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Utilization of waste glass powder in the production of cement and concrete

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HIGHLIGHTS

- Waste glass powder was added up to 25.0% as cement replacement and cement addition.
- The pozzolanic activity of waste glass powder was detected according to ASTM C311.
- Waste glass powder has a significant effect on concrete properties.
- Results are expected to provide a motivation to use waste glass powder on concrete.

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ABSTRACT

The aim objective of this work is to study of the use of waste glass powder obtained from grinding of crushed containers and building demolition to produce glass powder blended cement as concrete additives. The pozzolanic activity of glass powder and properties of glass powder blended cement were evaluated. Also, the effect of using glass powder as cement replacement and as cement addition was studied in the term of physical and mechanical properties. The considered glass powder contents were 0.0%, 5.0%, 10.0%, 15.0%, 20.0% and 25.0% by weight of cement. The test results showed that the glass powder had pozzolanic characteristic and the use of glass powder had insignificant effect on setting time and cement expansion. The use of 10% glass powder as cement replacement enhanced the mortar compressive strength by about 9.0%. Also, generally, the use of glass powder as cement replacement up to 15.0% enhanced the properties of concrete modified with glass powder. Finally, the use of 15% glass powder as cement addition increased concrete compressive strange by 16.0% in average and achieved better performance compared with as cement replacement.

1. Introduction

Concrete, a primary building construction material, is the world's most consumed man-made material. About 800 million tons of concrete was consumed in the U.S. in 2007, and the world consumption was estimated at 11 billion tons, or approximately 1.7 tons for every living human being [1]. Production of cement (the binder in concrete) is an energy-intensive and highly polluting process, which contributes about 5–8% to global CO_2 emissions [2]. This high contribution is due to that production of each ton of cement emits one ton of carbon dioxide (CO_2) to the atmosphere from both of fuel and cement raw material burning [3–6]. The use of solid waste materials or industrial by-products as partial replacement for cement in concrete is a viable strategy for reducing the use of Portland cement, and thus reducing the environmental and energy impacts of concrete production [7].

In Egypt, about 3.45 million tons of waste glass is generated annually and 84% of which is lift in landfills [6]. Fig. 1 shows the wastes of glass in solid resulted from crushed containers, constructions and demolishing in Egypt. Waste glass can be cost-effectively collected in mixed colors. According to Federico and Chidiac, and Jin et al. [8,9], mixed-color waste glass offers desired chemical composition and reactivity for use as a supplementary cementitious material which can benefit the chemical stability, moisture resistance and durability of concrete. To realize this potential, waste glass needs to be milled to micro-scale particle size in order to accelerate its beneficial chemical reactions in concrete.

According to the previous studies in the use of glass powder in concrete production, there were contradictions in the available test results. These contradictions involved fresh and hardened proprieties of concrete modified with glass powder.

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Fig. 1. Wastes of glass in solid form resulted from crushed containers and construction demolishing in Egypt.

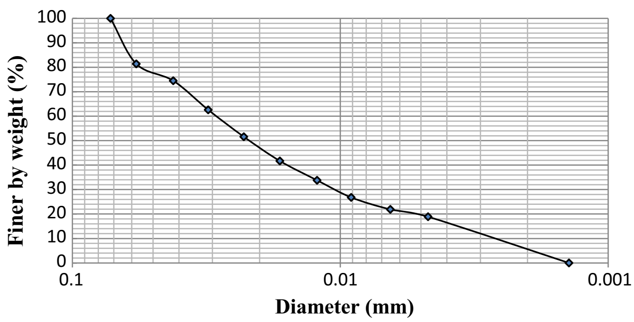


Fig. 2. Grain size analysis of used glass powder.

For fresh state of concrete, Kumarappan [10] presented that there is a systematic increase in the concrete slump as the glass powder passed through 300 μm sieve in the mix increase. The slump ranged from around 40 mm for the reference mix from 0% glass powder to 160 mm at 40% glass powder. Khatib [11] showed that there was a systematic increase in the slump as the glass powder content in the mix increase. Khatib did not mention the size distribution of used glass powder. Chikhalikar [12] investigated on the characteristics properties of fiber reinforced concrete containing 600 μm waste glass powder. Chikhalikar concluded that there is an enhancement in concrete slump is observed up to 40% glass powder as cement replacement. Soroushian [13] utilized milled 13 μm waste glass powder and resulted that slump is

Table 1
Grading and ASTM C33-04 specification limits of used aggregates.

Sieve size (mm)		25.00	19.00	12.0	9.50	4.75	2.36	1.18	0.60	0.30	0.10
Sand	Used sand	100	100	100	100	99	96	80	58	22	5
	Specification limits	100	100	100	100	95:100	80:100	50:85	25:60	5:30	0:10
Coarse aggregate	Used coarse aggregate	100	100	96	45	9	0	0	0	0	0
	Specification limits	100	100	90:100	40:70	0:15	0	0	0	0	0

Table 2
Chemical analysis of Portland cement and glass powder.

Component	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	CL^-	L.O.I
Cement	21.73	3.60	1.50	63.20	3.20	2.50	0.27	0.96	0.03	1.90
Glass powder	71.40	2.54	0.37	11.2	1.60	0.16	0.36	12.25	0.04	0.82

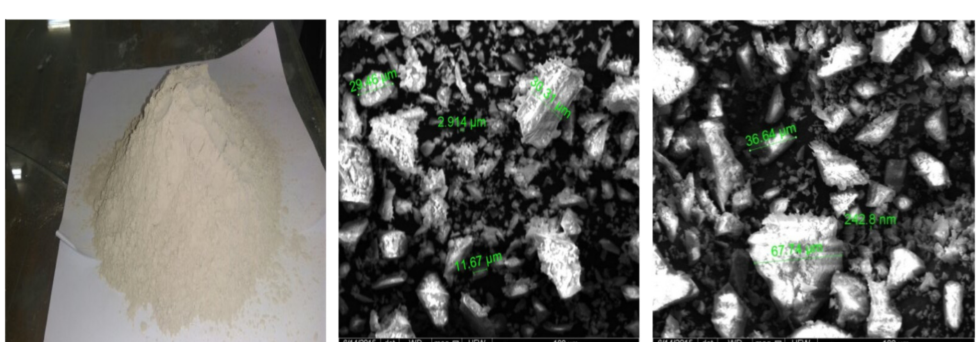


Fig. 3. Particle shape and size of glass powder grains.

Table 3
Proportions of concrete mixtures.

Mix no.	Notes	Cement (kg/m^3)	Glass powder (%)	Glass powder (kg/m^3)	Water content (kg/m^3)	w/cementitious ratio	Sand (kg/m^3)	Coarse aggregate (kg/m^3)
1	Control Mix 1	350	0.0	0	175.0	0.50	723	1084
2	Cement Replacement	332.5	5.0	17.5	175.0	0.50	721	1082
3		315.0	10	35.0	175.0	0.50	720	1080
4		298.0	15	52.0	175.0	0.50	718	1078
5		280.0	20	70.0	175.0	0.50	717	1076
6		262.5	25	87.5	175.0	0.50	716	1074
7	Cement Addition	350.0	5.0	17.5	175.0	0.50	716	1073
8		350.0	10	35.0	175.0	0.50	709	1063
9		350.0	15	52.0	175.0	0.50	702	1053
10		350.0	20	70.0	175.0	0.50	695	1042
11		350.0	25	87.5	175.0	0.50	688	1032
12	Control Mix 2	450.0	0.0	0	157.5	0.35	706	1059
13	Cement Replacement	427.5	5.0	22.5	157.5	0.35	704	1056
14		405.0	10	45.0	157.5	0.35	703	1054
15		382.5	15	67.5	157.5	0.35	702	1052
16		360.0	20	90.0	157.5	0.35	700	1050
17		337.5	25	112.5	157.5	0.35	698	1048
18	Cement Addition	450.0	5.0	22,5	157.5	0.35	697	1045
19		450.0	10	45.0	157.5	0.35	688	1032
20		450.0	15	67.5	157.5	0.35	679	1019
21		450.0	20	90.0	157.5	0.35	670	1005
22		450.0	25	112.5	157.5	0.35	661	992

Table 4
The standard used and age of testing.

