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Assessment of the compressive strength of recycled waste LCD glass concrete using the ultrasonic pulse velocity

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HIGHLIGHTS

- A UPV-based compressive strength prediction model of waste LCD glass concrete is proposed.
- The relationship between compressive strength and UPV present a nonlinearly increasing curve.
- The strength-UPV curve has a right shift tendency as the glass replacement increases.
- The UPV increases with the waste glass replacement G value, but the compressive strength decreases as the G value increases.

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ABSTRACT

This study uses a fixed weight ratio of 7:2:1 of cement, fly ash and slag powder as binder material and uses waste liquid crystal display (LCD) glass sand through a No. 4 sieve to replace 0%, 10%, 20% and 30% of the fine aggregate using the volumetric method, combined with water-binder ratios (w/b) of 0.28, 0.32 and 0.36 for a series of tests to determine the compressive strength and ultrasonic pulse velocity (UPV) of self-consolidating glass concrete (SCGC). The test results show that the compressive strength and UPV increase with age but decrease as the water-binder ratio increases. The compressive strength and UPV present a nonlinearly increasing relation curve, the water-binder ratio influences the curve insignificantly, and there is a right shift as the waste glass replacement increases. Therefore, the UPV of SCGC increases with the waste glass replacement G value, but the compressive strength decreases as the G value increases. In addition, this study uses the exponential function as a basis, combined with the compressive strength and UPV characteristics of waste LCD glass concrete; by considering the w/b, waste glass replacement G and UPV variables, the compressive strength prediction model is deduced. The analysis results show that the mean absolute percentage error (MAPE) value for the compressive strength test result and the assay value of SCGC is 6.45–7.97%; compared with the MAPE value, which is 8.61–12.51%, as obtained by linear function regression, the analysis result accuracy is increased by 25.1–36.3%. In the same way, the MAPE value of the WGCLSM (waste glass controlled low strength material) is 8.15–11.24%; compared with the MAPE value, which is 21.33–26.19%, as obtained by linear function regression, the accuracy is increased by 51.2–62.2%. Furthermore, the MAPE value obtained by a compressive strength prediction analysis of HPGC (high-performance recycled liquid crystal glass concrete) is 7.18–8.65%. Therefore, this study builds an analytical model that uses UPV to evaluate the compressive strength; its forecast accuracy is good, and it is applicable to waste LCD glass concrete for different functional requirements. It is very helpful for the safety assessment analysis of concrete structures with similar mix proportions and nondestructive testing UPV.

1. Introduction

Taiwan's flat-panel display industry has flourished over the past decade. Taiwan's output accounted for 38% of the global large-size LCD (liquid crystal display) panel production in 2011, and it has become one of the largest producers of LCD panels, second only to Korea. Large amounts of waste are derived from the manufacturing process with the substantial increase in production [1]. The output of waste LCD glass in Taiwan reached 20,000 tons in 2007 [2]. Waste glass recycling can reduce the material cost and demand for valuable landfill space, thereby decreasing both the effect on

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the environment and CO_2 emission, which are the preferred outcomes for sustainable environmental protection. Recycled glass has been used and applied in asphalt concrete, normal concrete, back-filling, sub-base, tiles, masonry blocks, paving blocks and other decorative purposes [3]. Adding crushed waste glass to concrete as a fine aggregate can reduce the concrete air content and unit weight, more efficiently pack the concrete pores, and provide better durability, surface resistance, resistance to acid, salt and alkali [4–6]. Hence, waste glass has been widely used to replace some of the concrete or cement mortar material [4–14].

The compressive strength of concrete is an excellent indicator of concrete quality, and it invariably forms the most important basis of specifications and quality control [15]. In addition, in designs, concrete is mostly used under compression loading; therefore, concrete is directly related to the compressive strength from a design perspective [16]. Thus, for the safety assessment of existing structures, compressive strength is an important indicator. In engineering practice, the in situ compressive strength can be obtained by coring samples, and it is often suggested when no more strength information can be referenced. However, coring is a destructive technique and may have some limitations in structures. Ultrasonic pulse velocity (UPV) is a non-destructive technique that involves measuring the speed of a wave through material to predict its strength, calculate the low-strain elastic modulus or detect the presence of internal flaws, such as cracking, voids, honeycomb, decay and other damage. This technique is applicable where intrusive (destructive) testing is not desirable, and it can be applied to concrete, ceramics, stone and timber. UPV values are affected by a number of factors, including the mix proportions, aggregate type, age of concrete, and moisture content. However, the factors that might significantly affect the strength of the concrete have little influence on the UPV [17–19]. If the relationship between the compressive strength and UPV could be established, it would be very helpful for the safety assessment and analysis of structures during its service period. In this study, a series of compressive strength and UPV tests were carried out with a varied water-binder ratio on the self-consolidating glass concrete (SCGC), and an assessment of the compressive strength using UPV was proposed.

2. Experimental plan

2.1. Test materials

1. Cement: Type I Portland cement produced by the Taiwan Cement Corporation was used; its properties conformed to the Type I Portland cement specified in ASTM C150.
2. Mixing water: Conforms to ASTM C94 concrete mixing water.
3. Aggregate: The aggregate originated from the Ligang District and conformed to ASTM C33.
4. Fly ash: Class F fly ash from the Taiwan Taipower Xing-Da Thermal Power Plant conformed to ASTM C618.
5. Slag: GGBFS (ground-granulated blast-furnace slag) was produced by the CHC Resources Corporation and was ground into 4000 cm^2/g, and its properties conformed to ASTM C989.
6. Glass sand: TFT-LCD (thin film transistor-liquid crystal display) waste LCD glass sand able to pass through a No. 4 sieve was provided by Chi-Mei Optoelectronics. The glass sand had a smooth surface with edges and corners, and the fineness modulus and SSD (saturated-surface-dry) specific weight were 3.37 and 2.45, respectively. The particle size distribution curve was also close to the natural sand of the Ligang District.
7. Superplasticizer: A Type 1000 superplasticizer that complied with the ASTM C494 type G admixture.

2.2. Test variables and method

The volumetric method was used for the proportion design of the mixture. In this study, the fly ash and slag powder were added and mixed with cement as binder material. The ratio of cement-fly ash-slag was 7:2:1 by weight. The water-binder ratios were 0.28, 0.32, and 0.36, and four types of glass sand as fine aggregate were added at volume replacement ratios of 0%, 10%, 20%, and 30%. A 10 cm * 20 cm cylindrical concrete specimen was made and solidified. The specimens were placed and cured at room temperature (23–25 °C) and in saturated limewater. The compressive strength and UPV were tested at the ages of 1, 7, 28, 56, 90, and 180 days in accordance with ASTM C31, ASTM C39, and ASTM C597.

