of GP is increased to more than 5%.

For HCCM (Fig. 14), using up to 10% GP-B and GP-A, the flexural tensile strength of concrete slightly improved, and beyond which, the flexural strength values are almost equal to that of the reference specimen. The size impact of GP on the flexural strength was observed to be insignificant. For instance, the maximum difference between the flexural strength of the concrete modified with GP-A and GP-B for the same GP amount is 0.05 MPa.

3.5. Elastic modulus

Figures 15 and 16 represent the size effect of GP replacing cement on the 180-day elastic modulus of concrete containing a relatively low and high cement content, respectively. From Fig. 15, it can generally be found that the replacement of cement by GP-A and GP-B in LCCM slightly increases the elastic modulus except for a mixture containing 5% GP-A, where the elastic modulus is almost the same as the control mixture. The optimal content of GP was determined to be 10%, for which the elastic modulus for GP-A and GP-B was 6.6% and 5.1% higher, respectively than the reference mixture.

In the case of HCCM, and whatever the size of the GP particles, using GP up to 15% improves elastic modulus except for mixture containing 15% GP-B, where the elastic modulus is almost the same as the control mixture (Fig. 16). Given the maximum elastic modulus obtained, the optimum GP level is 5% for which the elastic modulus for GP-B and GP-A was 12.49% and 9.80% higher, respectively than the reference mixture. Meanwhile, the acceptable GP dosage for cement replacement was found to be 15% for which the elastic modulus for GP-B was equal to the control mixture and 5.02% for GP-A was higher than the reference mixture..

The improvement in the elastic modulus of concrete modified with GP over the long term age was attributed to the pozzolanic activity of GP and the microstructure improvement of concrete [4, 30].

3.6. Compression stress-strain curves

Figures 17 and 18 represent the results of the 180-day compressive stress-strain behavior of low and high cement content mixtures modified with varying percentages of GP-A and GP-B.

Similar trends in stress-strain curves can generally be seen in all mixtures (with or without GP) of both HCCM and LCCM. Due to the brittle characteristics of all specimens, the descending part of the curve could not be defined in any of these specimens.

In terms of LCCM, Fig. 17, a relative improvement can be observed in the stress values for the same strain levels of the mixtures modified with 5% and 10% GP-B compared to that of the control mixture. The same improvement can be seen for mixtures modified with 10% GP-A up to approximately 85% of the peak stress, while the stress and the corresponding strain values for the mixture containing 5% GP-A are almost similar to those of the control mixture. The results generally imply that the increase in deformation of concrete specimens with GP was slower than that of the control specimen. The concrete specimens with fine GP (GP-B) exhibited less deformation in comparison with that of GP-A.

Regarding HCCM, Fig. 18, the mixture modified with 5% GP-B shows a steeper stress-strain curve (less deformation) than any other mixtures, while that with 15% GP-B displays more deformation. For the given compressive stress and except a mixture containing 15% GP-B, the GP-containing mixture shows a rela-

Table 5.
Results of the average value of the two tested cylinders used for calculating the modulus of elasticity and compression toughness at 180 days of testing

Mix. type	Specimen detail	w/b	Compressive strength (MPa)	Modulus of elasticity (GPa)	Toughness (MPa x 10^{-2})	Specific Toughness (%)	Peak strain (micro-strain)
LCCM	CR-2	0.54	52.76	31.08	9.950	0.189	2870
	A5-2	0.54	51.40	30.60	7.990	0.155	2495
	A10-2	0.54	49.85	33.12	8.790	0.176	2645
	B5-2	0.54	52.86	31.56	8.540	0.162	2549
	B10-2	0.54	55.45	32.69	8.290	0.150	2436
HCCM	CR-3	0.41	64.25	33.87	8.600	0.134	2341
	A5-3	0.41	63.50	37.19	8.106	0.128	2196
	A10-3	0.41	67.91	37.04	9.360	0.138	2388
	A15-3	0.41	66.29	35.57	8.610	0.130	2283
	B5-3	0.41	65.34	38.10	8.240	0.126	2147
	B10-3	0.41	65.76	35.15	9.270	0.141	2407
	B15-3	0.41	65.12	33.75	9.430	0.145	2502

tively small strain compared to the control mixture, indicating that the use of GP serves to make the concrete relatively stiffer under the compression load.

