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Prediction of Compressive Strength Using Ultrasonic Pulse Velocity for CLSM with Waste LCD Glass Concrete

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Abstract: The purpose of this paper is to develop a prediction model of WGCLSM (waste LCD (liquid crystal display) glass controlled low strength materials) concrete, the relationship between UPV (ultrasonic pulse velocity) and compressive strength, UPV-strength model. The power function was used to perform the nonlinear-multivariate regression analysis of UPV with water-binder ratio (w/b), curing age (t) and waste glass content (G) in our previous study. Test results show that the compressive strength increases with UPV and approach to a linear relationship. Thus, the UPV-strength model was established by linear-multivariate regression analysis and the compressive strength evaluated by ultrasonic pulse velocity. The calculated results are in accordance with the laboratory measured data ultrasonic pulse velocity and compressive strength. In addition, the statistical analysis shows that the coefficient of determination R^2 and the *MAPE* (mean absolute percentage error) were from 0.916 to 0.951 and 12.6% to 15.1% for the compressive strength, respectively. The proposed models are highly accurate in predicting the compressive and ultrasonic pulse velocity of WGCLSM concrete. However, with other ranges of mixture parameters, the predicted models must be further studied.

Key words: Glass concrete, CLSM, ultrasonic pulse velocity, compressive strength.

1. Introduction

CLSM (controlled low strength materials) are a new type of material being capable of replacing excellent class materials and the compressive strengths range between 345 kPa and 8,400 kPa. Also known as "flowable fill", these materials are used mainly for filling cavities in civil engineering projects where the application of granular fill is either impossible or difficult [1, 2]. CLSM mixtures have superior shear strength, cohesion intercept and angle of shearing resistance values compared to conventional soil materials after 7 days, making them ideal candidate materials for backfill applications [3]. The type of CLSM to be used needs to be selected according to technical and economic considerations for specific applications [4].

However, the compressive strength of concrete invariably forms the most important basis of specifications and quality control, as many other properties are directly or indirectly related to it [5]. And the compressive strength known as one of the most important characteristic in concrete is conventionally evaluated from the empirical velocity-strength relationships often given by manufactures of device or built up by users [6].

Recently, the investigation of non-destructive testing techniques is a very popular subject [7]. And the ultrasonic method is one of the non-destructive testing techniques and is frequently adopted for evaluating the quality of in situ concrete structures. It can measure the speed of wave through materials in order to predict material strength, calculate low-strain elastic modulus or to detect the presence of internal flaws such as cracking, voids, honeycomb, decay and other damages. This technique is applicable where intrusive (destructive) testing is not desirable and can be applied to concrete, ceramics, stone and timber [8]. And also, application of UPV (ultrasonic pulse velocity) to the non-destructive evaluation of normal strength concrete

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(≤ 41 MPa) quality has been widely investigated for decades [5].

In addition, many authors have studied how UPV can be correlated with concrete strength. An extensive review of their contributions has been undertaken [9]. Some previous researchers made use of the UPV of concrete to predict compressive strength and it is fundamental in such research work to study the relationship between UPV and compressive strength. Previous studies concluded that, for concrete with a particular mix proportion, there is a good correlation between UPV and the compressive strength. No clear rules have been presented to describe how the relationship between UPV and the compressive strength of concrete changes with its mix proportion. Therefore, there exists a high uncertainty when one try to make use of UPV to predict the strength of concrete in different mix proportions. It has also been established that UPV of hardened concrete is predictable based on its mix proportion. In addition, it has been known that the compressive strength of concrete corresponds with the mix proportion [10]. Yusuf and Jimoh [8], Mahure et al. [10] and Lawson et al. [11] developed theoretical UPV-strength models for normal concrete with high correlation at different times. Therefore, the purpose of this paper is to use the power function to perform the nonlinear-multivariate regression analysis of the UPV prediction model for self-compacting waste LCD (liquid crystal display) glass concrete, which was obtained in our previous study and the effects of water-binder ratio (*w/b*), curing age (*t*) and waste glass content (*G*) were considered [12]. Thus, this model was used and the relationship of UPV-strength was discussed to establish the UPV-strength model by multivariate regression analysis in WGCLSM (waste LCD glass controlled low strength materials) concrete.