The physical properties of the aggregate and glass sand are shown in Table 1. The unit weight of the mix design SCGC materials are shown in Table 2. The chemical properties of the cement, fly ash, slag, and glass sand and the particle size distribution curves of aggregate and glass sand can be found in our previous study [20,21].

3. Experimental results

3.1. Effect of water-binder ratio on compressive strength and UPV

Figs. 1 and 2 show the test results of the relationships of the compressive strength and UPV to the age of the SCGC with different w/b ratios and waste glass replacements (G). It is observed that within a curing age of 180 days, the compressive strength and UPV increase with age but decrease as w/b increases, consistent with the findings of other studies [22,23]. Disregarding the effect of waste glass replacement, the average gradient of the decrease of the compressive strength at the age of 28 days with w/b is approximately −210 MPa, and the decreasing gradient at an age of 90 days is approximately −160 MPa, as shown in Fig. 3(a). Therefore, the effect of w/b on the short age strength is slightly greater than that on the long age strength. In the same way, disregarding the effect of waste glass replacement, the average gradient of the decrease of the UPV at an age of 28 days with w/b is approximately −620 m/s, and the decreasing gradient at an age of 90 days is approximately −720 m/s, as shown in Fig. 3(b). However, the effect of w/b on the short-age UPV is slightly less than that on the long-age UPV.

In terms of the concrete material, the UPV is likely to be influenced by age, w/b, cement content, water and aggregate property; thus, the pulse velocity and transmission path will be different. Generally speaking, coarse aggregate has a higher pulse velocity than fine aggregate does, and fine aggregate has a higher pulse velocity than cement mortar does. Therefore, the more coarse aggregate the concrete contains, the higher the pulse velocity is in the same unit volume. The pulse velocity decreases as the water consumption and gaps increase. Therefore, the relationship between the compressive strength and UPV is closely related to the concrete mix. Breysse [24] further condensed the UPV strength and rebound number strength models by utilizing three commonly

Table 1
Physical properties of aggregate and glass sand.

Properties	Coarse aggregate	Fine aggregate	Glass sand
Unit weight (kg/m^3)	1530	1820	1680
Particle density (g/cm^3)	2.62	2.57	2.45
D_{max} (mm)	9.50	1.18	2.36
Water absorption (%)	0.7	1.2	0.4
Fineness modulus (FM)	5.02	3.22	3.37
Soil content (%)	0.5	1.3	–

Table 2
Mixture proportions of SCGC.

w/b	No.	Substation (%)	Binding materials (kg/m^3)			Aggregate (kg/m^3)			Water content (kg/m^3)	
			Cement	Fly ash	Slag	Coarse aggregate	Sand	Glass sand	Water	SP
0.28	SC28G0	0	463	132	66	786	850	0	185	7.2
	SC28G10	10	463	132	66	786	765	74	185	7.2
	SC28G20	20	463	132	66	786	680	159	185	7.2
	SC28G30	30	463	132	66	786	595	238	185	7.2
0.32	SC32G0	0	420	116	58	786	850	0	185	6.5
	SC32G10	10	420	116	58	786	765	74	185	6.5
	SC32G20	20	420	116	58	786	680	159	185	6.5
	SC32G30	30	420	116	58	786	595	238	185	6.5
0.36	SC36G0	0	360	103	51	786	850	0	185	5.7
	SC36G10	10	360	103	51	786	765	74	185	5.7
	SC36G20	20	360	103	51	786	680	159	185	5.7
	SC36G30	30	360	103	51	786	595	238	185	5.7

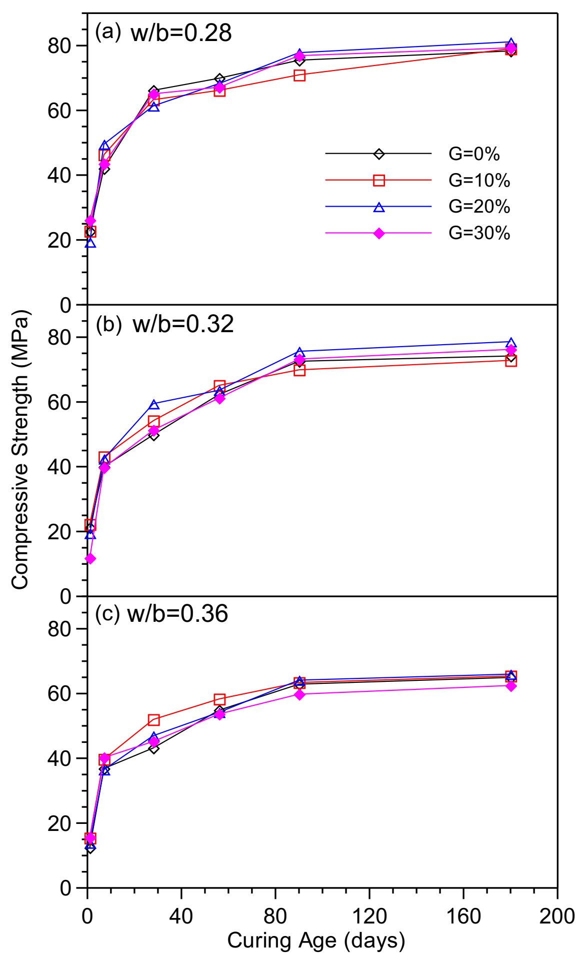

Fig. 1. Relationship between compressive strength and curing age of SCGC.

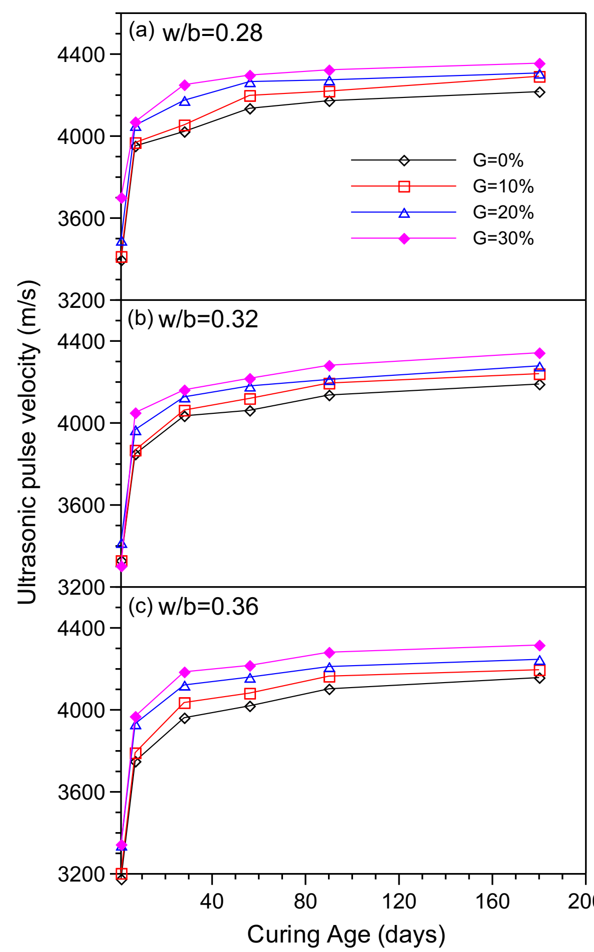

Fig. 2. Relationship between UPV and curing age of SCGC.