3.7. Compression toughness

Generally, compression toughness reveals the property of energy absorption and damage resistance when the material is damaged by compression. In this study, the compression toughness was obtained by calculating the area under the stress-strain curve to the ultimate stress value [40]. The specific toughness in (%) was also determined by calculating the ratio of toughness to compression strength [41, 42]. Table 5 shows the results of compression toughness and specific toughness in (%) attained from different concrete mixtures with a maximum corresponding strain.

The 180-day results of compression toughness of the concrete mixtures with a relatively low cement content (LCCM) indicate that the use of GP reduces the compression toughness relative to the control mixture, and the maximum reduction was observed when the percentage replacement of GP-A and GP-B is 5% and 10%, respectively. However, for HCCM, using GP up to 5% reduces the compression toughness of concrete, whereas the increase in GP-A and GP-B levels from 5% to 15% enhances the compression toughness. The maximum compression toughness was achieved when the GP-B and GP-A contents were 15% and 10%, respectively.

The relative reduction in the toughness of the concrete specimens with GP compared to the plain concrete (without GP) in LCCM could be due to a slower dissipation of the absorbed energy in the plain concrete than the specimens with GP during failure. This is due to the lower compressive stiffness of plain concrete than specimens containing GP, which can be seen in the compressive stress-strain relationships (Fig. 17). However, in HCCM, the concrete strength of all mixtures is high (exceeding 55 MPa). The absorbed energy dissipation of high strength concrete during a failure is relatively higher than that of normal strength concrete. The same observations were made on GP-concrete specimens. However, the progression of GP's long-term reaction leads to an improvement in the internal microstructure of concrete (i.e., a relatively higher compressive strength and stiffness), thereby the compression toughness of concrete specimens containing GP above 5% was relatively higher than that of free-GP concrete.

4. CONCLUSIONS

In this paper, a comprehensive experimental study was conducted into the long-term effect of two different grain size distributions of GP as a partial cement replacement by weight on the mechanical behavior of concrete made from two different cement contents. Based on the results obtained, the following findings can be observed:

1. Generally, there is a clear improvement in the compressive strength of GP-modified concrete over the long-term age (180-days) compared to that of the early age (28-days).
2. In contrast to the GP substitution amount, the contribution of the GP particle sizes to the improve-

ment of compressive strength, tensile strength, and elastic modulus was generally found to be small.

3. Long-term tensile strength (splitting and flexural) results have generally indicated that using GP up to 10% for LCCM and 15% for HCCM, regardless of its particle size, can be used in concrete structures without underestimating their tensile performance.
4. All specimens tested showed the same stress-strain and brittle failure patterns. Besides, the use of GP contributes to making concrete relatively stiffer under compression load compared to GP-free concrete.
5. Irrespective of the size of the GP particles, it was observed that the maximum elastic modulus was attained for mixtures modified with 10% and 5% of GP for LCCM and HCCM, respectively. However, mixtures containing up to 10% for LCCM and up to 15% for HCCM exhibited an equal or slightly better elastic modulus compared to the reference mixture
6. In the case of LCCM, the compression toughness of GP-concrete specimens was found to be less than that of GP-free specimens, while in the case of HCCM, the compression toughness was shown to increase when the GP replacement levels were 10% and 15%.
7. Overall, the results show that incorporating 10% GP for LCCM and 15% of GP for HCCM with a particle size of less than 135 μm has a positive effect on the long-term mechanical behavior of concrete, indicating that GP can be used as a partial cement replacement material.

For further research, an experimental work should be carried out on the effect of various waste GP contents with different particle size distributions on the microstructural and mechanical performance of concrete subject to alternate wetting and drying conditions. Further work is also recommended to investigate microstructural, mechanical, and durability assessments of GP-concrete subject to sulfate attacks, different curing temperatures and conditions.

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