2. Experimental Program

The purpose of this study is to integrate a series of experimental results with various mixture ratios of waste LCD glass applied to CLSM to discuss the relationship between concrete compressive strength and ultrasonic pulse velocity, and also to establish the UPV predictive analysis models to evaluate the concrete compressive strength. The multiple influencing factors of prediction models such as waste glass content, water-binder ratio and age. The types of material and mixture ratios are described in literatures [13-16].

The cement, fly ash and aggregate used in this study are local materials in compliance with specifications in ASTM (American Society of Testing Materials) C150, ASTM C618 and ASTM C33, respectively. Particulate waste glass sand, able to pass through a No. 8 sieve, was provided by Chi Mei Optoelectronics. The physical properties of the aggregate and glass sand are shown in Table 1 and the particle size distribution curves of the aggregate and glass sand are shown in Fig. 1.

The water-to-binder ratios were 1.1, 1.3 and 1.5, and four types of glass sand were added at volume replacement ratios of 0%, 10%, 20% and 30%. Fly ash and water quenched slag were added and blended using a CLSM mixing design method. The mixture proportions are shown in Table 2. And the compressive strength and ultrasonic pulse velocity, among other parameters, were measured.

3. Studying and Planning the Prediction Model for the UPV

3.1 UPV Prediction Model

Chen et al. [17] use mixture design of high performance recycled liquid crystal glasses concrete,

Table 1 Physical properties of aggregate and glass sand.

Items	$D_{\max}$ (mm)	Specific gravity	Unit weight (kg/m^3)	Water absorption (%)	Finess modulus
Coarse aggregate	125	2.65	1,530	-	-
Fine aggregate	23.6	2.63	1,760	1.5	2.73
LCD glass	11.8	2.42	1,680	0.45	3.37

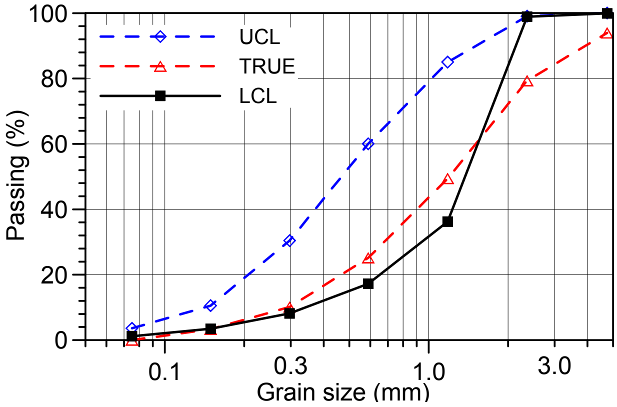


Fig. 1 Glass sand composition curve.

indicating that the UPV tends to increase with increasing waste glass content and maintenance age. However, after a period of time, the increase of the ultrasonic pulse velocity tends to become smooth. The relationship curve of the UPV and age is found to be similar to the power function. Hence, Wang et al. [12] suggested a prediction model of UPV for self-compacting waste LCD glass concrete with the replacement of waste LCD glass for the fine aggregate (sandy soil), which was our previous study and was shown in Eqs. (1) and (2). The prediction model was based on power function and nonlinear-multivariate regression analysis. In addition, this prediction model considering multiple variables of water-binder ratio, waste glass content and age and the test result exhibit good predictive capabilities. The details of predicted model and related parameters can be referred from Ref. [12].

As shown in Fig. 2, the experiment results of the WGCLSM UPV and age for various waste glass contents when the water-binder ratio is 1.1. For the same waste glass content G, the UPV V_s increases with the age t. However, the increasing tendency becomes smooth as the age t further increases. And the relation between the UPV and the age is simulated using a power function, as shown in Eq. (1). Figs. 3a-3c show the predicted results for the UPV of controlled low strength materials concrete with the replacement of waste LCD glass for the fine aggregate of 0%, 10%, 20% and 30%, respectively, in different water-binder ratios. As a result, UPV analysis value of the prediction model (Eq. (2)) can be reasonably calculated. When the prediction model of the waste glass concrete UPV is applied in the regression analysis of the experiment results, the model parameters are $\alpha_s = 330$, $\beta_s = 0.0255$, m_{s1} = 1,768.5, m_s2 = -248.3, n_{s1} = 0.1540 and n_{s2} = 0.0059:

$$V_s = a_{cs} \times t^{b_{cs}} \tag{1}$$

$$V_s = \left[m_{s1} + m_{s2} \times (w/b) + \alpha_s \times G\right] \times t^{\left[n_{s1} + n_{s2} \times (w/b) + \beta_s \times G\right]} \tag{2}$$

where, parameters a_s and b_s are the coefficients of the power function, and t is the curing age, α_s and β_s are the parameters that are related to the waste glass content