found mathematic models: exponential law, power law and linear law. Shan et al. [25] found that the residual strength of damaged concrete could be reasonably predicted and analyzed using the non-linear UPV method. Sturrup et al. [26] proposed a logarithmic relationship between the UPV and compressive strength, but the linear relationships were suggested in other studies [27–29]. Wang et al. [30,31] indicated that the compressive strength and UPV of SCGC and WGCLSM (waste glass controlled low strength material) increased approximately linearly. The test results in Fig. 4 show that the compressive strength of waste LCD glass concrete can be evaluated reasonably according to the aforesaid linear model, but the compressive strength and UPV have a truly nonlinear increasing relationship. Chen et al. [23] obtained the same trend in the study of high-performance waste LCD glass concrete. Therefore, using a nonlinear function to simulate the relationship between the compressive strength and UPV matches the test result trend and increases the accuracy of the analysis result. In addition, the test results show that with the same waste glass replacement, the relation curve of the compressive strength and UPV is influenced by the w/b slightly, as shown in Fig. 5.

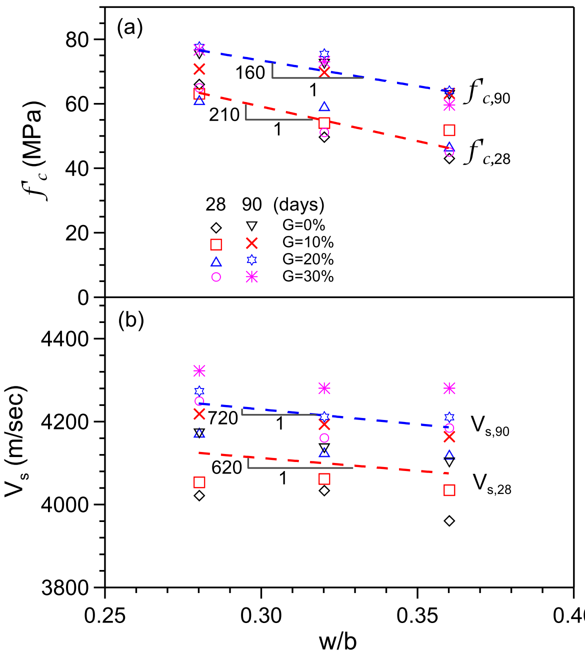

Fig. 3. Relationship of compressive strength and UPV versus water-binder ratio of SCGC.

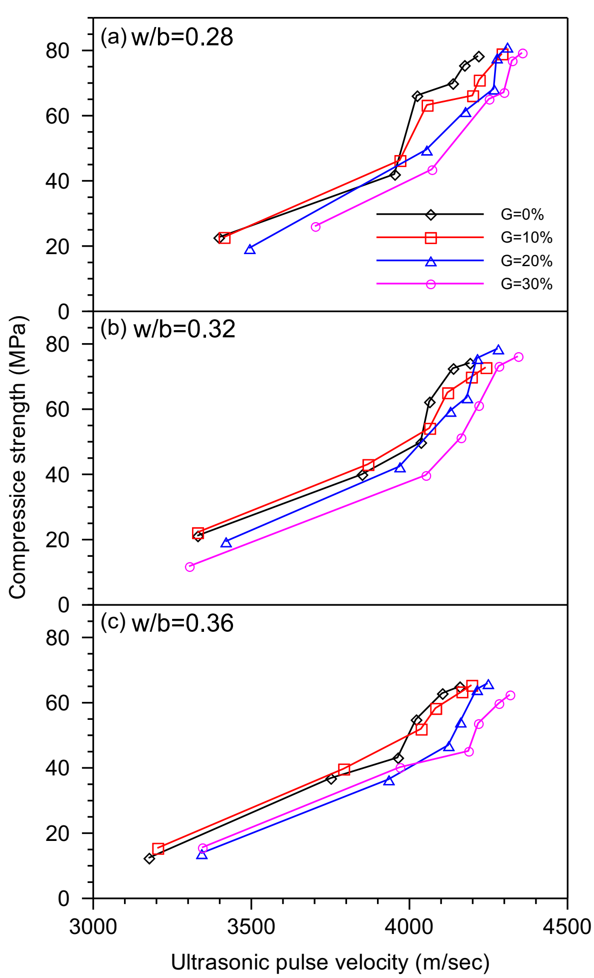

Fig. 4. Relationship between compressive strength and UPV of SCGC.

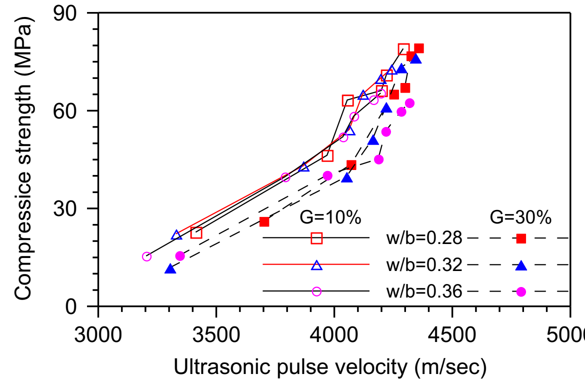

Fig. 5. Relationship between compressive strength and UPV on glass replacement of 10% and 30% for SCGC.

