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Assessment of compressive strength of cement mortar with glass powder from the early strength

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Abstract. The sustainable development principle of replacing natural resources with renewable material is an important research topic. In this study, waste LCD (liquid crystal display) glass powder was used to replace cement (0%, 10%, 20% and 30%) through a volumetric method using three water-binder ratios (0.47, 0.59, and 0.71) to make cement mortar. The compressive strength was tested at the ages of 7, 28, 56 and 91 days. The test results show that the compressive strength increases with age but decreases as the water-binder ratio increases. The compressive strength slightly decreases with an increase in the replacement of LCD glass powder at a curing age of 7 days. However, at a curing age of 91 days, the compressive strength is slightly greater than that for the control group (glass powder is 0%). When the water-binder ratios are 0.47, 0.59 and 0.71, the compressive strength of the various replacements increases by 1.38-1.61 times, 1.56-1.80 times and 1.45-2.20 times, respectively, during the aging process from day 7 to day 91. Furthermore, a prediction model of the compressive strength of a cement mortar with waste LCD glass powder was deduced in this study. According to the comparison between the prediction analysis values and test results, the MAPE (mean absolute percentage error) values of the compressive strength are between 2.79% and 5.29%, and less than 10%. Thus, the analytical model established in this study has a good forecasting accuracy. Therefore, the proposed model can be used as a reliable tool for assessing the design strength of cement mortar from early age test results.

Keywords: cement mortar; LCD glass powder; prediction model

1. Introduction

Advances in optoelectronics technology, software, and other high-tech industries have made Taiwan a "green silicon island" in the global high-tech manufacturing and service industries. However, these developments have also generated a considerable amount of industrial waste, which could lead to environmental damage if handled incorrectly. Recycling industrial waste has the potential to generate enormous economic benefits and reduce the dependency on national resources (Cheng 2002). Rapid industrial development and an increasing standard of living have increased the production of waste glass, of which only a small amount is reused or recycled (Mohamad 2006). Liquid crystal products, such as LCD screens and mobile phone panels have become increasingly popular in recent years. As the world's leading manufacturer, Taiwan's TFT-LCD panel production accounts for approximately 39.2% of the total world output. Waste materials generated from manufacturing account for approximately 12,000 tons of LCD waste glass per year (Cheng 2002, Fang 2006, Wang 2009).

The major materials of liquid crystal displays include glass (85-87%), polymer membranes (12.7-14%), and liquid crystals (0.12-0.14%) (Chang 2005, Roland *et al.* 2004). The main chemical constituents of waste LCD glass are SiO_2, Na_2O, and a small amount of an indium-tin-oxide conducting film. The conducting film coated on the LCD to reduce the resistance of the substrate's surface enhances light transmittance and conductivity. Therefore, the treatment of waste LCD glass by landfill, incineration, and composting is inappropriate (Lin 2007). Thus, how to reuse or recycle LCD glass waste is an important issue for Taiwan because the glass contains a large amount of silicon and calcium and is classified as a Portland material. In addition, its properties such as the unit weight, compressive strength, elasticity modulus, thermal expansion coefficient and heat transfer coefficient are notably close to concrete. Accordingly, previous studies (Topcu and Canbaz 2004, Wang *et al*. 2007, Wang and Huang 2010) indicate that adding crushed waste glass to concrete as a fine aggregate can reduce the concrete air content and unit weight, more

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efficiently pack the concrete pores, provide better durability, surface resistance, resistance to acid, salt and alkali ions, chlorine iontophoresis, and better performance of the concrete ultrasonic pulse velocity. Islam *et al*. (2017) presented that the manufacturing of cement (key ingredient used to produce concrete) is a major source of greenhouse gas emissions; thus, the use of supplementary cementitious materials (SCMs) to offset a portion of the cement in concrete is a promising method for reducing the environmental impact from the industry. Therefore, waste glass recycling can reduce the material costs, and the effect on the environment and CO_2 emission, which are the preferred outcomes for sustainable environmental protection.