Properties	Specifications	Age of testing
Slump	ASTM C 143	After mixing
Compressive strength	BS 1881: Part 3	7, 28, 56 days
Splitting tensile strength	ASTM C 496	7, 28, 56 days
Density, absorption and voids ratio	ASTM C642	56 days

observed to slightly increase with milled waste glass powder content increase. On the contrary, Vandhiyan [14] test results showed that the use of glass powder has a negative effect on concrete workability. Vandhiyan used angular shape of glass powder passes through 90 μm sieve and 50% retained in 75 μm sieve.

For hardened concrete properties, there are variations in the effect of glass powder in concrete compressive strength (the best contents of glass powder content). Kumarappan and Khatib [10,11] concluded that there is an improvement in concrete compressive strength is observed up to 10.0% glass powder cement replacement. Vandhiyan [14] studied the replacement of cement by waste glass powder and concluded that the considerable increase in the early strength gain particularly at specimen containing 15% glass powder gave a 29% increase in the strength at 7 day more than control specimen. At 28 day this difference in strength reduces to 23%. The strength increment is optimal at 10% replacement. Dali [15] studied the effect of glass powder sieved through 600 μm sieve and observed that the compressive strength increment is observed up to 25% replacement of cement, but the peak of increment is at 20% replacement. Patil [16] used glass powder with particle size less than 90 μm through an experimental work and concluded that there is an improvement in concrete compressive strength is observed up to 10.0% glass powder cement replacement. The test results of Vasudevan [17] showed that the use of glass powder up to 20.0% enhanced the concrete compressive strength. Moreover, Chikhalikar [12] observed that the concrete compressive strength increases as a result of glass powder cement replacement up to 20.0% and Vijayakumar [18] concluded that using 75 μm sieved glass powder up to contents of 40.0% enhanced concrete compressive strength.

The pervious behavior of concrete compressive strength of concrete modified with glass powder as cement replacement also observed in tensile and flexure strengths [6,12,14,15,18]. Finally, there are limit works on pozzolanic effect of glass powder material and the behavior of concrete modified with glass powder as cement addition.

2. Research significance

Due to the contradictions and variations of the available test results of concrete modified with glass powder, this work presents

Table 5
Physical and chemical properties of glass powder compared with ASTM C618 requirements.

Component	Percentage of used glass powder	Limits (%)		
		N	F	C
Silicon dioxide (SiO_2) plus aluminum oxide (Al_2O_3) plus iron oxide (Fe_2O_3), min %	74.31	70	70	50
SO_3	0.16	4	5	5
Loss on ignition, max %	0.82	10	6	6
pH	11.30			
Moisture content, max %	2.00	3	3	3
Amount retained when wet-sieved on 45 μm (No. 325) sieve, Max %	23.20	34	34	34
Strength activity index With Portland cement, at 7 days, min, percent of control	83.38	75	75	75
Strength activity index with Portland cement, at 28 days, min, percent of control	87.12	75	75	75

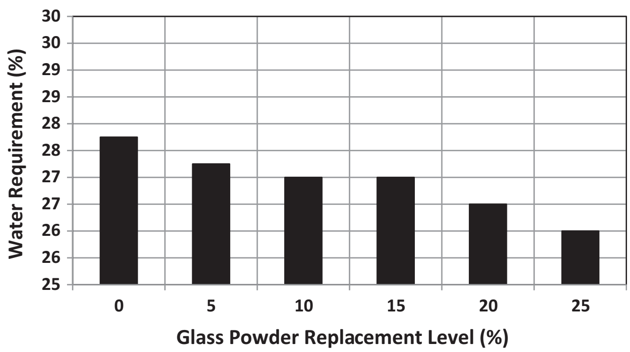


Fig. 4. Water requirement for standard Portland cement pastes modified with glass powder as cement replacement.

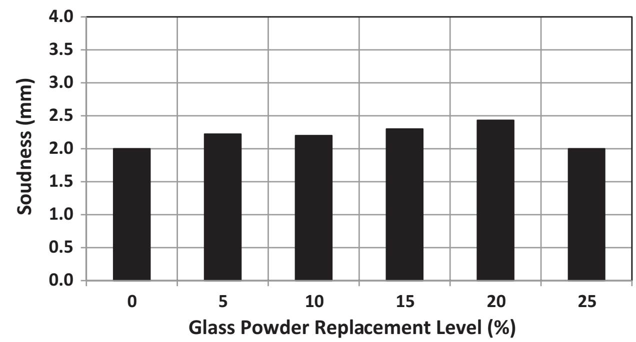


Fig. 6. Soundness of Portland cement pastes modified with glass powder as cement replacement.

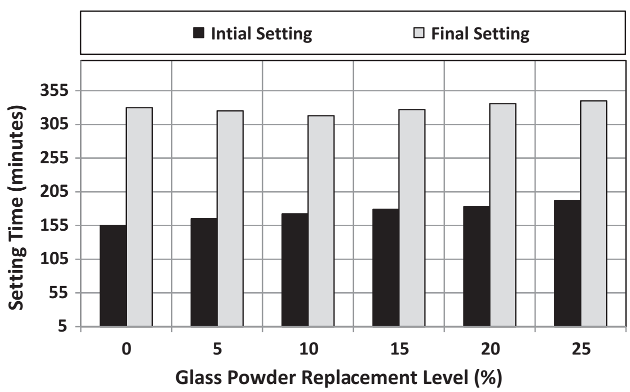


Fig. 5. Setting times of Portland cement pastes modified with glass powder as cement replacement.

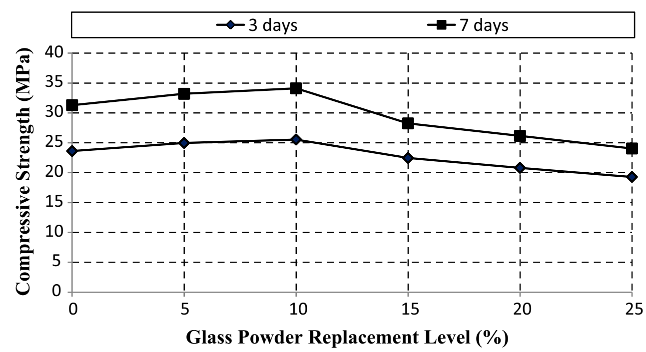


Fig. 7. Effect of glass powder cement replacement on mortar compressive strength.

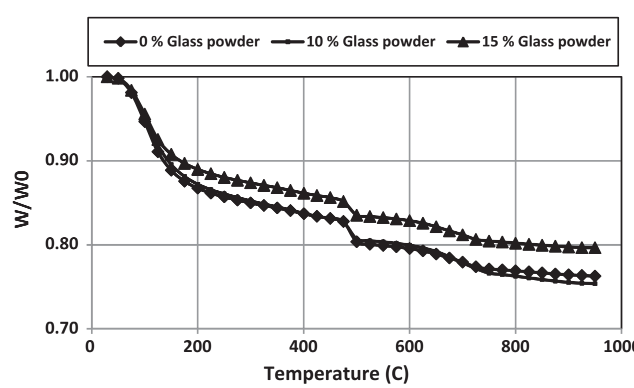


Fig. 8. Thermo-gravimetric analysis (TGA) curves of pastes samples modified with glass powder.

an experimental program to study in details the effect of glass powder in concrete properties. The suggested scenario involves three phases to study the effect of concrete in concrete industry. These phases include evaluation the pozzolanic effect of glass powder itself where the second phase involves studying the properties of glass powder blended cement. Finally, the third phase interested in the properties of concrete modified with glass powder. This third phase involves glass powder as cement replacement and as cement addition due to the lack of the available data on the performance of concrete modified with glass powder as cement addition.