3.2. Effect of waste glass replacement on compressive strength and UPV

The test result shows that in the case of different w/b ratios, the compressive strength at various ages increases or decreases with waste glass replacement, but it mostly decreases as the waste glass replacement increases, as shown in Fig. 1. Wang et al. [10,32] found that the compressive strength of waste LCD glass concrete also decreased as the replacement with waste glass increased. The compressive strength of other waste glass concretes has the same trend [22,33]. Generally speaking, the compressive strength decreases as the waste glass replacement increases. The UPV increases with the waste glass replacement, as shown in Fig. 2. This may occur because the specific gravity of waste LCD glass sand is 2.45, which is lower than the specific gravity of natural river sand, 2.57. When the sand is replaced by the same weight of waste glass, because the volume of waste glass is relatively large, the fine grained glass sand may fill the natural river sand pores, thereby reducing the internal porosity of concrete. Therefore, the UPV increases with waste LCD glass sand replacement. Figs. 4 and 5 show that the relation curve of the compressive strength and UPV is influenced by w/b slightly but that the trend of the right shift with increasing waste glass replacement is quite significant. This result is identical to the findings of Wang [10]. Therefore, at the same compressive strength, the UPV increases with glass replacement. This result is considered when the nondestructive UPV is used to evaluate the compressive strength of waste glass concrete.

4. Relationship between compressive strength and UPV

Wang et al. [34] studied SCGC and proposed a prediction model for the relationships between both the compressive strength and UPV and age by using a hyperbolic function and power function, respectively, expressed as Eqs. (1) and (2). The prediction model can evaluate the test result reasonably, but at the initial age of curing, after the final setting time of concrete, the concrete material strength and UPV increase sharply because of the hydration. Therefore, in terms of the UPV, the power function has large errors at the initial age. In the same way, the UPV changes smoothly after a long age. However, the power function still increases, so there will also be large errors when the power function is used to analyze the long-age UPV. Therefore, when Eqs. (1) and (2) are combined for the prediction analysis of the relationship between the compressive strength and UPV, there will be large errors in the assay values of the initial and long ages, as shown in Fig. 6. In addition, Eqs. (1) and (2) are evaluation equations derived from the analysis of the

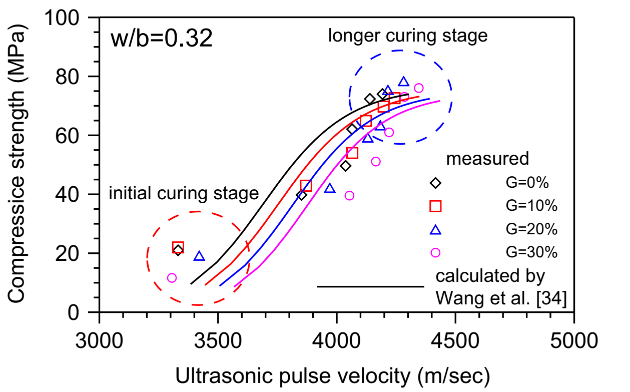

Fig. 6. Comparison of measured and calculated results of the strength-UPV relationship for SCGC.

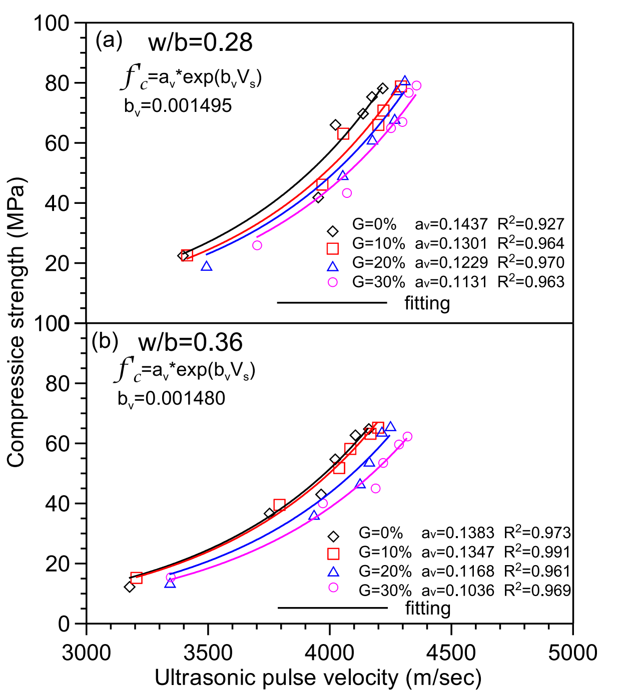

Fig. 7. The characteristics of strength-UPV relationship for SCGC.

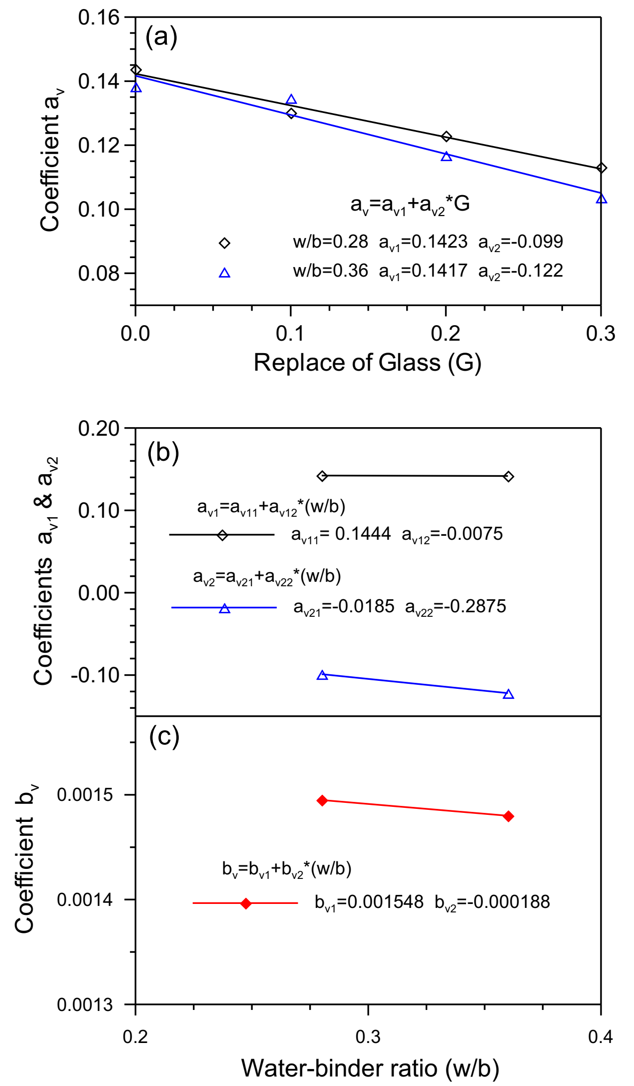

Fig. 8. The parameter characteristics versus water-binder ratio for compressive strength prediction model.

compressive strength and UPV test results. When the two equations are combined to validate the test results, there will be error accumulation. To remedy these errors in the analysis results effectively, this study will use the compressive strength and UPV test results directly for regression analysis and study the relationship between the compressive strength and UPV. The established evaluation method is quite helpful for the safety assessment analysis of structures using nondestructive testing UPV.

$$\frac{f'_c}{f'_{c,28}} = \frac{t}{[(m_1 + m_2(w/b)) + \alpha \times G] + [(n_1 + n_2(w/b)) + \beta \times G] \times t} \tag{1}$$

$$V_S = (m_{s1} + m_{s2} \times (w/b) + \alpha_s \times G) \times t^{(n_{s1}+n_{s2}\times(w/b)+\beta_s\times G)} \tag{2}$$

where α, β, α_s and β_s are parameters related to the waste glass content G. m_1, m_2, n_1, n_2, m_{s1}, m_{s2} n_{s1}, and n_{s2} are coefficients related to the water-binder ratio (w/b). $f'_{c,28}$ is the compressive strength on day 28.