Sakale *et al*. (2016) reported that glass is an amorphous material with high silica content and thus is potentially pozzolanic when the particle size is less than 75 μm. Therefore, glass powder (GP) can be used as an alternative supplementary cementing material in concrete (Omran and Tagnit-Hamou 2016). A significant increase in the properties and durability of concrete was reported, when glass with fine particles was used as a cement replacement (Carsana *et al*. 2014, Schwarz *et al*. 2008, Matos and Sousa-Coutinho 2012). The application of waste glass as a finely ground mineral additive (FGMA) in cement is another possibility for recycling (Bashar and Ghassan 2008). A major concern regarding the use of glass in concrete is the chemical reaction that occurs between the silica-rich glass particles and the alkali ions in the pores of concrete (alkali-silica reaction). This reaction is detrimental to the stability of concrete unless appropriate precautions are taken to minimize its effect. Preventative action includes the incorporation of suitable pozzolanic materials such as fly ash, ground blast furnace slag, or met kaolin in the concrete mix (Al-Mutairi *et al*. 2004). Shayan and Xu (2004) found that 30% glass powder could be incorporated as an aggregate or cement replacement in concrete without any long-term detrimental effects. Furthermore, the results have demonstrated an increase in the compressive strength of concrete made with very fine waste glass (Federico and Chidiac 2009). Islam *et al*. (2017) reported that when the waste glass powder was used as a partial replacement of cement, lower mean compressive strengths compared to that of the control mortar (0% glass replacement) were obtained at ages of 7, 14, 28 and 56 days. However, all other cement-replaced mortar mean compressive strength values exceeded that of control mortar at 90, 180 and 365 days. Aliabdo *et al*. (2016) indicated that when glass powder with particles finer than 75µm and a specific gravity of 2.62 was used, an increase in the replacement level of more than 10% decreases the mortar compressive strength. In addition, the compressive strength of LGP (the glass powder produced by liquid crystal display (LCD)-processed waste glass (LPWG)) concrete specimens was generally higher than that of OPC. However, after 3 days, the compressive strength with a replacement level of 15% and 20% was lower than that of OPC, and all the specimens were higher than that of OPC after 7 days (Kim *et al.* 2017). Shi *et al*. (2005) observed that a replacement level of 20% of the cement with ground glass powder demonstrated a lower strength and a higher strength than that of 100% Portland cement at 7 days and 28 days, respectively. Thus, the compressive strength may be affected by particle size and glass powder replacement.

Table 1 The physical properties of the materials

Items	Specific gravity	Water absorption (%)	F.M	Fineness (cm^2/g)
Fine Aggregate	2.58	2.2	2.9	-
Cement	3.15	-	-	3510
Glass Powder	2.56	-	-	4500

Table 2 Chemical properties of the relevant materials. Unit: %

Properties	Cement	Glass Powder
SiO_2	22.0	62.5
Al_2O_3	5.6	16.8
Fe_2O_3	3.3	9.4
CaO	62.9	2.7
MgO	2.6	0.2
SO_3	2.0	-
K_2O	0.8	1.4

With sustainable development and the reuse of waste materials as a starting point, applications involving the addition of glass powder to replace the cement of the raw materials in concrete or mortar constitute a research topic worthy of study. Additionally, the compressive strength on day 28 has typically been used as the design strength value for a concrete structure. Thus, an assessment of the compressive strength of cement mortar with glass powder from the early strength properties is desirable, and this assessment will be helpful for the safety evaluation and analysis of structures throughout the construction phase. In this study, a series of compressive strength tests were conducted on cement mortars with three types of water-binder ratios (0.47, 0.59 and 0.71) containing glass powder (the cement is replaced by 0%, 10%, 20% and 30% glass powder), and a compressive strength prediction model encompassing such influence factors as the water-binder ratio, glass powder replacement and age was proposed.

2. Experimental plan

2.1 Test materials

Cement: Type I Portland cement produced by the Taiwan Cement Corporation was used; its properties conformed to those of Type I Portland cement specified in ASTM C150.

Mixing water: Conforms to ASTM C1602 for concrete mixing water.

Fine aggregate: Natural sand able to pass through a No. 8 sieve was provided from the Ligang District and conformed to ASTM C295. The fineness modulus, specific weight, and water absorption of sand were 2.90, 2.58, and 2.2%, respectively.

Glass powder: The TFT–LCD waste glass was obtained from the Chi-Mei Industrial Corp. in Taiwan. To

Table 3 Unit weight of the mix design cement mortar with the addition of glass powder (Unit: g)

No.	w/b	Cement	Glass powder	Sand	Water
G0	0.47	500	0	1375	265
G1		450	50		
G2		400	100		
G3		350	150		
G0	0.59	500	0	1375	325
G1		450	50		
G2		400	100		
G3		350	150		
G0	0.71	500	0	1375	385
G1		450	50		
G2		400	100		
G3		350	150		

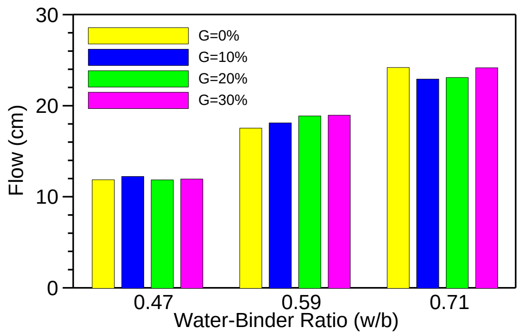

Fig. 1 Relationship between the flow value and the water-binder ratio

achieve uniform particle sizes, the TFT–LCD waste glass was crushed and ground, passed through a No. 16 mesh sieve and dried for further applications using a planetary mill (Pulverisette 4). The glass powder was ground to 4500 cm^2/g and was utilized as a partial substitute for cement.