It is important to note that this research does not address alkali silica reaction which is a major criterion for the glass powder in concrete.

Table 6
Compressive strength test results of mortar.

Age	Replacement level	Experimental test results (Mpa)			Average (MPa)	Standard deviation (MPa)	Coefficient of variation (%)
		Specimen No. 1	Specimen No. 2	Specimen No. 3			
3 days	0	24.06	23.32	23.48	23.62	0.39	1.65
	5	24.58	24.72	25.64	24.98	0.58	2.31
	10	25.46	25.74	25.45	25.55	0.16	0.64
	15	22.52	22.08	22.81	22.47	0.37	1.64
	20	20.62	21.6	20.21	20.81	0.71	3.43
	25	19.27	18.68	19.92	19.29	0.62	3.22
7 days	0	31.68	32.48	29.74	31.30	1.41	4.50
	5	33.06	32.68	33.86	33.20	0.60	1.81
	10	34.56	33.96	33.80	34.11	0.40	1.16
	15	29.70	28.01	27.04	28.25	1.35	4.77
	20	25.07	26.64	26.74	26.15	0.94	3.58
	25	24.25	23.86	24.04	24.05	0.20	0.81

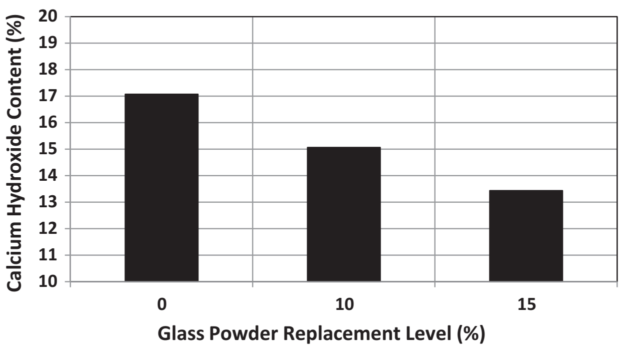


Fig. 9. Calcium hydroxide contents of pastes samples modified with glass powder.

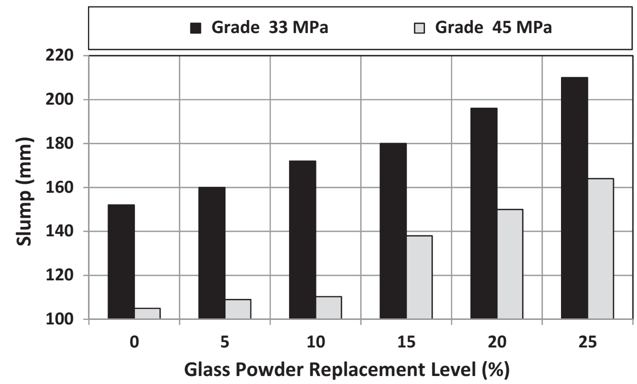


Fig. 10. Effect of using glass powder as cement replacement on concrete slump.

3. Materials, experimental program and testing

3.1. Materials

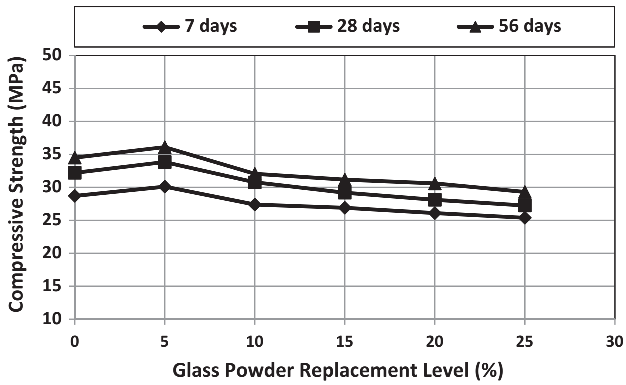
Natural siliceous sand with 2.4 fineness modulus and crushed pink lime stone with 12.5 mm nominal maximum aggregate size were used as a concrete aggregates. The used aggregate satisfied the ASTM C33-04 specification limits. Table 1 presents the grading and specification limits of used aggregates. Ordinary Portland cement according to ASTM C150 was used. This type of cement satisfies also the limits of ESS 2421-1993 specification limits. Chemical analysis of used cement is presented in Table 2. Glass powder with particles finer than 75 μm and 2.62 specific gravity is used in this research work. This powder was prepared by sieving on sieve No. 200 (75 μm). The grading of used glass powder using hydrometer method is shown in Fig. 2. Chemical analysis of glass powder is presented in Table 2. The particle shape and size of glass powder using scanning electron microscope is shown in Fig. 3. Type G high range water reducing admixture according to ASTM C494 was used. Potable water was used for mixing and curing processes.

3.2. Experimental parameters

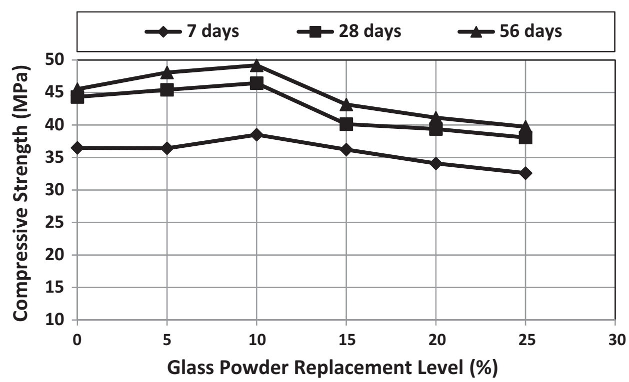
The experimental program extended in this research work through three phases. The first phase includes evaluation of pozzolanic effect of glass powder using strength activity index

Table 7
Compressive strength test results of glass powder cement replacement mixes.

Concrete grade	Age	Replacement level	Experimental test results (Mpa)			Average (MPa)	Standard deviation (MPa)	Coefficient of variation (%)
			Specimen No. 1	Specimen No. 2	Specimen No. 3			
33 Mpa	7 days	0	28.59	28.04	29.47	28.70	0.72	2.51
		5	30.38	29.98	29.95	30.10	0.24	0.80
		10	27.50	27.90	26.73	27.38	0.59	2.17
		15	26.41	26.68	27.58	26.89	0.61	2.28
		20	26.43	25.84	26.00	26.09	0.31	1.17
		25	25.30	25.42	25.41	25.38	0.07	0.26
	28 days	0	32.00	32.11	32.49	32.20	0.26	0.80
		5	34.09	34.01	33.41	33.84	0.37	1.10
		10	30.05	30.96	31.24	30.75	0.62	2.02
		15	29.91	29.01	28.63	29.18	0.66	2.25
		20	28.19	27.59	28.53	28.10	0.48	1.69
		25	28.04	27.59	26.09	27.24	1.02	3.75
	56 days	0	35.56	33.35	34.59	34.50	1.11	3.21
		5	35.71	35.79	36.78	36.09	0.60	1.65
		10	32.02	31.91	32.19	32.04	0.14	0.44
		15	31.28	30.99	31.19	31.15	0.15	0.48
		20	30.96	30.97	29.80	30.58	0.67	2.20
		25	29.99	29.30	28.59	29.29	0.70	2.39
45 Mpa	7 days	0	36.68	36.94	35.86	36.49	0.56	1.54
		5	35.59	36.40	37.27	36.42	0.84	2.31
		10	39.08	38.37	38.08	38.51	0.51	1.34
		15	36.23	36.29	36.16	36.23	0.07	0.18
		20	33.09	34.65	34.52	34.09	0.87	2.54
		25	33.02	33.00	31.78	32.60	0.71	2.18
	28 days	0	44.02	44.50	44.45	44.32	0.26	0.60
		5	45.42	45.39	45.45	45.42	0.03	0.07
		10	46.90	46.00	46.45	46.45	0.45	0.97
		15	40.02	39.97	40.42	40.14	0.25	0.61
		20	38.09	39.96	40.11	39.39	1.13	2.86
		25	38.00	37.96	38.29	38.08	0.18	0.47
	56 days	0	46.02	45.02	45.50	45.51	0.50	1.10
		5	47.09	48.00	49.14	48.08	1.03	2.14
		10	48.23	49.19	50.13	49.18	0.95	1.93
		15	43.10	43.10	43.25	43.15	0.09	0.20
		20	40.77	41.49	41.10	41.12	0.36	0.88
		25	38.89	39.73	40.58	39.73	0.85	2.13



(a) Concrete mix grade 33 MPa compressive strength



(b) Concrete mix grade 45 MPa compressive strength

Fig. 11. Concrete compressive strength test results of concrete modified with glass powder as cement replacement.