This study will discuss the test results of w/b ratios 0.28 and 0.36 to build a UPV-based compressive strength prediction model, and the test result of w/b = 0.32 is used for model validation analysis. The test results show that in the case of a fixed w/b, the compressive strength and UPV have a nonlinear increasing relationship. This study uses an exponential function for the regression analysis of the test results. The analysis results show that the curves of the compressive strength and UPV of different waste

Table 3
Coefficients of compressive strength model based on UPV.

Material type	a_{v11}	a_{v12}	a_{v21}	a_{v22}	b_{v1}	b_{v2}
SCGC	0.1444	−0.0075	−0.0185	−0.2875	0.0016	-1.90×10^{-4}
WGCLSM	0.1597	−0.0508	−0.2079	0.0790	0.0013	-1.00×10^{-5}
HPGC	5.2694	−15.0283	−1.6449	4.5067	−0.0011	7.03×10^{-3}

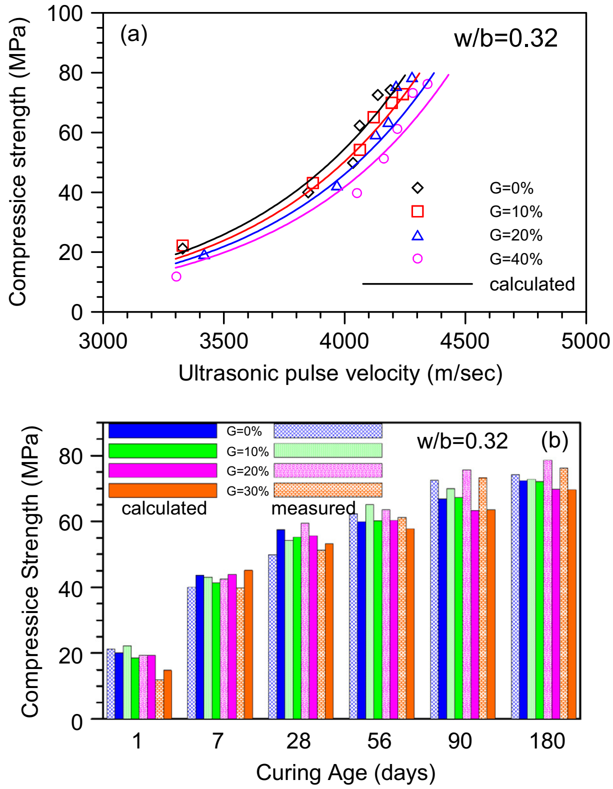

Fig. 9. Relationships of strength-UPV and strength-curing age were compared between the measured results and those calculated by the prediction model of this study. (w/b = 0.32 for SCGC).

glass replacements are approximately in a mutually parallel exponential function relationship. The coefficient of determination R^2 is between 0.927 and 0.991, as shown in Eq. (3) and Fig. 7. Therefore, the coefficient a_v is related to the w/b and glass replacement G value, expressed as Eq. (4). The coefficient a_v is determined by exponential function regression, and it decreases linearly as the waste glass replacement G value increases, as shown in Fig. 8(a) and Eq. (5). The a_{v1} and a_{v2} values decrease approximately linearly with w/b, as shown Fig. 8(b) and Eqs. (6) and (7). In the case of the same w/b, the compressive strength and UPV of different waste glass replacements have approximately a mutually parallel relationship. Therefore, the coefficient b_v value is unrelated to the waste glass replacement G value but has an approximately linear decreasing relationship to the w/b value, as shown in Fig. 8(c) and Eq. (8). Combining Eqs. (4)–(8), the compressive strength Eq. (3) can be changed to Eq. (9), and the model coefficients are shown in Table 3.

$$f'_c = f(w/b, G, V_s) = a_v \times \exp(b_v V_S) \tag{3}$$

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

$$a_v = a_{v1} + a_{v2} \times G \tag{5}$$

$$a_{v1} = a_{v11} + a_{v12} \times (w/b) \tag{6}$$

$$a_{v2} = a_{v21} + a_{v22} \times (w/b) \tag{7}$$

$$b_v = b_v(w/b) = b_{v1} + b_{v2} \times (w/b) \tag{8}$$

$$f'_c = [(a_{v11} + a_{v12}(w/b)) + (a_{v21} + a_{v22}(w/b))G] \times \exp[(b_{v1} + b_{v2}(w/b))V_S] \tag{9}$$

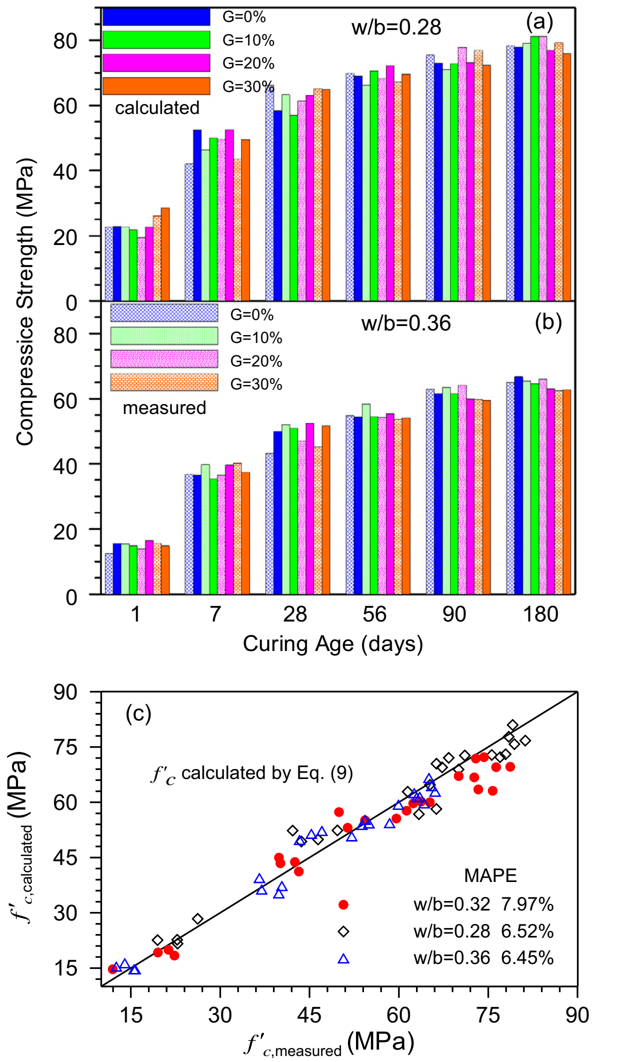

Fig. 10. Comparison of the measured results and those calculated by the prediction model of this study. (w/b = 0.28 and 0.36 for SCGC).