Table 2 Mixture proportions of WGCLSM.

w/b	No.	Binding materials (kg/m^3)			Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)			Water (kg/m^3)
		Cement	Glass powder 10%	Fly ash		Substitution (%)	Glass sand	Sand	
1.1	N11GS0	100	10	10	480	0	0	1,080	195.4
	N11GS1	100	10	10	480	10	108	972	195.4
	N11GS2	100	10	10	480	20	216	864	195.4
	N11GS3	100	10	10	480	30	324	756	195.4
1.3	N11GS0	100	10	10	480	0	0	1,080	230.9
	N11GS1	100	10	10	480	10	108	972	230.9
	N11GS2	100	10	10	480	20	216	864	230.9
	N11GS3	100	10	10	480	30	324	756	230.9
1.5	N11GS0	100	10	10	480	0	0	1,080	266.4
	N11GS1	100	10	10	480	10	108	972	266.4
	N11GS2	100	10	10	480	20	216	864	266.4
	N11GS3	100	10	10	480	30	324	756	266.4

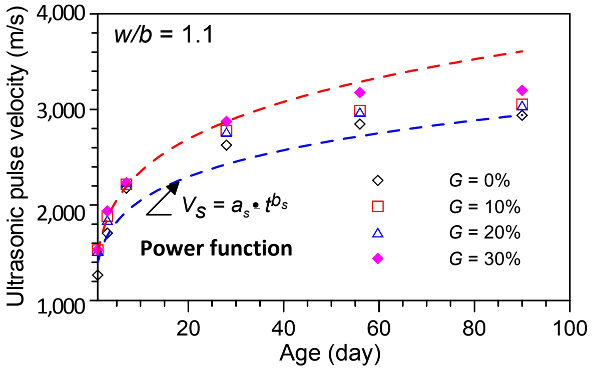
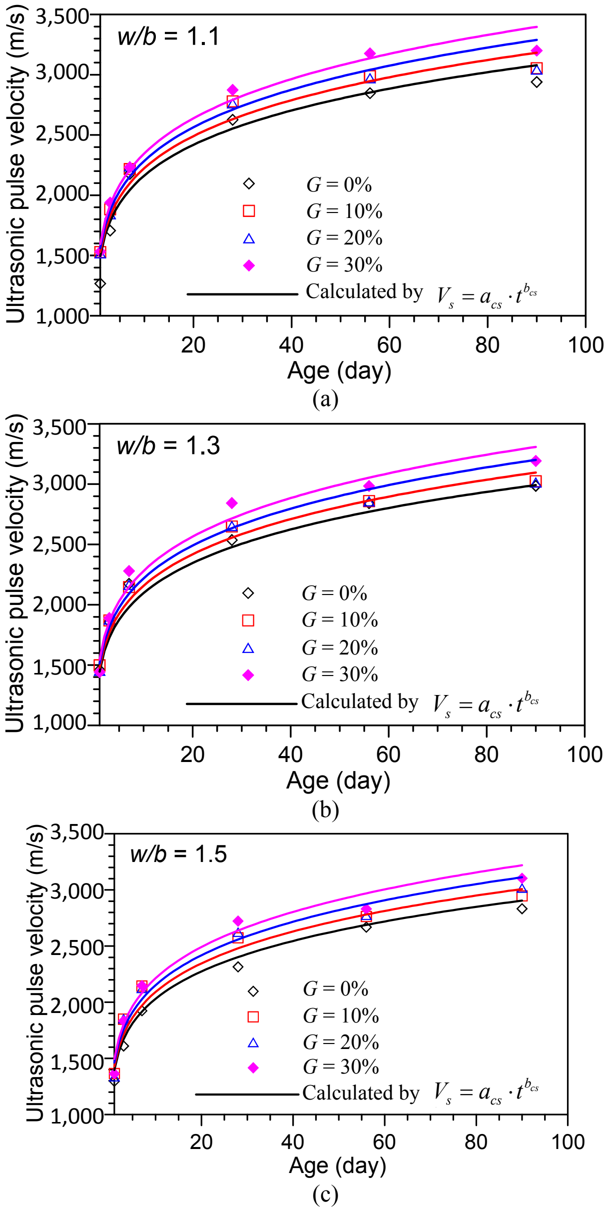