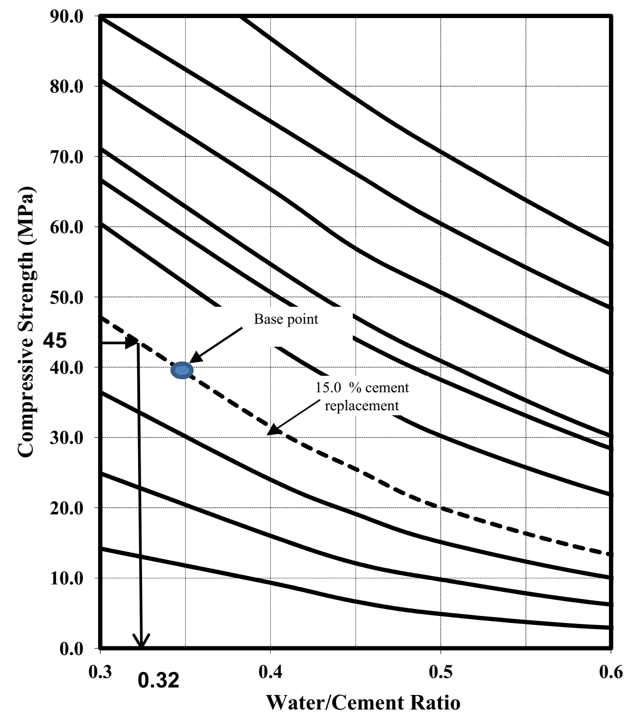


Fig. 12. Water/cement – compressive strength BS No. 882 design chart.

whereas phase two presents utilization of glass powder in cement production to produce glass powder blended cement. This phase includes tests carried out on powder, paste and mortars. In this phase, glass powder was used as cement replacement. The mix proportions of this phase were considered as Egyptian standard specification of cements ESS 2421-1993 for cement paste and cement mortar. For standard cement paste, the standard water content using Vicat test was used whereas for cement mortar, the ratio of cement sand ratio of 1:3 and 0.40 water cement ratio were used as presented in the same specification.

The effect of using glass powder in concrete production is presented through phase three. In this phase two grades of concrete compressive strength. These grades involve 28 days cube compressive strength of 33 MPa and 45 MPa. These strengths were achieved using 350 kg/m^3 and 450 kg/m^3 cement content with 0.50 and 0.35 water cement ratio, respectively. In this phase, glass powder was used as cement replacement and cement addition. The glass powder ratio in all phases were 0%, 5%, 10%, 15%, 20% and 25% either as cement replacement or cement addition. Mix proportions of the studied concrete mixes are given in Table 3. The dose of chemical admixture is kept constant for all concrete mixes (1.8% L by weight of cement).

3.3. Testing

As mentioned before, the research work divided into three phases. Each phase includes some related standard tests. Strength activity index according to ASTM C618 was investigated in phase one. For phase two, tests of cement which includes, water requirement for standard paste, setting time, soundness and compressive strength were conducted according to ESS 2421-1993. Thermo gravimetric analysis (TGA) at 28 days were investigated in this phase. In concrete phase (phase three), slump, compressive strength, splitting tensile strength, absorption, voids ratio and density were conducted. Table 4 presents the considered specification, test specimens and age of testing for concrete phase.

4. Test results and discussions

4.1. Pozzolanic effect of glass powder (phase one)

According to ASTM C618 specification limits, there are some requirements to consider the glass powder as pozzolanic material. These requirements include physical and chemical properties. Table 5 presents the properties of used glass powder and limits of ASTM C618.

Form Table 5, the chemical analysis and fineness fulfills the limits of ASTM C618 of pozzolanic materials. In addition to chemical and physical properties, strength activity index is required to consider the glass powder as pozzolanic materials. According to the requirement of ASTM C618, cement mortar modified with 20% glass powder as cement replacement should provide at least 75% of the strength of the control mortar (without glass powder) at both ages of 7 and 28 days to be considered as pozzolanic material. The strength activity index at the ages of 7 and 28 days are 83.38% and 87.12% respectively as presented in Table 5. From the previous test results, glass powder has pozzolanic properties and meets Class F and Class C (artificial pozzolanic materials) according to ASTM C618. The calcium oxide content of used glass powder according chemical analysis is 11.2% which meets the Class C pozzolanic materials. This means that the glass powder has a hydraulic effect in addition to its pozzolanic effect.

4.2. Properties of glass powder blended cement (phase two)

4.2.1. Water requirement, setting time and soundness

Portland cement performance is evaluated using some standard tests. The common tests are setting time, soundness (Le Chatelier method) and mortar compressive strength. The determination of setting time and soundness needs the value of water requirement to produce paste with the standard consistency. Fig. 4 shows the values of water requirement using Vicat test method corresponding to standard consistency for different glass powder cement replacement levels. From this figure, it is obvious that the use of glass powder as cement replacement decreases the water requirement percentage where the value of water of water requirement percentage decreases linearly with the increase of glass powder replacement level. From the test results, approximately, each 5% of glass powder cement replacement decreases water requirement by 0.4%. This behavior may be due to the glassy surface of glass powder grains or due to the coarser glass powder particles compared to cement particles. This behavior may enhance the concrete workability at the same mixing water content.

The effect of glass powder cement replacement on the initial and final setting time is shown on Fig. 5. From this figure, the glass powder replacement level has insignificant effect on the value of initial and final setting times. Also, it is noted that all values of setting times fulfill the limits of Egyptian standard ESS No. 2421 and ASTM C 150 of Portland cement. The value of initial setting time according to ESS and ASTM should not less than 45 min and the final setting time should not be greater than 600 min according to ESS 2421and 375 min according to ASM C 150.

Finally, the use of glass powder as cement replacement does not affect negatively the soundness of standard Portland cement pastes modified with glass powder as shown in Fig. 6. According to ESS 2421and ASTM C 150, the maximum allowable expansions is 10.0 mm, so all test samples with or without glass powder satisfy the limits of these standards. This behavior confirms that no considerable volume increase as a result of the presence of glass powder in the cement paste. This behavior may be due to the lower concentration of calcium oxide, magnesium oxide and sulfate content in glass powder material as shown in Table 2.