f'_c is the compressive strength, V_S is the UPV, w/b is the water-binder ratio, G is the glass replacement, and a_{v11}, a_{v12}, a_{v21}, a_{v22}, b_{v1}, and b_{v2} are the model coefficients related to w/b.

5. Comparison between prediction and test result

In the model derivation process, the compressive strength and UPV are discussed only according to the two groups of test results of w/b ratios 0.28 and 0.36, and the regression analysis of the influencing parameters is implemented. To validate the predictive ability of the compressive strength analysis model built in this study, the w/b ratios 0.28 and 0.36 are analyzed, and the test result of w/b = 0.32 and the findings for the waste LCD glass concrete of Chen et al. [23] and Wang et al. [31] are analyzed and compared.

Fig. 9(a) compares the assay value and test result of the relationship between the compressive strength and UPV when w/b = 0.32 using the prediction model of this study. The analysis result shows that the assay values of the compressive strength at various ages of different waste glass replacements are close to the test results, as shown in Fig. 9(b). The MAPE value is 7.97%, as shown in Fig. 10(c). The two groups of assay values of w/b ratios 0.28 and 0.36 are compared with the test results in Fig. 10 (a) and (b), and the corresponding MAPE values are 6.52% and

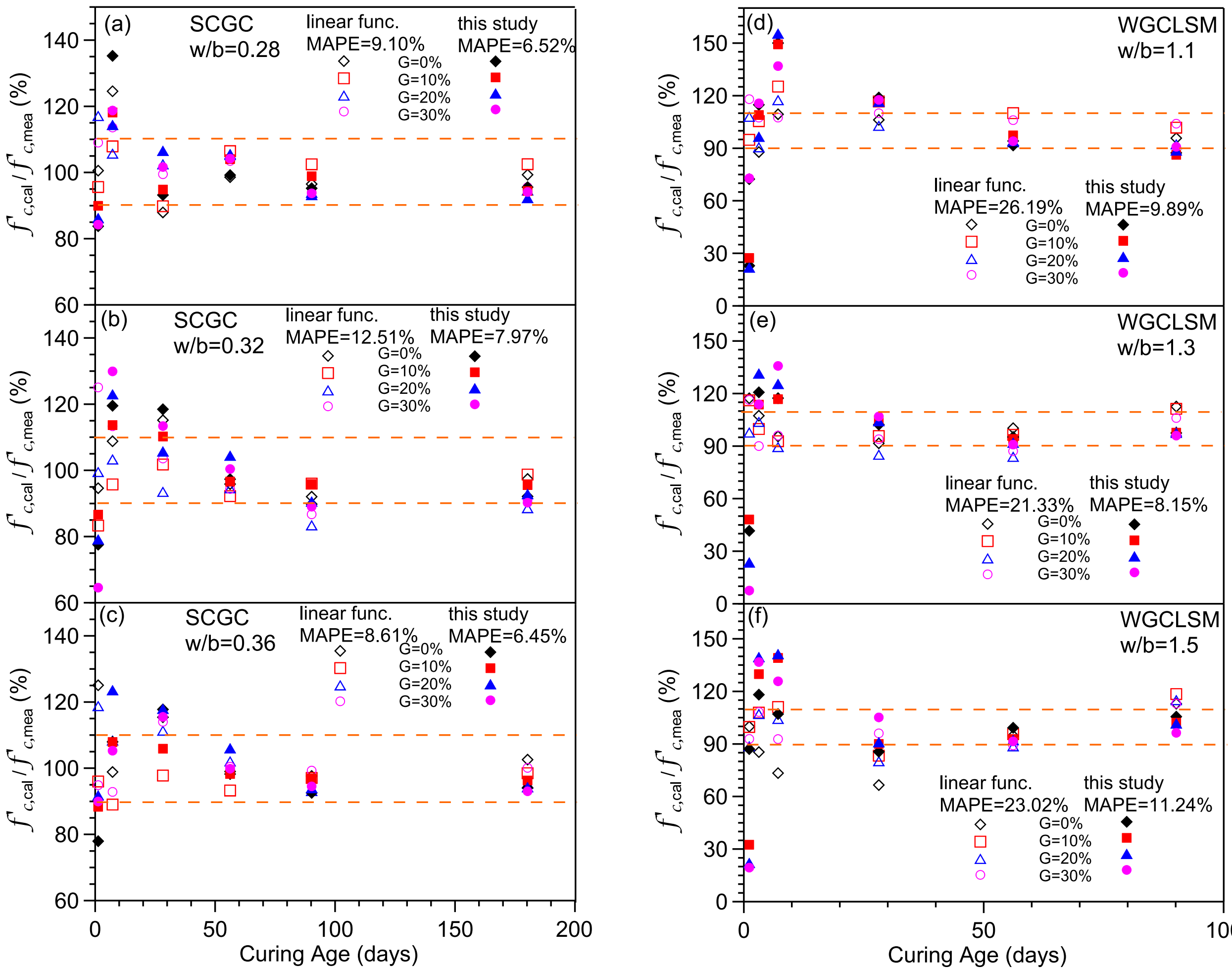

Fig. 11. Relationship between the compressive strength ratio and curing age for SCGC and WGCLSM.

6.45%, as shown in Fig. 10(c). When the compressive strength of SCGC is evaluated by a linear increasing relationship, the MAPE values corresponding to the w/b ratios 0.28, 0.32 and 0.36 are 9.10%, 12.51% and 8.61%, respectively. Therefore, the prediction model of the nonlinear exponential function relation between the compressive strength and UPV can decrease the MAPE value from 8.61–12.51% to 6.45–7.97%, and the analysis result accuracy is increased by 25.1–36.3%. The analysis result shows that the ratio of the compressive strength prediction analysis obtained by the nonlinear exponential function established in this study to the test result is mostly 90–110%, which is much more accurate than the ratio of 80–120% obtained by using a linear function, as shown in Fig. 11(a)–(c).