Fig. 2 Relationship of UPV and curing age.



(a)

(b)

(c)

Fig. 3 Comparison of predicted and measured results for ultrasonic pulse velocity: (a) water-binder ratio *w/b* is 1.1; (b) water-binder ratio *w/b* is 1.3; (c) water-binder ratio *w/b* is 1.5.

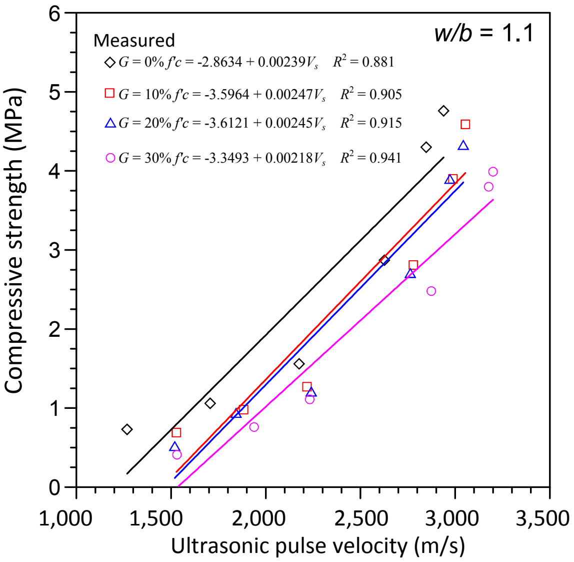


Fig. 4 Relationship of compressive strength and ultrasonic pulse velocity.

(G), and m_{s1}, m_{s2}, n_{s1} and n_{s2} are the coefficients of the water-binder ratio (w/b).

3.2 Development of UPV-Strength Predictive Model

Several relationships between UPV and compressive strength have been proposed, especially for normal density concrete [18-23]. Sturrup et al. [22] proposed a logarithmic relationship between UPV and compressive strength, while Price and Haynes [19], Phoon et al. [20] and Ben-Zeitun [21] suggested linear relationships. However, exponential relationships are the commonest [7, 18, 20, 24-28]. Furthermore, Breysse [29] found that the compressive strength of concrete can be reasonable evaluated by UPV, and the predicted model can be developed by linear, exponential and power law function.

Therefore, in this study, we explored the relationship between UPV and compressive strength. Fig. 4 illustrates the relationship of compressive strength and UPV for different waste glass contents when the water-binder ratio is 1.1. For the same waste glass content G, the compressive strength f_c' increases with UPV V_s and approaches to a linear relationship, and the coefficient of determination R^2 value between 0.88 and 0.94. Thus, the compressive strength can be established by a linear function of UPV, as shown in Eq. (3), where parameters a_{cs} and b_{cs} (shown in Table 3) are the coefficients of UPV-strength model by linear function. Similar phenomena were observed in other tests with various water-binder ratios. It is noteworthy that under identical conditions, parameter a_{cs} is in a certain range and slightly decreases with the waste glass content. Moreover, for different water-binder ratios, the trend tends to be a linear relationship of mutual parallel lines as shown in Fig. 5a. Therefore, in the model deduction, if parameter a_{cs} and the waste glass content G are in a linearly decreasing relationship, it can be described as shown in Eq. (4). Parameters m_{cs} and α_{cs} are the linear-relationship intercept and slope, respectively.