4.2.2. Compressive strength test results of glass modified mortar

According to the Egyptian standard specification ESS No. 2421 and ASTM C 150, mortar specimens are used to evaluate the compressive strength performance of cement. The test results of mortar compressive strength for individual samples, mean strength, standard deviation and coefficient of variation are tabulated in Table 6. Fig. 7 shows the test results of standard mortar modified with 0%, 5%, 10%, 15%, 20% and 25% glass powder cement replacement after 3 days and 7 days of water curing. From this figure, it is clear that the use of glass powder as cement replacement up to 10% improves slightly the mortar compressive strength at the considered ages. The increase of replacement level more than 10% decreases the mortar compressive strength. For example, after 7 days water curing, the increase in mortar compressive strength at 5% and 10% glass powder content is 6.1% and 9.0% whereas the reduction in mortar at 15%, 20% and 25% glass powder compressive strength is 9.7%, 16.5% and 23.2% compared with control mix. Also, compared with limits of ESS No. 2421, all studied mortar mixes achieve the minimum requirements of mortar compressive strength. This specification recommended that the value of 3 days and 7 days mortar compressive strength should be not be less than 18 MPa and 27 MPa, respectively.

Table 8
Tensile strength test results of glass powder cement replacement mixes.

Concrete grade	Age	Replacement level	Experimental test results (Mpa)			Average (MPa)	Standard deviation (MPa)	Coefficient of variation (%)
			Specimen No. 1	Specimen No. 2	Specimen No. 3			
33 Mpa	7 days	0	2.61	2.73	2.68	2.68	0.06	2.23
		5	3.04	3.00	3.26	3.10	0.14	4.48
		10	3.15	3.19	3.11	3.15	0.04	1.35
		15	2.79	3.02	2.94	2.92	0.12	4.03
		20	2.55	2.48	2.64	2.56	0.08	3.11
		25	2.21	2.31	2.26	2.26	0.05	2.38
	28 days	0	3.25	3.19	3.15	3.20	0.05	1.63
		5	3.62	3.68	3.88	3.73	0.14	3.71
		10	3.80	3.90	3.76	3.82	0.08	1.97
		15	3.34	3.39	3.43	3.39	0.05	1.34
		20	2.78	2.82	3.03	2.88	0.14	4.72
		25	2.72	2.75	2.80	2.76	0.04	1.46
	56 days	0	3.67	3.75	3.66	3.70	0.05	1.34
		5	4.30	4.27	4.28	4.28	0.02	0.40
		10	4.45	4.49	4.39	4.44	0.05	1.22
		15	3.75	3.90	3.91	3.85	0.09	2.29
		20	3.23	3.36	3.34	3.31	0.07	2.08
		25	3.25	3.19	3.24	3.22	0.03	1.03
45 Mpa	7 days	0	3.55	3.63	3.55	3.58	0.05	1.33
		5	3.79	3.89	4.12	3.93	0.17	4.35
		10	3.93	4.01	3.97	3.97	0.04	1.00
		15	4.24	4.36	4.28	4.29	0.06	1.35
		20	3.46	3.45	3.47	3.46	0.01	0.41
		25	3.46	3.27	3.45	3.39	0.11	3.14
	28 days	0	3.95	3.79	3.85	3.86	0.08	2.15
		5	4.35	4.17	4.41	4.31	0.13	2.93
		10	4.25	4.46	4.38	4.36	0.11	2.42
		15	4.48	4.66	4.54	4.56	0.09	2.03
		20	3.79	3.67	4.00	3.82	0.16	4.27
		25	3.67	3.72	3.92	3.77	0.13	3.58
	56 days	0	4.46	4.36	4.37	4.40	0.05	1.20
		5	4.69	4.77	4.94	4.80	0.13	2.65
		10	4.92	4.97	4.95	4.95	0.03	0.52
		15	4.96	5.34	5.15	5.15	0.19	3.68
		20	4.30	4.35	4.51	4.38	0.11	2.56
		25	4.34	4.20	4.48	4.34	0.14	3.19

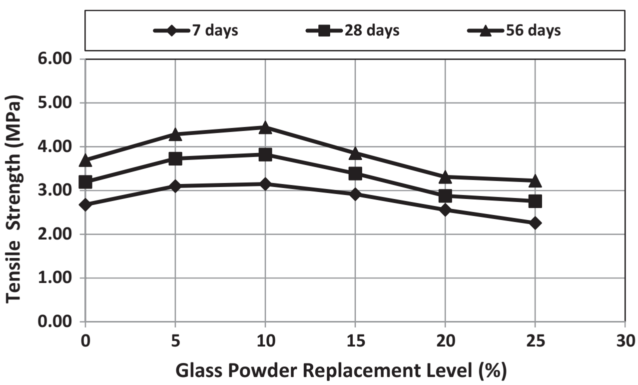
4.2.3. Thermo-gravimetric analysis (TGA)

Thermo-gravimetric analysis (TGA) is considered a precise quantitative measurement of the weight change percentage (W/W_o) of a solid as it is heated at a controlled rate. TGA test was conducted mainly to evaluate the difference in chemical phases in cement paste and to determine the calcium hydroxide (CH) content as a result of using glass powder as cement replacement. The amount of calcium hydroxide can be used to evaluate the pozzolanic effect of glass powder. Fig. 8 shows the test results of TGA test for control paste and cement pastes modified with 10.0% and 15.0% glass powder as cement replacement. From this figure, it is clear that all curves are almost similar and no observed difference between control paste and glass powder modified pastes. This means, no change in the chemical phases occurred due to the use of glass powder.

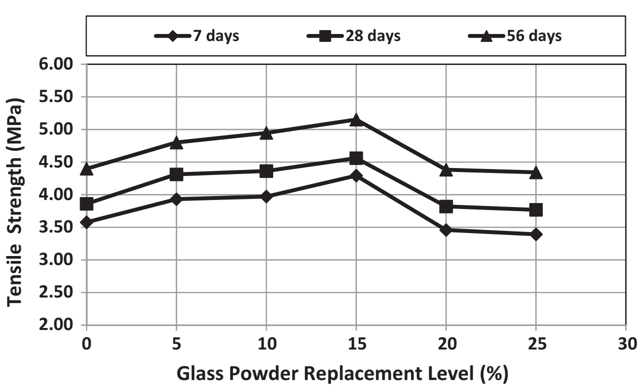
The effect of using glass powder on calcium hydroxide content is shown in Fig. 9. The calcium hydroxide content is determined using the drop in the TGA curve between 400 °C and 600 °C. Calcium hydroxide content can be calculated using the following equation:

$$CH\ (\%) = W_L \times (M_{CH}/M_w)$$

where W_L is the percentage weight loss occurred between 400 °C and 600 °C (the difference between w/wo at 400 °C and w/wo at 600 °C), M_{CH} is the molecular weight of calcium hydroxide (74.078 g/mol) and M_w is molecular weight of water (18 g/mol).



(a) Concrete mix grade 33 MPa compressive strength



(b) Concrete mix grade 45 MPa compressive strength

Fig. 13. Concrete tensile strength test results of concrete modified with glass powder as cement replacement.

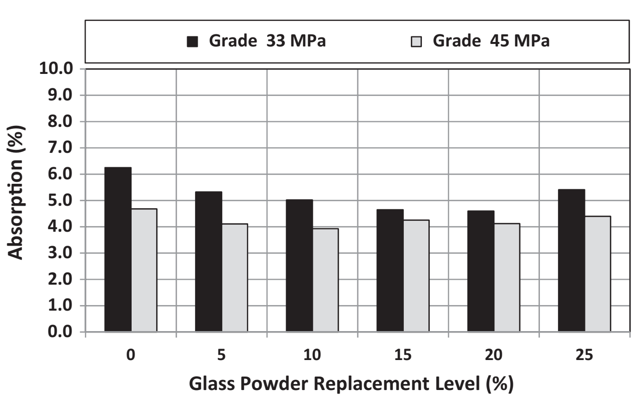


Fig. 14. Water absorption of concrete modified with glass powder as cement replacement.