When the UPV is used to evaluate the compressive strength of the WGCLSM (waste glass controlled low strength material) by a linear function, the MAPE values corresponding to the w/b ratios 1.1, 1.3 and 1.5 are 26.19%, 21.33% and 23.02%, respectively. However, when the nonlinear exponential function established in this study is used for compressive strength analysis (see Table 3 for model coefficients), the obtained MAPE values are 9.89%, 8.15% and 11.24%, as shown in Fig. 11(d) and (f). The analysis result shows that the ratio of the compressive strength prediction analysis result obtained by the nonlinear exponential function established in this study to the test result is mostly 90–110%, much more accurate than the ratio of 30–150% obtained by using the linear function, but the early strength within the age of 7 days predicted by the linear function has considerable errors. Generally speaking, the MAPE value of the linear function decreases from 21.33–26.19% to 8.15–11.24%, and the analysis result accuracy is increased by 51.2% to 62.2%. Furthermore, the established model predicts the UPV of the high-performance recycled liquid crystal glass concrete (HPGC) well, as noted by Chen et al. [23]. Fig. 12(a) and (b) illustrate the relationship between the predicted and observed compressive strength with various curing ages. Fig. 12(c) shows the comparison of the predicted and measured compressive strength with different water-binder ratios. It is also obvious that the compressive strengths calculated from the prediction model are highly reasonable and, based on the MAPE, are 8.65% and 7.18% with water-binder ratios of 0.28 and 0.34, respectively.

As suggested in Lewis [35], when the MAPE is less than 10%, it indicates an excellent predictive ability; when the MAPE is 10–20%, it indicates a good predictive ability; when the MAPE is 20–50%, it indicates a reasonable predictive ability; and when the MAPE is greater than 50%, it indicates a poor predictive ability. According to this check analysis, when the UPV is used to predict the compressive strength of SCGC, WGCLSM or HPGC using a nonlinear exponential function, the MAPE value of the WGCLSM is 11.24% when w/b = 1.5, which is slightly higher than 10%, and the other MAPE values are lower than 10%. Therefore, the evaluation model for the compressive strength of the waste LCD glass concrete built on the UPV in this study has a good analysis result.

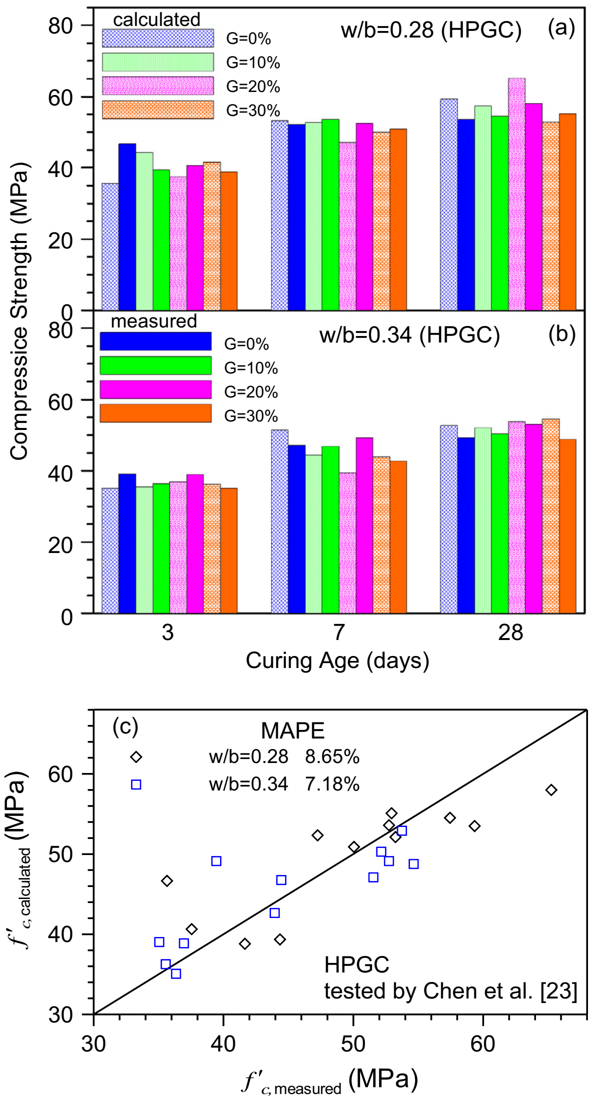

Fig. 12. Comparison of the measured results and those calculated by the prediction model of this study for HPGC.

6. Conclusions

1. Based on the exponential function, combining the compressive strength and UPV characteristics of waste LCD glass concrete, considering the w/b, waste glass replacement G and UPV variables, the compressive strength prediction analysis model is deduced. This evaluation method is very helpful for the safety assessment of concrete structures with similar mix proportions using nondestructive testing UPV.
2. The test result shows that the compressive strength and UPV of waste LCD glass concrete increase with age but decrease as the w/b increases. The compressive strength and UPV present an approximately nonlinear increasing relation curve. The w/b has an insignificant effect on the curve, but the trend of a right shift is quite obvious as the waste glass replacement increases. Therefore, at the same compressive strength, the UPV increases with the glass replacement. This result is considered when the nondestructive UPV is used to evaluate the compressive strength of waste glass concrete. In addition, the compressive strength of waste LCD glass concrete decreases as the waste glass replacement increases.
3. The check analysis of using this prediction model for the compressive strength of waste LCD glass concrete shows that the MAPE value of the compressive strength test result and assay value of SCGC is 6.45–7.97%, compared with the MAPE value of 8.61–12.51%, as obtained by linear function regression. The analysis result accuracy is increased by 25.1–36.3%. Similarly, the MAPE value of the WGCLSM is 8.15–11.24%, compared with the MAPE value of 21.33–26.19%, as obtained by linear function regression, and the accuracy is increased by 51.2–62.2%. Furthermore, the MAPE value of the HPGC is 7.18–8.65%. Therefore, the analytical model using the UPV to evaluate the compressive strength built in this study has good forecast accuracy for the waste LCD glass concrete for different functional requirements.