Furthermore, the relationship between parameter m_{cs} and water-binder ratio w/b is linearly increased as shown in Fig. 6a and expressed as Eq. (5). Table 3 shows that parameter b_{cs} did not affect various waste glass content. Therefore, no relationship is found as shown in Fig. 5b and the sensitivity of parameter b_{cs} expressed as Eq. (6). Similarly, a linear decreasing relationship (illustrated in Fig. 6b) between the parameter n_{cs} and the water-binder ratio w/b is shown in Eq. (7):

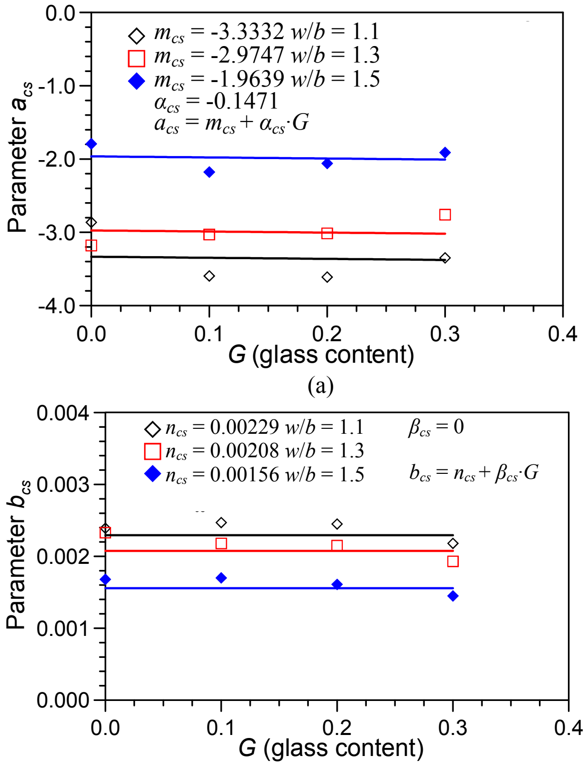
$$f_c' = a_{cs} + b_{cs} \times V_s \tag{3}$$

$$a_{cs} = m_{cs} + \alpha_{cs} \times G \tag{4}$$

$$m_{cs} = m_{cs1} + m_{cs2} \times (w/b) \tag{5}$$

Table 3 Values of parameter a_{cs} and b_{cs} for different mixtures.

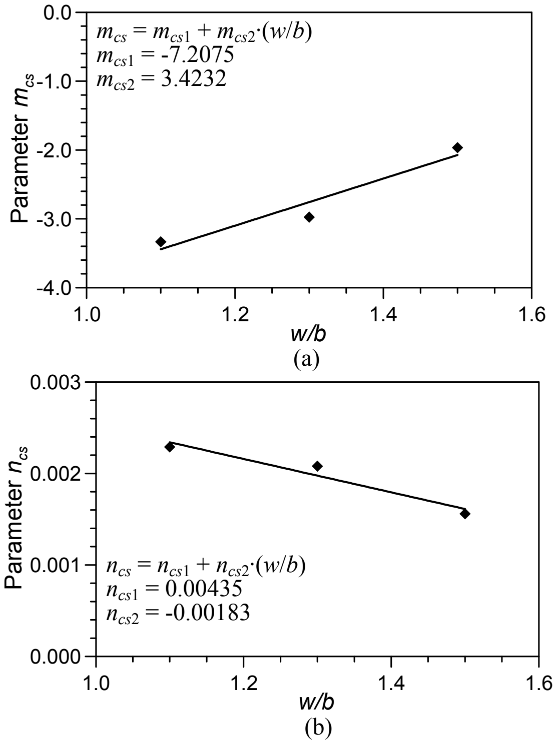
w/b	G	a_{cs}	b_{cs}
1.1	0.0	-2.863	0.00239
	0.1	-3.596	0.00247
	0.2	-3.612	0.00245
	0.3	-3.349	0.00218
1.3	0.0	-3.180	0.00233
	0.1	-3.031	0.00218
	0.2	-3.016	0.00215
	0.3	-2.761	0.00193
1.5	0.0	-1.793	0.00168
	0.1	-2.178	0.00170
	0.2	-2.059	0.00161
	0.3	-1.913	0.00145



(a)

(b)

Fig. 5 The characteristics of parameters of compressive strength predicted model: (a) parameter a_{cs} versus glass content; (b) parameter b_{cs} versus glass content.