The physical and chemical properties of the materials are shown in Tables 1 and 2.

2.2 Test variables and items

Three values of w/b (0.47, 0.59, and 0.71) were used. Different proportions (0%, 10%, 20% and 30%) of cement were replaced by the glass powder to produce the cement mortar. The mix proportion unit weights are shown in Table 3. A 5 cm×5 cm×5 cm cement mortar specimen was constructed and solidified. The forms were removed 24 hours after making the sample, and the specimens were continuously cured at room temperature (23-25℃) and placed in saturated limewater. The flow and setting time were tested in accordance with ASTM C230 and ASTM C403, respectively. The compressive strength was tested at the ages of 7, 28, 56 and 91 days according to ASTM C109.

3. Results and discussion

3.1 Flow and setting time

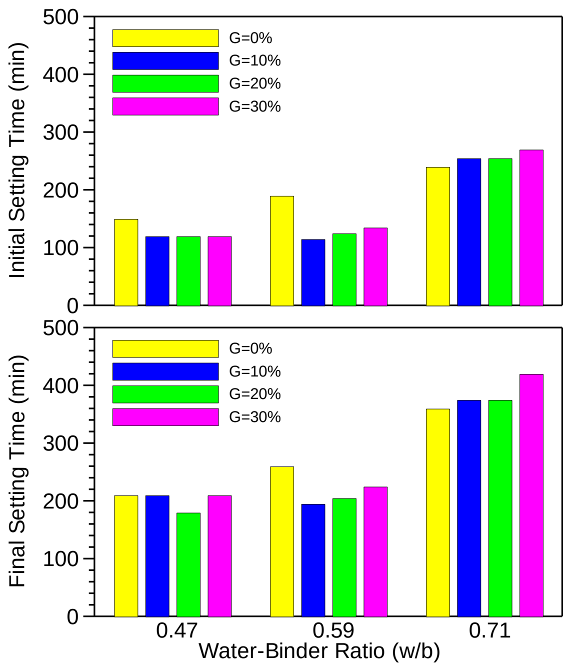

Fig. 2 Relationship between the setting time and the water-binder ratio

Fig. 1 illustrates how the fluidity increased with an increase in the water-binder ratio, and no obvious change was apparent in the fluidity with an increase in the displacement of waste LCD glass powder. This finding may be because hydration did not occur when the glass powder (to replace cement) was added. When the water-binder ratios are 0.47, 0.59 and 0.71, the flow values are approximately 11.9-12.3 cm, 17.6-19.0 cm and 23.0-24.3 cm, respectively.

Fig. 2 shows that the w/b value was influenced by the setting time. It is obvious that the setting time increases with an increase in the water-binder ratio. When the water-binder ratio is 0.47, the setting time is not significantly affected by the glass powder replacement. However, when the water-binder ratio is 0.71, the setting time slightly increases with increasing glass powder replacement. When the water-binder ratio is 0.47, the average initial setting time and final setting time are 128 min and 203 min, respectively. When the water-binder ratio is 0.59, the average initial setting time and final setting time are approximately 111% and 109%, respectively, of the 0.47 water-binder ratio. When the water-binder ratio is 0.71, the average initial setting time and final setting time are approximately 200% and 189%, respectively, of the 0.47 water-binder ratio. Notably, the low rate of water absorption by the waste LCD glass powder may have influenced the hydration of the cement, resulting in an extended setting time. However, this tendency of setting time should also be further validated by future studies or tests.

3.2 Compressive strength

Fig. 3 shows the compressive strength test results of the cement mortar with different mix proportions and glass powder replacements. The test results show that the