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References

[1] Y.Y. Gao, L.P. Liu, Y.J. Wang, LCD Panel Manufacturing Waste Resource Status of Comment, Green Foundation Newsletters, 2008 (Special Reports).
[2] C.C. Tseng, Competitiveness Analysis of Display Panel Industry in Taiwan and Korea (II), vol. 45, Chinese Society for Quality, 2009, pp. 48–52. Quality Magazine is Published by the Chinese Society for Quality, (2).
[3] S.C. Kou, C.S. Poon, Properties of self-compacting concrete prepared with recycled glass aggregate, Cem. Concr. Compos. 31 (2009) 107–113.
[4] I.B. Topcu, M. Canbaz, Properties of concrete containing waste glass, Cem. Concr. Res. 34 (2004) 267–274.
[5] H.Y. Wang, J.S. Chen, S.Y. Wang, Z.C. Chen, F.L. Chen, A study on the mix proportion and properties of wasted LCD glass applied to controlled low strength materials concrete (CLSM), J. Taiwan Concr. Inst. (2007).
[6] W.L. Huang, A Study on Waste LCD Glass Applied in Self-Compacting Concrete (Master dissertation), National Kaohsiung University of Applied Sciences, 2009 (in Kaohsiung).
[7] Z.Z. Ismail, E.A.A. Hashmi, Recycling of waste glass as a partial replacement for fine aggregate in concrete, Waste Manage. 29 (2009) 655–659.
[8] M.J. Terro, Properties of concrete made with recycled crushed glass at elevated temperatures, Build. Environ. 41 (2006) 633–639.
[9] S.B. Park, B.C. Lee, J.H. Kim, Studies on mechanical properties of concrete containing waste glass aggregate, Cem. Concr. Res. 34 (2004) 2181–2189.
[10] H.Y. Wang, A study of the engineering properties of waste LCD glass applied to controlled low strength materials concrete, Constr. Build. Mater. 23 (2009) 2127–2131.
[11] K.L. Lin, W.J. Huang, J.L. Shie, T.C. Lee, K.S. Wang, C.H. Lee, The utilization of thin film transistor liquid crystal display waste glass as a pozzolanic material, J. Hazard. Mater. 163 (2009) 916–921.
[12] R. Yu, D.V. Onna, P. Spiesz, Q.L. Yu, H.J.H. Brouwers, Development of ultra-lightweight fibre reinforced concrete applying expanded waste glass, J. Cleaner Prod. 112 (2016) 690–701.
[13] T.C. Ling, C.S. Poon, H.W. Wong, Management and recycling of waste glass in concrete products current situations in Hong Kong, Resour. Conserv. Recycl. 70 (2013) 25–31.
[14] H.Y. Wang, The effect of the proportion of thin film transistor-liquid crystal display (TFT-LCD) optical waste glass as a partial substitute for cement in cement mortar, Constr. Build. Mater. 25 (2011) 791–797.
[15] S.R.M. Khan, J. Noorzaei, M.R.A. Kadir, A.M.T. Waleed, M.S. Jaafar, UPV method for strength detection of high performance concrete, Struct. Surv. 25 (1) (2007) 61–73.
[16] C. Basyigit, B. Comak, S. Kılıncarslan, I.S. Uncu, Assessment of concrete compressive strength by image processing technique, Constr. Build. Mater. 37 (2012) 526–532.
[17] Y. Lin, C.P. Lai, T. Yen, Prediction of ultrasonic pulse velocity (UPV) in Concrete, ACI Mater. J. 100 (1) (2003) 21–28.
[18] G. Trtnik, F. Kavcic, G. Turk, Prediction of concrete strength using ultrasonic pulse velocity and artificial neural networks, Ultrasonics 49 (2009) 53–60.
[19] I.T. Yusuf, Y.A. Jimoh, Correlation of pundit ultrasonic pulse velocity with strength of palm kernel shell concrete, Ann. Faculty Eng. Hunedoara Int. J. Eng., 1584-2673 2 (2014) 51–57.
[20] H.Y. Wang, W.L. Huang, A study on the properties of fresh self-consolidating glass concrete (SCGC), Constr. Build. Mater. 24 (2010) 619–624.
[21] H.Y. Wang, W.L. Huang, Durability of self-consolidating concrete is using waste LCD glass, Constr. Build. Mater. 24 (2010) 1008–1013.
[22] M.C. Limbachiya, Bulk engineering and durability properties of washed glass sand concrete, Constr. Build. Mater. 23 (2009) 1078–1083.

[23] S.H. Chen, C.S. Chang, H.Y. Wang, W.L. Huang, Mixture design of high performance recycled liquid crystal glasses concrete (HPGC), Constr. Build. Mater. 25 (2011) 3886–3892.
[24] D. Breysse, Nondestructive evaluation of concrete strength: an historical review and a new perspective by combining NDT methods, Constr. Build. Mater. 33 (2012) 139–163.
[25] A.A. Shah, S.H. Alsayed, H. Abbas, Y.A. Al-Salloum, Predicting residual strength of non-linear ultrasonically evaluated damaged concrete using artificial neural network, Constr. Build. Mater. 29 (2012) 42–50.
[26] V. Sturrup, F. Vecchio, H. Caratin, Pulse velocity as a measure of concrete compressive strength, ACI Spec. Publ. 82 (1984) 201–208.
[27] W.F. Price, J.P. Haynes, In-situ strength testing of high strength concrete, Mag. Concr. Res. 4 (176) (1996) 189–197.
[28] K.K. Phoon, T.H. Wee, C.S. Loi, Development of statistical quality assurance criterion for concrete using ultrasonic pulse velocity method, ACI Mater. J. 96 (5) (1999) 568–573.
[29] A.E. Ben-Zeitun, Use of pulse velocity to predict compressive strength of concrete, Int. J. Cem. Compos. Lightweight Conc. 8 (1) (1986) 51–59.
[30] C.C. Wang, H.Y. Wang, S.H. Chen, C. Huang, Analytical model of ultrasonic pulse velocity of waste LCD glass concrete, J. Marine Sci. Technol. 23 (5) (2015) 732–740.
[31] C.C. Wang, H.Y. Wang, C.H. Chen, C. Huang, Prediction of compressive strength using ultrasonic pulse velocity for CLSM with waste LCD glass concrete, J. Civil Eng. Arch. 9 (5) (2015) 691–700.
[32] H.Y. Wang, J.S. Chen, Study of thin film transition liquid crystal display (TFT-LCD) optical waste glass applied in early-high-strength controlled low strength materials, Comput. Concr. 5 (5) (2008) 491–501.
[33] S.B. Park, B.C. Lee, J.H. Kim, Studies on mechanical properties of concrete containing waste glass aggregate, Cem. Concr. Res. 34 (2004) 2181–2189.
[34] C.C. Wang, H.Y. Wang, C. Huang, Predictive models of hardened mechanical properties of waste LCD glass concrete, Comput. Concr. 14 (5) (2014) 577–597.
[35] C.D. Lewis, Industrial and Business Forecasting Method, Butterworth Scientific Publishers, London, 1982.