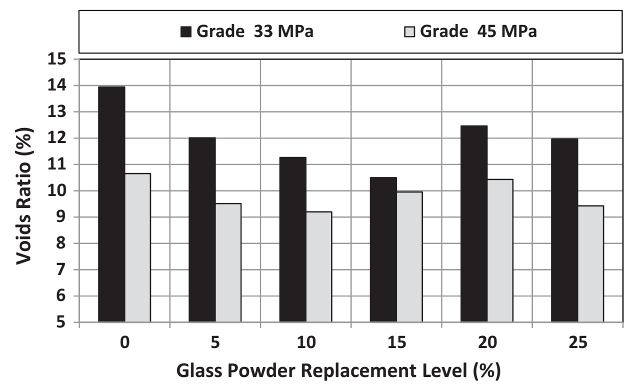


Fig. 15. Voids ratio of concrete modified with glass powder as cement replacement.

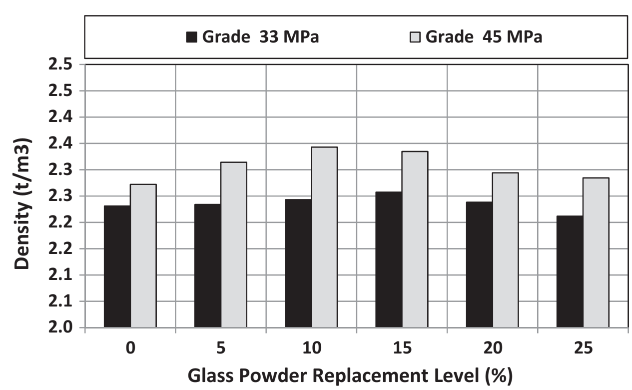


Fig. 16. Hardened density of concrete modified with glass powder as cement replacement.

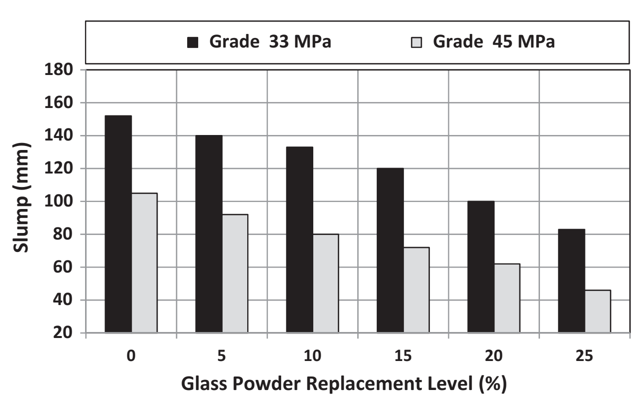


Fig. 17. Effect of using glass powder as cement addition on concrete slump.

From Fig. 9, it is clear that the glass powder cement replacement decreases the amount of calcium hydroxide content. This trend may be due to the reduction in cement content and may be due to the pozzolanic effect of glass powder (reaction between silicon oxide and calcium hydroxide). The analysis of test results confirms that the two mechanisms have occurred where the reduction percentage in calcium hydroxide as a result of using 10.0% glass powder is about 12.0% (if no pozzolanic effect occurred, the reduction percentage in calcium hydroxide should be 10% only). This behavior is also observed at 15.0% glass powder cement replacement where the reduction percentage in calcium hydroxide is about 21.0%. These results confirm the pozzolanic effect of glass powder as presented in Section 4.1.

4.3. Test results of glass powder modified concrete (phase three)

In this section, the performance of concrete modified with glass powder as cement replacement and as cement addition is evaluated in the terms of concrete slump, compressive strength, tensile strength, water absorption, voids ratio and density.

4.3.1. Effect of using glass powder as cement replacement

The concrete workability as a function of initial slump of concrete modified with glass powder as cement replacement is shown in Fig. 10. As mention before, the mixing water content and the amount of concrete chemical admixture were kept constant in each concrete grade. From the test results, it is noticed that the increase of glass powder cement replacement level increases concrete slump. This trend is the same for 33 MPa and 45 MPa concrete grade mixes. These results agree with the test results of water requirement to produce the standard consistency cement paste where the use of glass powder decreases the required water content to produce the same consistency. This behavior may be due to the glassy surface and low water absorption of glass powder or may be attributed to the coarser particles of glass powder compared with cement.

The test results of concrete compressive strength for mixes with glass powder as cement replacement for individual samples, mean strength, standard deviation and coefficient of variation are given in Table 7. The effect of using glass powder as cement replacement on cube concrete compressive strength (fc) at 7, 28 and 56 days is shown in Fig. 11. From this figure, it is clear that the use of 5.0% glass power as cement replacement enhances slightly concrete compressive strength for concrete mix grade 33 MPa where this value extends to 10% for 45 MPa concrete grade. This behavior is the same at different testing ages. Also, the use of glass powder as cement replacement greater than 10% has a negative effect on concrete compressive strength. This may be due to the lower content of Portland cement at higher glass powder replacement level. For example, for concrete with 45 MPa grade at 28 days, the reduction in concrete compressive strength is 9.4%, 11.1% and 12.5% for concrete modified with 15%, 20% and 25% glass powder as cement replacement compared with concrete without glass powder (control mix), respectively. This reduction in concrete compressive strength can be eliminated by decreasing concrete water/ cement ratio.

The required reduction in w/c ratio to increase the 28 days concrete compressive strength for glass powder cement concrete

Table 9
Compressive strength test results of glass powder cement addition mixes.

Concrete grade	Age	Replacement level	Experimental test results (Mpa)			Average (MPa)	Standard deviation (MPa)	Coefficient of variation (%)
			Specimen No. 1	Specimen No. 2	Specimen No. 3			
33 Mpa	7 days	0	28.59	28.04	29.47	28.70	0.72	2.51
		5	31.02	30.81	31.47	31.10	0.34	1.08
		10	32.90	31.54	33.06	32.50	0.84	2.57
		15	35.03	33.57	34.00	34.20	0.75	2.19
		20	29.03	29.50	29.97	29.50	0.47	1.59
		25	29.04	28.97	29.83	29.28	0.48	1.63
	28 days	0	32.00	32.11	32.49	32.20	0.26	0.80
		5	33.70	34.01	33.39	33.70	0.31	0.92
		10	37.33	37.29	36.08	36.90	0.71	1.93
		15	37.00	37.93	38.77	37.90	0.89	2.34
		20	33.12	32.84	33.04	33.00	0.14	0.44
		25	31.02	31.53	30.75	31.10	0.40	1.27
	56 days	0	35.56	33.35	34.59	34.50	1.11	3.21
		5	35.90	36.06	35.98	35.98	0.08	0.22
		10	39.62	38.90	39.68	39.40	0.43	1.10
		15	41.52	41.83	39.65	41.00	1.18	2.88
		20	34.45	34.60	33.70	34.25	0.48	1.41
		25	32.52	32.09	32.08	32.23	0.25	0.78
45 Mpa	7 days	0	36.68	36.94	35.86	36.49	0.56	1.54
		5	38.94	37.98	38.88	38.60	0.54	1.39
		10	39.94	38.93	38.73	39.20	0.65	1.65
		15	40.70	40.38	41.02	40.70	0.32	0.79
		20	42.68	41.82	40.90	41.80	0.89	2.13
		25	40.09	40.50	42.11	40.90	1.07	2.61
	28 days	0	44.02	44.50	44.45	44.32	0.26	0.60
		5	45.90	46.08	45.30	45.76	0.41	0.89
		10	46.84	46.99	46.69	46.84	0.15	0.32
		15	47.09	48.09	47.32	47.50	0.52	1.10
		20	49.92	49.21	48.50	49.21	0.71	1.44
		25	47.94	48.03	49.32	48.43	0.77	1.59
	56 days	0	46.02	45.02	45.50	45.51	0.50	1.10
		5	47.21	46.58	47.81	47.20	0.62	1.30
		10	48.50	48.62	49.16	48.76	0.35	0.72
		15	51.13	49.87	51.70	50.90	0.94	1.84
		20	55.06	54.03	55.43	54.84	0.73	1.32
		25	52.03	52.17	53.90	52.70	1.04	1.98

which affected negatively due to the use of high level of glass powder as cement replacement can be determined using the mix proportions design chart of British standard BS 882. For example, for 45 MPa concrete grade, the use of 15.0% glass powder as cement replacement reduces the 28 days concrete compressive strength to about 40 MPa. Using the BS 882 design chart at 40 MPa compressive strength and 0.35 w/c ratio (base point), a parallel curve to the original curves can be drawn as shown in Fig. 12. Using the drawn curve, the required w/c ratio to achieve 45 MPa is about 0.32. This means, it is enough to decrease the water cement ration by about 0.03 to cancel the negative effect of using 15% glass powder as cement replacement.