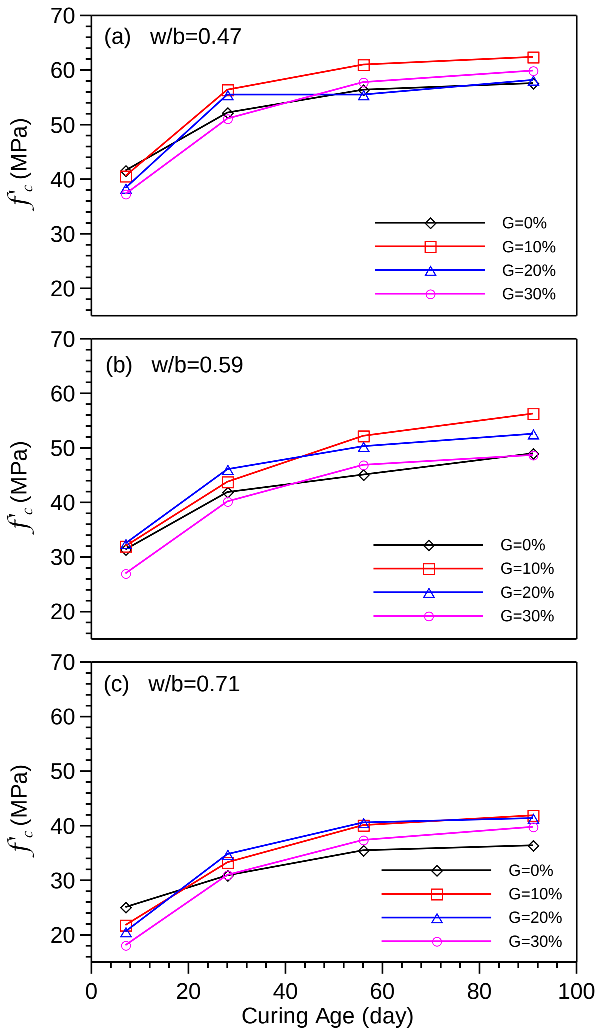

Fig. 3 Relationship between the compressive strength and the curing time

compressive strength increases with increasing curing age but decreases as the water-binder ratio increases. When the water-binder ratio and curing age are 0.47 and 7 days, respectively, the compressive strength slightly decreases with increasing glass powder replacement. However, when the glass powder is used as a partial substitute for cement and at a curing age of 91 days, the compressive strength is slightly greater than that for the control group (glass powder is 0%). Similarly, the test results of other water-binder ratios of 0.59 and 0.71 also exhibit the same trend and show a similar tendency with other reported test results (Kim *et al*. 2017, Shi *et al*. 2005). Thus, the effect of glass powder substitution on the compressive strength is not consistent with the early and late strength tendencies. This finding is because the Pozzolanic materials begin to contribute in earnest to the Pozzolanic reaction 3 to 14 days after hydration begins. At that time, approximately 70% to 80% of the alit in OPC already reacted. Therefore, the Si and Al ions eluted from the LGP may have reacted with the Ca ions in the pores to produce C-S-H and C-A-H to make a dense and more compact material (Kim *et al*. 2017). This trend is the same as that reported in other studies (Islam *et al*. 2017, Rahma *et al*. 2017, Kim *et al*. 2015).

Taking *w/b*=0.47 as an example, the compressive strengths at the ages of 7 and 91 days are lower and higher than the strength values at 28 days by 69.2-79.7% and 104.9-117.2%, respectively. When *w/b*=0.59, the compressive strengths at the ages of 7 and 91 days are lower and higher than the strength values at 28 days by 67.2-74.9% and 114.1-128.5%, respectively. When w/b=0.71, the compressive strengths at the ages of 7 and 91 days are lower and higher than the strength values at 28 days by 58.4-81.2% and 117.8-128.4%, respectively. In addition, when the water-binder ratios are 0.47, 0.59 and 0.71, the compressive strengths of the various replacements increased by 1.38-1.61 times, 1.56-1.80 times and 1.45-2.20 times, respectively, after aging from day 7 to day 91.

4. Development of the compressive strength prediction model and a comparison between the analysis and test results

4.1 Compressive strength prediction model

Wang *et al*. (2014a, b) proposed compressive strength, bending strength and ultrasonic pulse velocity prediction analysis models that consider the waste glass content, water-binder ratio and age factors based on the self-compacting waste LCD glass concrete test results. In their study, a hyperbolic function was suggested to evaluate the compressive strength, shown as Eq. (1). It showed that under the same conditions, the compressive strength decreases as the replacement rate of waste glass. In addition, Wang (2016) indicated that the normalized compressive strength increases with age and then becomes smooth with age, approximately presenting a hyperbolic formula. Thus, a compressive strength prediction model using a hyperbolic function based on a furnace and desulfurization slag mortar material from the early strength of the seven-day test result was proposed. Similarly, Chen *et al.* (2017) reported that the relationship between the normalized compressive strength in composite cement mortar with slag and curing age could also be represented as a hyperbolic function. Hence, this concept was applied and the assessment of the developed strength in composite cement mortar with slag was proposed, as shown in Eq. (2).

$$\frac{f_c'}{f_{c,28}'} = \frac{t}{\left[\left(m_1 + m_2\left(\frac{w}{b}\right)\right) + \alpha G\right] + \left[\left(n_1 + n_2\left(\frac{w}{b}\right)\right) + \beta G\right] t} \quad (1)$$

$$f_c' = \frac{t}{(a_1 + a_2 B_s + a_3 B_s^2) + (b_1 + b_2 B_s + b_3 B_s^2) t} \times f_{c,7}' \quad (2)$$

where f_c' refers to the compressive strength at any curing age (t); $f_{c,7}'$ and $f_{c,28}'$ refer to the compressive strength at an age of 7 days and 28 days; w/b refers to the water-binder ratio; G and B_s refer to the replacement rate of glass sand and Baosteel slag; m_1, m_2, n_1, n_2, α and β are the model coefficients related to the replacement rate of glass sand; and a_1, a_2, a_3, b_1, b_2, b_3 are the model coefficients related to the replacement rate of B_s.