(a)

(b)

Fig. 6 The characteristics of parameters of compressive strength predicted model: (a) parameter m_{cs} versus water to binder ratio ; (b) parameter n_{cs} versus water-binder ratio.

$$b_{cs} = n_{cs} + \beta_{cs} \times G \tag{6}$$

$$n_{cs} = n_{cs1} + n_{cs2} \times (w/b) \tag{7}$$

$$\begin{aligned} f_c' = {} & [m_{cs1} + m_{cs2} \times (w/b) + \alpha_{cs} \times G] \\ & + [n_{cs1} + n_{cs2} \times (w/b) + \beta_{cs} \times G] \times V_s \end{aligned} \tag{8}$$

where, α_{cs}, β_{cs}, m_{cs} and n_{cs} are the parameters related to waste glass content (G), and m_{cs1}, m_{cs2} and n_{cs1}, n_{cs2} are the coefficients related to water-binder ratio (w/b).

Eqs. (3)-(7) are combined, the compressive strength prediction model, based on function of ultrasonic pulse velocity, can be described as shown in Eq. (8). Thus, the established UPV-strength predictive model can be used to calculate the compressive strength by using UPV.

It is noteworthy that the factors of mixed proportion, water-binder ratio and admixture of replacement for fine aggregate, were not seldom considered to establish in most of the UPV-strength predictive model [30]. Furthermore, there are three factors can be considered in the UPV-strength predictive model suggested in this study, including the water-binder ratio, waste glass content and curing age. The factor of curing age was hidden in the predictive model of ultrasonic pulse velocity (Eq. (1)). When the prediction of the waste glass concrete compressive strength prediction model is applied in the regression analysis of the testing results, model parameters are α_{cs} = -0.1471, β_{cs} = 0, m_{cs1} = -7.208, m_{cs2} = 3.423, n_{cs1} = 0.00435 and n_{cs2} = -0.00183.

4. Comparison between the Predictive Analysis and Test Result

To determine the error between the model analysis result and the measured value, the MAPE (mean absolute percentage error) of Eq. (9) can be used for the evaluation. If the *MAPE* value is less than 10%, the model has excellent predictive ability; If *MAPE* is in range of 20%~50%, the model has good predictive ability; If the *MAPE* is more than 50%, the prediction results of the model are not accurate [31]. Furthermore, the coefficient of determination R^2 was used, obtained from regression analysis using the model for the predicted model analysis value and the experimental result. Mousavi et al. [32] studied high performance concrete and found that when comparing between the analytical result of a prediction model and the experimental value, if the coefficient of determination R^2 value is greater than 0.8, there is an excellent correlation. Therefore, we adopted the *MAPE* and R^2 values to determine the accuracy of various types of prediction models:

$$MAPE = \frac{1}{k}\sum_{i=1}^{k}\left|\frac{y_i - \hat{y}_i}{y_i}\right| \tag{9}$$

where, y_i = measured value, $\hat{y}_i$ = model analysis value and k = number of analytic data.

4.1 Ultrasonic Pulse Velocity

As shown in Fig. 7, the UPV prediction model (Eq. (2)) is applied in the analysis and the testing results of various waste glass content for different water-binder ratios. The comparison between the predicted ultrasonic pulse velocity values using the model and the actual experimental values is shown in Table 4.

In addition, the coefficient of determination R^2 was obtained from the regression analysis using the model for the predicted UPV analysis value and test result: when w/b is 1.1, R^2 = 0.973; when w/b is 1.3,