Table 8 presents the test results of concrete tensile strength for mixes with glass powder as cement replacement for individual samples, mean strength, standard deviation and coefficient of variation. The effect of using glass powder as cement replacement on concrete splitting tensile strength (f_t) for 33 MPa and 45 MPa concrete grade is shown in Fig. 13. From these test results, the positive effect of using glass powder as cement replacement extends to 15% on concrete tensile strength either for concrete having 33 MPa concrete grade or 45 MPa concrete grade. The optimum glass powder replacement level is 10.0% and 15.0% for 33 MPa and 45 MPa concrete grade level, respectively. The maximum achieved 28 days concrete tensile strength improvement is 19.5% and 18.1% for 33 MPa and 45 MPa concrete grade level, respectively.

The durability indices for glass powder modified concrete as cement replacement is studied in the term of water absorption and voids ratio, Figs. 14 and 15 show the absorption and the voids ratio of concrete modified with glass powder as cement replacement. From the test results, generally, the use of glass powder up to 15.0% decreases the water absorption and voids ratio. The reduction in absorption and voids ratio indicates to an improvement in concrete durability. This reduction explains the improvement in concrete mechanical properties up to 15.0% glass powder cement replacement. The change in voids ratio as a result of using glass powder has a direct effect on hardened concrete density as shown in Fig. 16. From this figure, the use of glass powder as cement replacement has significant effect on concrete density especially for concrete having 45 Mpa grade level.

4.3.2. Effect of using glass powder as cement addition

The effect of using glass powder as cement addition on initial concrete slump is shown in Fig. 17. From the slump test results, the use of glass powder as cement addition decreases concrete slump. Approximately, each 5.0% glass powder addition decreases the slump value by 10.0 mm. This trend may be due to the increase of fine material content which increase the cohesion of concrete mix and thus decrease the concrete slump. The reduction in concrete slump due to addition of glass powder can be eliminated by adding plasticizing chemical admixtures.

The test results of concrete compressive strength for mixes with glass powder as cement addition for individual samples, mean strength, standard deviation and coefficient of variation are given in Table 9. Compressive strength test results of concrete modified with glass powder as cement addition is shown in Fig. 18. From this figure, for concrete having 33 MPa grade, the addition of glass powder up to 15.0% increases the concrete compressive strength. The shifting of the optimum value of glass powder as cement addition may be due to the filling, pozzolanic and hydraulic effect of glass powder material. As an example, after 28 days water curing, this increase is 4.7%, 14.6% and 16.8% for concrete modified with 5.0%, 10.0% and 15.0% glass powder cement addition compared

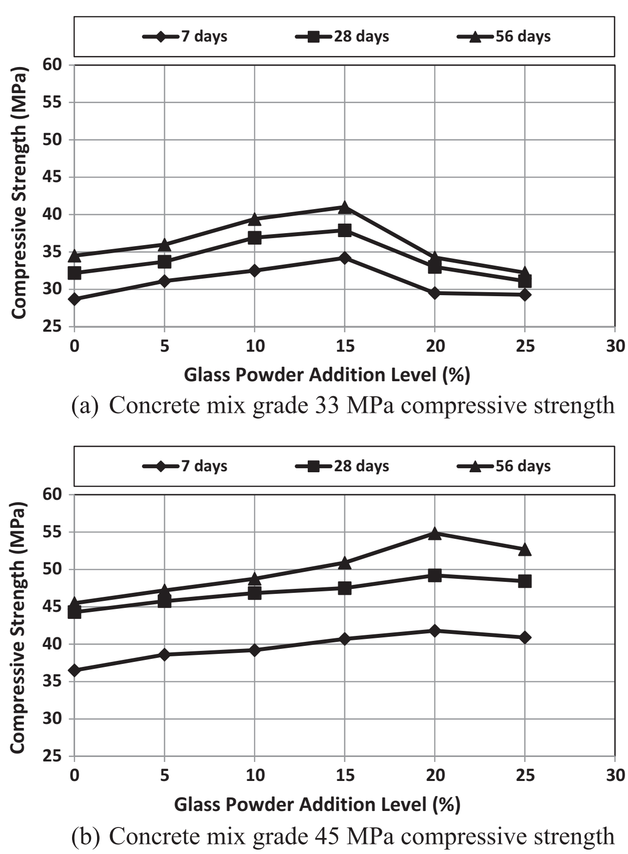


Fig. 18. Concrete compressive strength test results of concrete modified with glass powder as cement addition.

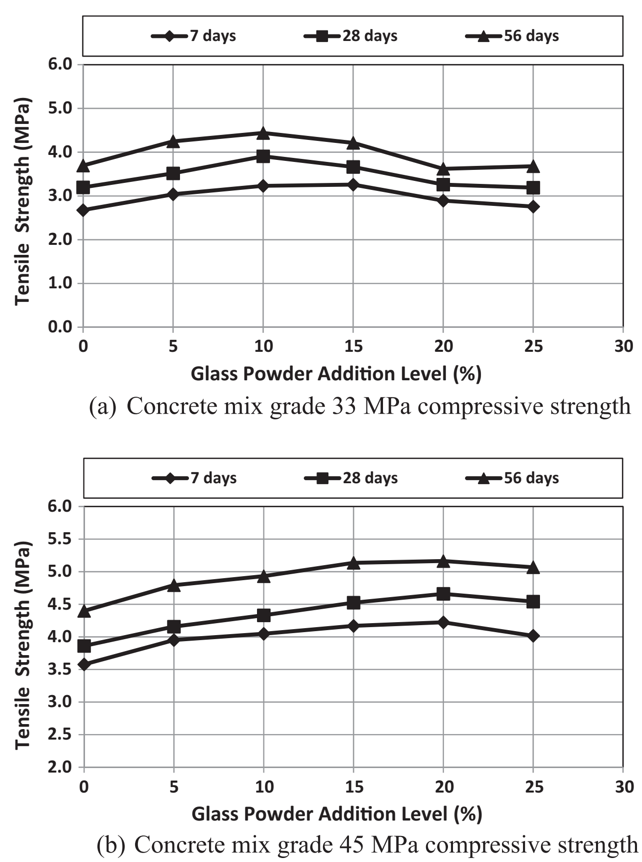


Fig. 19. Concrete tensile strength test results of concrete modified with glass powder as cement addition.

Table 10
Tensile strength test results of glass powder cement addition mixes.