In this study, both a hyperbolic function and normalized compressive strength with seven-day test results are used

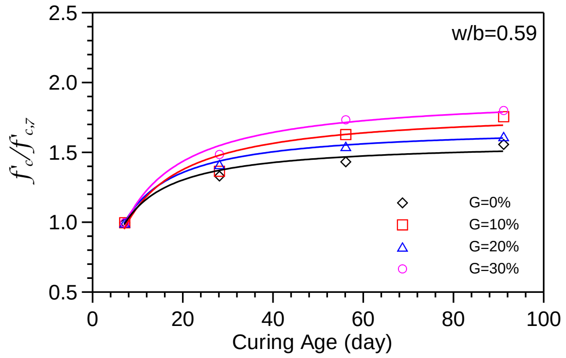

Fig. 4 Relationship between the normalized compressive strength and curing age

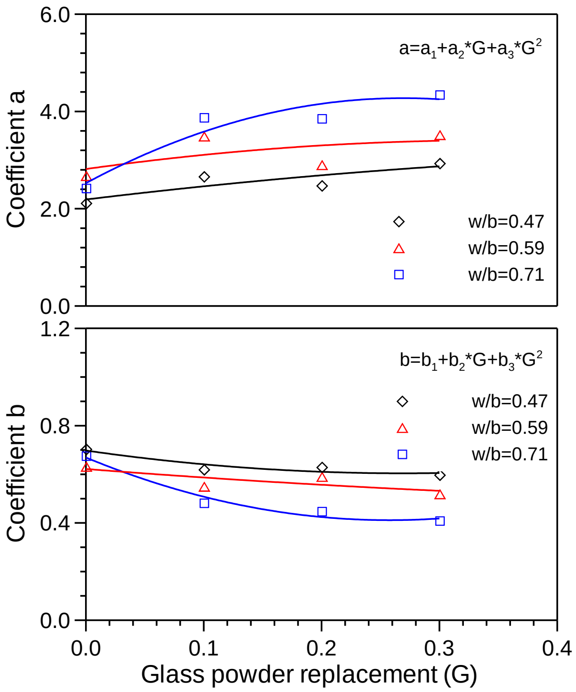

Fig. 5 Relationship between the coefficients of the hyperbolic function and the glass powder replacement

for the establishment of the prediction model. When the water-binder ratio is 0.59, the analysis results show that the regressions of the normalized compressive strength by seven-day test results are consistent with the hyperbolic function, shown as Eq. (3) and in Fig. 4. In addition, the other water-binder ratio test results exhibit the same trends.

According to the results, the values of coefficients a and b are related to the water-binder ratio w/b and the glass powder replacement G. Therefore, the values of coefficients a and b could be expressed as functions of w/b and G, as given by Eqs. (4) and (5). The relationship between the values of the hyperbolic function coefficients a and b and the replacement of glass powder G is shown in Fig. 5. The value of coefficient a increases as the amount of glass powder replacement G increases in a manner that can be described as a nonlinear quadratic polynomial function, as shown in Fig. 5 and given by Eq. (6). In addition, the value of coefficient b decreases as the amount of glass powder replacement G increases and can

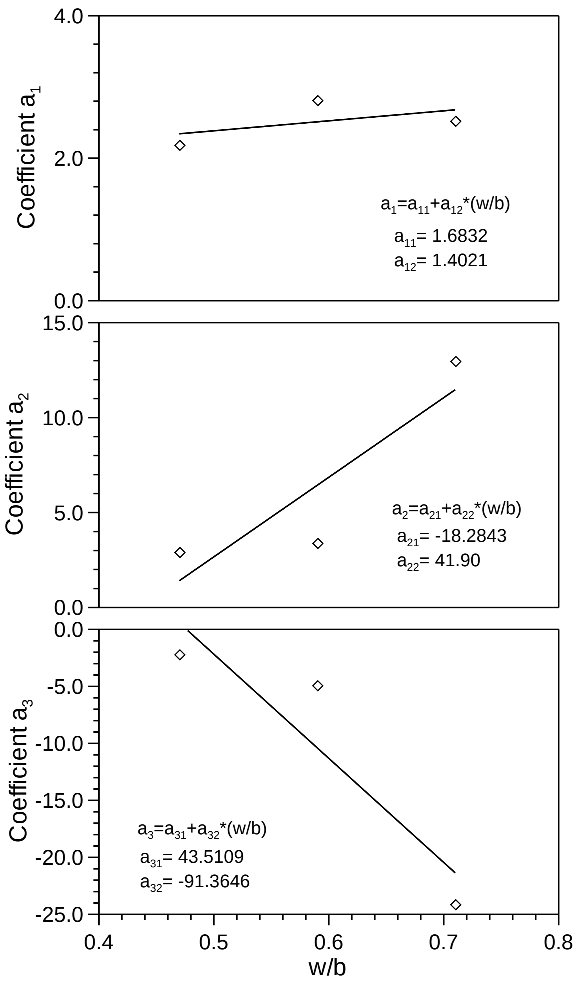

Fig. 6 Relationship between the coefficient a and water-binder ratio

be described as a nonlinear quadratic polynomial function, as shown in Fig. 5 and given by Eq. (7).