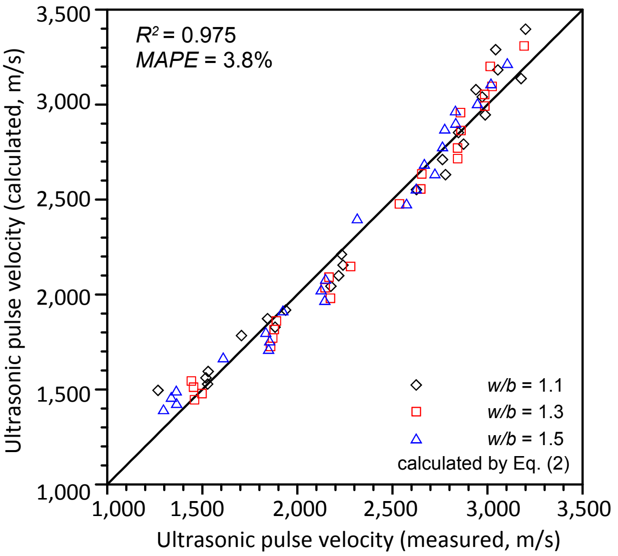
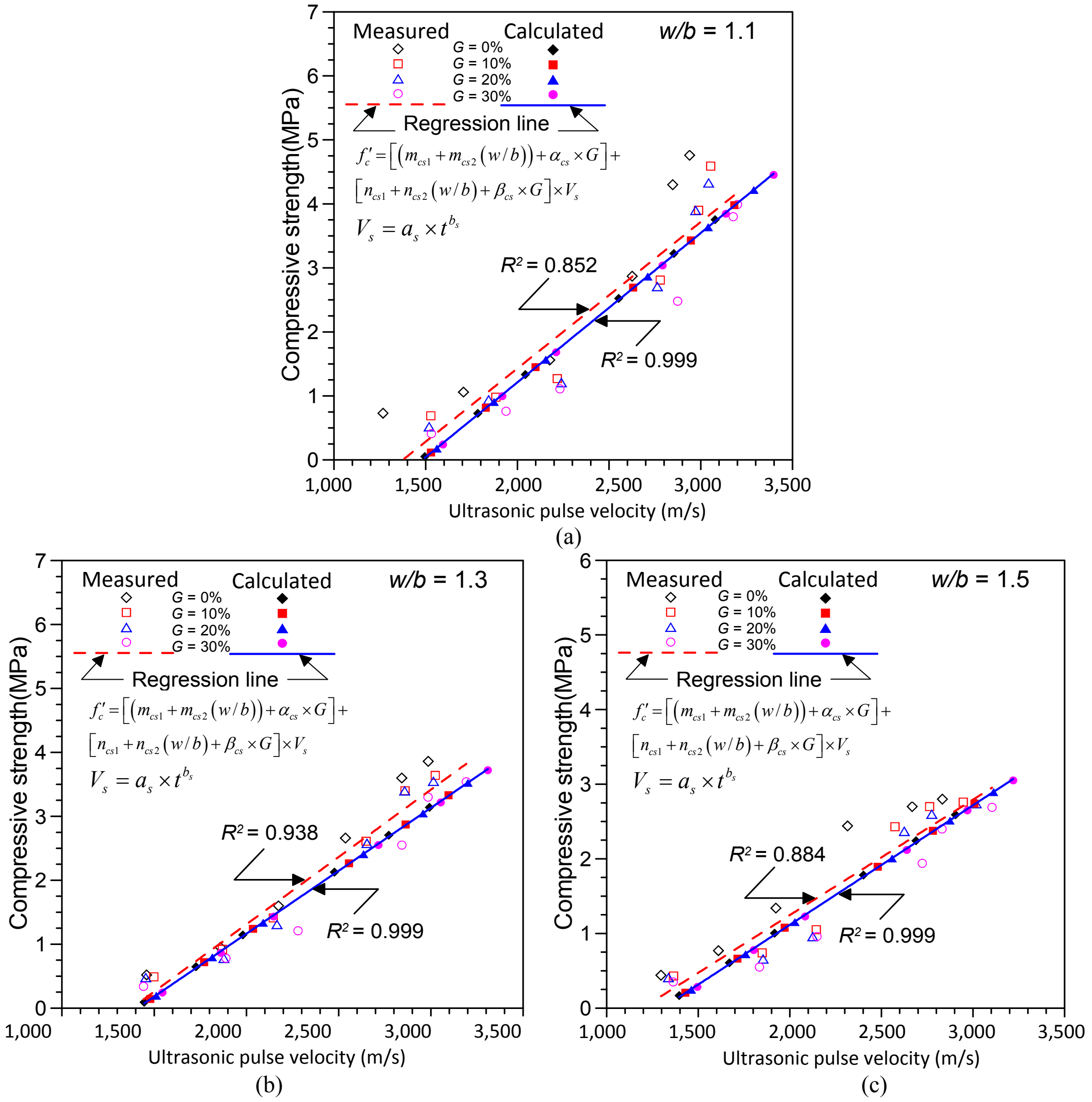


Fig. 7 Comparison of predicted and measured ultrasonic pulse velocity.