Concrete grade	Age	Replacement level	Experimental Test results (Mpa) Specimen No. 1	Specimen No. 2	Specimen No. 3	Average (MPa)	Standard deviation (MPa)	Coefficient of variation (%)
33 Mpa	7 days	0	2.61	2.73	2.68	2.68	0.06	2.23
		5	3.00	2.97	3.15	3.04	0.10	3.25
		10	3.22	3.25	3.23	3.23	0.01	0.46
		15	3.26	3.34	3.18	3.26	0.08	2.43
		20	2.84	3.01	2.84	2.89	0.10	3.50
		25	2.64	2.82	2.81	2.76	0.10	3.63
	28 days	0	3.25	3.19	3.15	3.20	0.05	1.63
		5	3.51	3.45	3.59	3.52	0.07	2.10
		10	3.86	3.94	3.91	3.91	0.04	1.02
		15	3.67	3.75	3.57	3.66	0.09	2.56
		20	3.19	3.22	3.37	3.26	0.10	3.05
		25	3.37	3.03	3.16	3.19	0.17	5.37
	56 days	0	3.67	3.75	3.66	3.70	0.05	1.34
		5	4.22	4.18	4.34	4.25	0.08	1.94
		10	4.41	4.49	4.41	4.44	0.05	1.07
		15	4.21	4.01	4.42	4.21	0.20	4.83
		20	3.56	3.57	3.73	3.62	0.09	2.62
		25	3.63	3.79	3.62	3.68	0.09	2.49
45 Mpa	7 days	0	3.89	3.91	3.55	3.78	0.20	5.28
		5	3.89	3.90	4.06	3.95	0.10	2.44
		10	4.07	3.95	4.13	4.05	0.09	2.23
		15	4.28	4.08	4.15	4.17	0.10	2.41
		20	4.19	4.13	4.36	4.22	0.12	2.84
		25	4.11	3.93	4.01	4.02	0.09	2.19
	28 days	0	3.95	3.79	3.85	3.86	0.08	2.15
		5	4.14	4.19	4.14	4.16	0.03	0.75
		10	4.28	4.26	4.45	4.33	0.11	2.46
		15	4.48	4.57	4.53	4.53	0.05	1.06
		20	4.72	4.73	4.54	4.66	0.11	2.28
		25	4.43	4.66	4.54	4.54	0.11	2.49
	56 days	0	4.46	4.36	4.37	4.40	0.05	1.20
		5	4.79	4.85	4.74	4.79	0.05	1.13
		10	4.92	4.77	5.10	4.93	0.17	3.39
		15	5.20	5.06	5.14	5.14	0.07	1.33
		20	5.06	5.19	5.23	5.16	0.09	1.78
		25	5.06	4.99	5.15	5.07	0.08	1.56

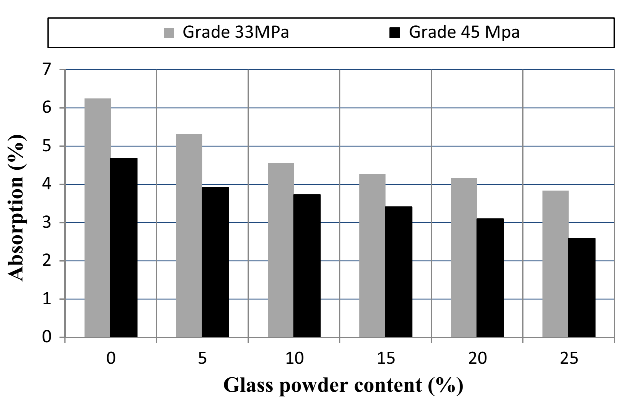


Fig. 20. Water absorption of concrete modified with glass powder as cement addition.

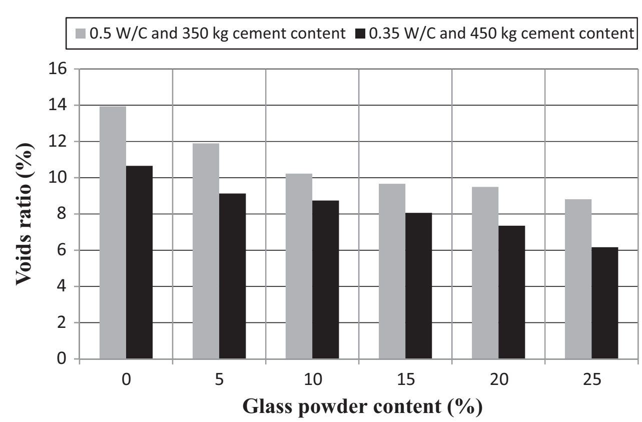


Fig. 21. Voids ratio of concrete modified with glass powder as cement addition.

with control mix. Also, for concrete having 33 MPa grade, there is a drop in compressive strength when more than 15.0% glass powder is used. This may be due to the agglomeration of glass powder particles at high glass powder content. For 45 MPa concrete grade, the use of glass powder as cement addition up to 25.0% enhances the concrete compressive strength.

Table 10 presents the test results of concrete tensile strength for mixes with glass powder as cement replacement for individual samples, mean strength, standard deviation and coefficient of variation. From these test results and Fig. 19, the pervious behavior of compressive strength is the same for concrete tensile strength. The pronounced enhancement in tensile strength test results may be attributed to the enhancement of transition zone properties which significantly affected in concrete tensile strength.

The water absorption and voids radio of concrete modified with glass powder as cement addition are shown in Figs. 20 and 21. The increase of glass powder cement addition decreases water absorption and voids ratio as a result of the pore filling and pozzolanic effect of glass powder. The reduction of voids ratio increases the hardened density of glass powder modified concrete as shown in Fig. 22.

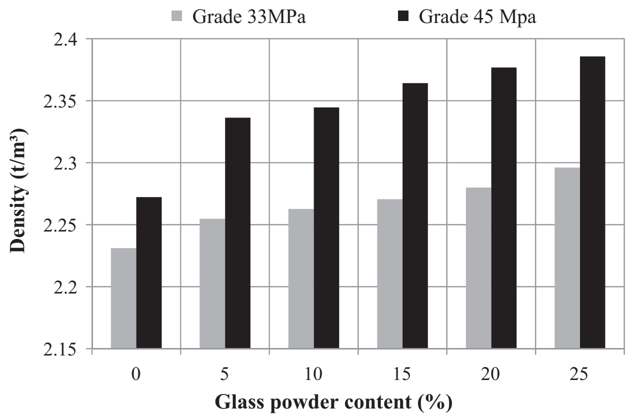


Fig. 22. Hardened density of concrete modified with glass powder as cement addition.

5. Conclusions

In this work, glass powder with grain size distribution ranges 0.0015–0.070 mm is used as cement replacement and as cement addition. Based on physical and mechanical properties of cement and concrete, the following conclusions can be drawn:

- Glass powder material fulfills the limits of Class F and Class C pozzolanic materials according to ASTM C 618 of pozzolanic materials based on physical, mechanical and chemical characteristics. This behavior is confirmed by TGA test results.
- Setting time and soundness of glass powder Portland cement is similar to unblended Portland cement.
- The use of glass powder up to 10.0% enhances the mortar compressive strength. This increase is about 9.0%.
- The use of glass powder as cement replacement up to 25.0% fulfills the limits of Egyptian Portland cement specification ESS No. 2421 when CEM I 42.5 N Portland cement is used.
- The use of glass powder refines the pores of cement paste and this reflects the mortar and concrete properties.
- The increase of glass powder cement replacement level increases concrete slump. For concrete mix having 33 MPa, the use of each 5.0% glass powder increases concrete slump around 10 mm.
- Concrete compressive strength, tensile strength, absorption, voids ratio and density are improved as a result of using 10.0% glass powder cement replacement.
- The use of glass powder more than 15.0% as cement replacement decreases the 28 days concrete compressive strength. Reduction in w/c ratio is required to cancel the reduction in concrete compressive strength. For 45 MPa concrete mix, it is enough to decrease the water cement ration by about 0.03 to cancel the negative effect of using 15% glass powder as cement replacement.
- The use of glass powder as cement addition up to 15.0% enhances concrete compressive strength, tensile strength and voids ratio for 33 MPa concrete grade. This increase is 4.7%, 14.6% and 16.8% for concrete modified with 5.0%, 10.0% and 15.0% glass powder cement addition compared with control mix. For 45 MPa concrete grade, these mechanical and physical properties are improved up to 25.0% glass powder cement addition.
- The concrete tensile strength modified with glass powder is about 9–13% of concrete compressive strength.

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