$$\frac{f_c'}{f_{c,7}'} = f(w/b, G, t) = \frac{t}{a + b \times t} \tag{3}$$

$$a = a(w/b, G) \tag{4}$$

$$b = b(w/b, G) \tag{5}$$

$$a = a_1 + a_2 G + a_3 G^2 \tag{6}$$

$$b = b_1 + b_2 G + b_3 G^2 \tag{7}$$

where f_c' refers to the compressive strength at any curing age, $f_{c,7}'$ refers to the compressive strength at an age of 7 days, t refers to the age; a and b refer to the coefficients of the hyperbolic function; G refers to the glass powder replacement; w/b refers to the water-binder ratio and a_1, a_2, a_3 and b_1, b_2, b_3 are the model coefficients related to the replacement rate of glass powder G.

Fig. 6 shows the relationship between the model coefficients a_1, a_2 and a_3 and the water-binder ratio w/b. The relationship between coefficients a_1 & a_2 and w/b could be represented as a linear increasing function, whereas that between coefficient a_3 and *w/b* could be

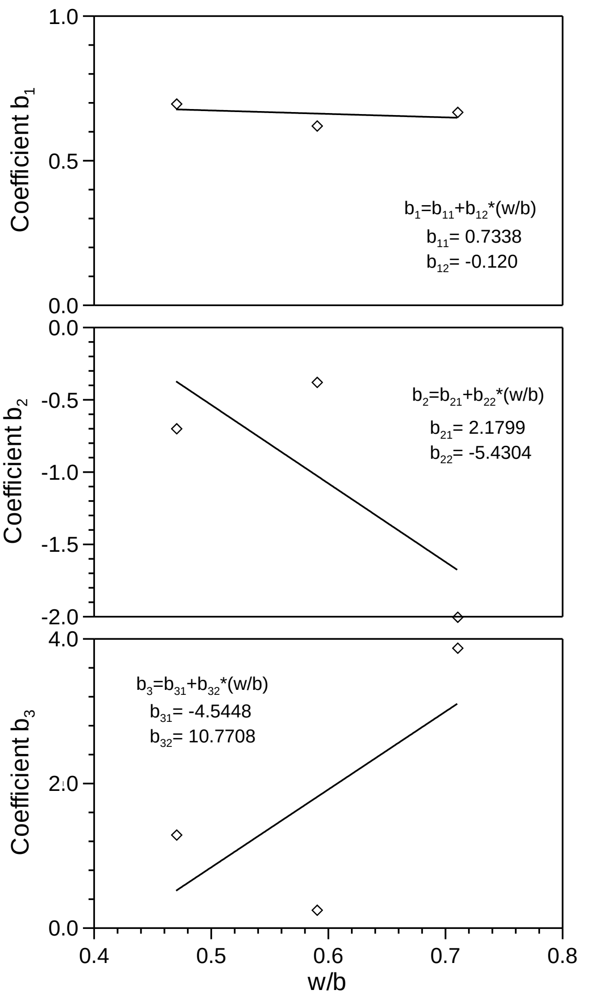

Fig. 7 Relationship between the coefficient b and water-binder ratio

represented as a linear decreasing function. Therefore, coefficients a_1, a_2 and a_3 could be expressed as Eq. (8). Coefficients b_1, b_2 & w/b and coefficient b_3 & w/b have relationships that are similar to linear decreasing and increasing functions, respectively, as shown in Fig. 7. Thus, b_1, b_2, and b_3 could be represented as Eq. (9). After Eqs. (6) to (9) are combined, Eq. (3), the equation for the prediction of the compressive strength of the glass powder cement mortar, could be rewritten as Eq. (10). Therefore, as long as the compressive strength on the 7th day $f'_{c,7}$ is obtained, it is possible to predict the compressive strength at any other age and under other mixture ratios using Eq. (10). Table 4 shows the values of the model coefficients $a_{11}, a_{12}, a_{21}, a_{22}, a_{31}, a_{32}, b_{11}, b_{12}, b_{21}, b_{22}, b_{31}, b_{32}$, etc. that are obtained by regressing the results of the test samples in the function.

$$\left.\begin{aligned} a_1 &= a_{11} + a_{12}(w/b) \\ a_2 &= a_{21} + a_{22}(w/b) \\ a_3 &= a_{31} + a_{32}(w/b) \end{aligned}\right\} \text{(for coefficient } a \text{)} \qquad (8)$$

$$\left.\begin{aligned} b_1 &= b_{11} + b_{12}(w/b) \\ b_2 &= b_{21} + b_{22}(w/b) \\ b_3 &= b_{31} + b_{32}(w/b) \end{aligned}\right\} \text{(for coefficient } b \text{)} \qquad (9)$$

Table 4 Coefficients of the compressive strength prediction model

a		b		x and θ	
a_{11}	1.683	b_{11}	0.734	x_1	77.468
a_{12}	1.402	b_{12}	-0.120	x_2	-75.313
a_{21}	-18.284	b_{21}	2.180	θ	-16.667
a_{22}	41.900	b_{22}	-5.430	—	—
a_{31}	43.511	b_{31}	-4.545	—	—
a_{32}	-91.365	b_{32}	10.771	—	—

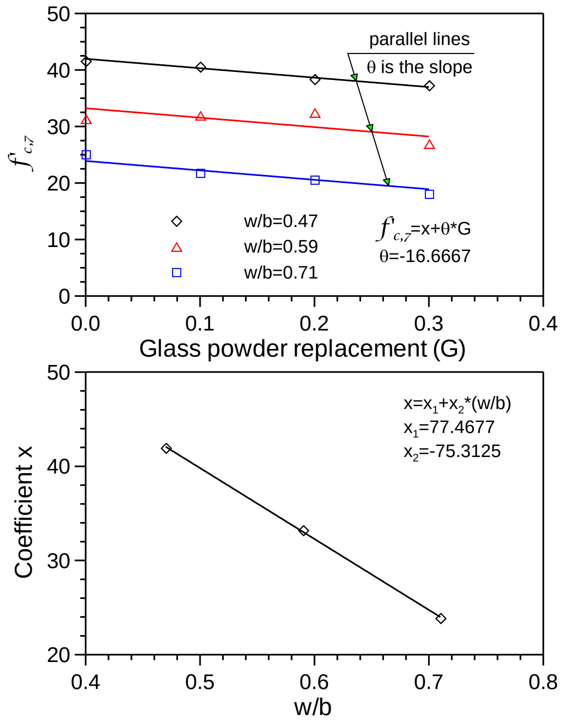

Fig. 8 Compressive strength on day 7 vs. the glass powder content and the coefficient of x vs. *w/b*

$$f'_c = \frac{t}{(a_1 + a_2 G + a_3 G^2) + (b_1 + b_2 G + b_3 G^2)t} \times f'_{c,7}$$
$$= \frac{t}{\left[\left(a_{11} + a_{12}\left(\frac{w}{b}\right)\right) + \left(a_{21} + a_{22}\left(\frac{w}{b}\right)\right)G + \left(a_{31} + a_{32}\left(\frac{w}{b}\right)\right)G^2\right] + \left[\left(b_{11} + b_{12}\left(\frac{w}{b}\right)\right) + \left(b_{21} + b_{22}\left(\frac{w}{b}\right)\right)G + \left(b_{31} + b_{32}\left(\frac{w}{b}\right)\right)G^2\right]t} f'_{c,7} \qquad (10)$$

$$f'_{c,7} = x + \theta \times G \qquad (11)$$

$$\theta = constant \qquad (12)$$

$$x = x_1 + x_2 \times (w/b) \qquad (13)$$

According to the test results, the relationship between the compressive strength of the glass powder cement mortar on day 7 and glass powder replacement G exhibits both of a linearly decreasing and a parallel relationship, as shown in Fig. 8, and $f'_{c,7}$ is expressed as Eq. (11). Thus, the slope value θ is a constant. In addition, a linear decreasing relationship between the coefficient x and water-binder ratio w/b is shown in Fig. (8) and is expressed as Eq. (13). Table 4 shows the values of the model coefficients x_1, x_2, θ, etc. When predicting the compressive strength at other

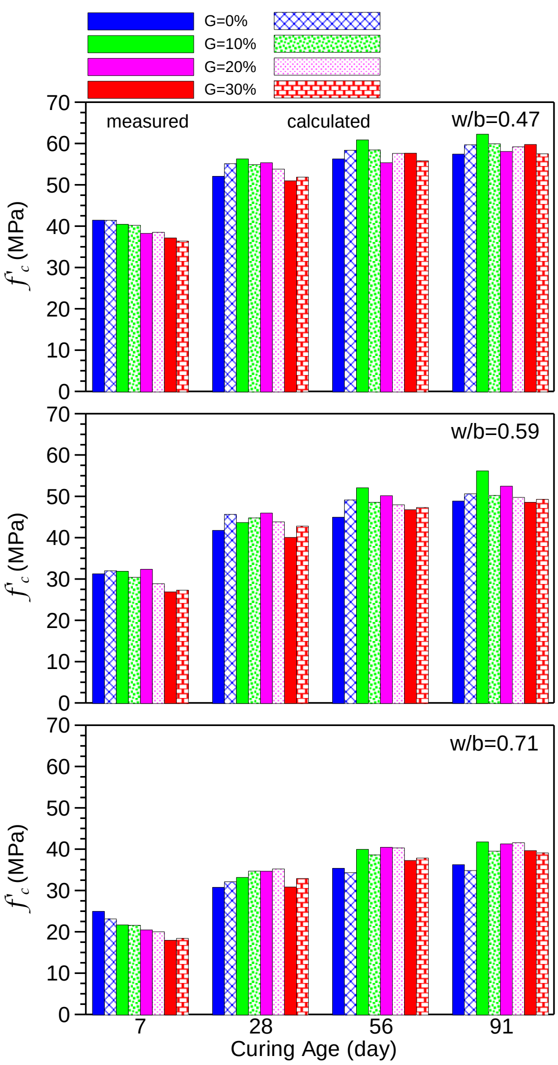

Fig. 9 Comparison of the calculated and measured compressive strengths

ages and under different mixture ratios, the necessary value of the compressive strength on day 7 $f'_{c,7}$ could be calculated with Eq. (11).

4.2 Comparison between the prediction and test results

Fig. 9 shows and compares the results of the compressive strength tests conducted at different curing ages based on the early strength of day 7 when the water-binder ratio changes. According to the figure, the compressive strength prediction model established in this study can be used to evaluate the relationship between the compressive strength and the curing age when the water-binder ratio and glass powder replacement change. According to the analytical results, when the water-binder ratio w/b is 0.47, 0.59 and 0.71, the MAPE (mean absolute percentage error) value is 2.79%, 5.29% and 3.07%, respectively, as shown in Fig. 10. Thus, the MAPE values of different water-binder ratios range from 2.79-5.29%, and the overall MAPE mean is 3.72%.

As suggested in Lewis (1982), an MAPE value of less

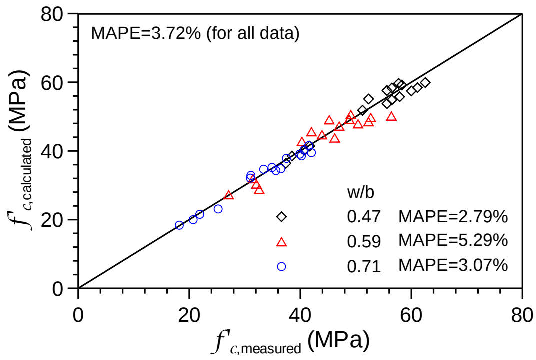

Fig. 10 Comparison of compressive strength and the MAPE value calculated by the proposed model and the test results

than 10% indicates an excellent predictive ability; an MAPE value of 10%-20% indicates a good predictive ability; an MAPE value of 20%-50% indicates a reasonable predictive ability; and an MAPE value greater than 50% indicates a poor predictive ability. Because all of MAPE values are less than 10%, an excellent predictive ability is indicated. Therefore, the prediction model established in this study to predict the compressive strength of the glass powder cement mortar from the early strength on day 7 was proved to deliver satisfactory results.

5. Conclusions

1. The test results show that the compressive strength increases with age but decreases as the water-binder ratio increases. In addition, the compressive strength slightly decreases with increasing glass powder replacement at a curing age of 7 days. However, when the glass powder is used as a partial substitute for cement at a curing age of 91 days, the compressive strength is slightly greater than that for the control group (glass powder is 0%). When the water-binder ratios are 0.47, 0.59 and 0.71, the compressive strengths of the various replacements increase by 1.38-1.61 times, 1.56-1.80 times and 1.45-2.20 times, respectively, during the aging process from day 7 to day 91.
2. In this study, the compressive strength prediction model of cement mortar with waste glass powder is deduced based on a hyperbolic function. The proposed model could predict the compressive strength at other curing ages from the early strength on day 7. This model is useful for the safety assessment of concrete structures during the construction phase, and it can serve as a reference for the mixture ratio design in future engineering practices. However, the model should be tested further with confirmatory analyses.
3. According to the comparisons between the predicted values and the test results, the MAPE values of compressive strength are between 2.79 and 5.29%, and the average of MAPE values for all of test results is approximately 3.72%. Because all of MAPE values are less than 10%; thus, the built analysis models have good forecasting accuracy for waste glass powder cement mortar.

4. The applicability of the compressive strength prediction model, which was established using deduction and the tendency of the test results, to other mixing conditions remains to be studied and verified in the future.

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