Table 4 Comparison of predicted and measured values of UPV.

w/b	No./age (day)	Experimental UPV (m/s)						Predicted ultrasonic pulse velocity (m/s)					
		1	3	7	28	56	90	1	3	7	28	56	90
1.1	N11GS0	1,267	1,706	2,176	2,626	2,847	2,939	1,495	1,784	2,043	2,553	2,853	3,079
	N11GS1	1,528	1,883	2,217	2,779	2,988	3,054	1,529	1,828	2,099	2,631	2,946	3,183
	N11GS2	1,519	1,843	2,240	2,763	2,972	3,043	1,561	1,873	2,155	2,711	3,041	3,289
	N11GS3	1,531	1,938	2,232	2,874	3,177	3,200	1,594	1,918	2,211	2,792	3,137	3,397
1.3	N11GS0	1,459	1,859	2,174	2,537	2,842	2,986	1,446	1,727	1,980	2,477	2,771	2,992
	N11GS1	1,498	1,870	2,146	2,649	2,860	3,024	1,479	1,771	2,035	2,556	2,864	3,096
	N11GS2	1,454	1,878	2,166	2,654	2,858	3,014	1,512	1,816	2,091	2,635	2,958	3,201
	N11GS3	1,442	1,889	2,280	2,843	2,985	3,192	1,545	1,860	2,147	2,716	3,054	3,309
1.5	N11GS0	1,296	1,610	1,924	2,315	2,668	2,833	1,396	1,670	1,916	2,402	2,689	2,905
	N11GS1	1,365	1,849	2,144	2,574	2,763	2,947	1,429	1,714	1,971	2,478	2,781	3,008
	N11GS2	1,337	1,854	2,125	2,625	2,775	3,018	1,462	1,758	2,027	2,558	2,874	3,113
	N11GS3	1,363	1,834	2,148	2,723	2,831	3,104	1,495	1,803	2,083	2,639	2,969	3,200



(a)

(b)

(c)

Fig. 8 Comparison of predicted and measured UPV-strength relationship: (a) water-binder ratio *w/b* is 1.1; (b) water-binder ratio *w/b* is 1.3; (c) water-binder ratio *w/b* is 1.5.

R^2 = 0.976; when *w/b* is 1.5, R^2 = 0.974. The analytic result shows that the *MAPE* value is 3.85%, 3.57% and 4.16% when the water-binder ratio *w/b* is 1.1, 1.3 and 1.5, respectively. The comparison of all water-binder ratio analysis values and testing results suggest that the coefficient of determination should be R^2 = 0.975, which is greater than 0.8, and *MAPE* = 3.80%, as shown in Fig. 7. Therefore, the UPV prediction model suggested by author's previous study, also has excellent prediction abilities in WGCLSM.

4.2 Comparison between the Test Result and Predictive Analysis by UPV-Strength Model.

Figs. 8a-8c show the results of the UPV-strength relationship for different water-binder ratio, the compressive strength established by the UPV-strength prediction model (Eq. (8)). The comparison of actual experimental values with predicted values of compressive strength by the UPV-strength model was shown in Table 5. All of the coefficients of determination R^2 for the regression results of calculated, when the water-binder ratio *w/b* is 1.1, 1.3 and 1.5, respectively, were equal to 0.999 and close to 1.0. In addition, the value of R^2 for test result is 0.852, 0.938 and 0.884, when the water-binder ratio is 1.1, 1.3 and 1.5, respectively. Thus, the analysis value and the test result show good accuracy, and the compressive strength and UPV has a linear relationship.

Furthermore, the coefficient of determination R^2 was obtained from the regression analysis using the UPV-strength prediction model for the predicted compressive strength analysis value and test result: when *w/b* is 1.1, R^2 = 0.916; when *w/b* is 1.3, R^2 = 0.951; when *w/b* is 1.5, R^2 = 0.917. In addition, the compressive strength and UPV of concrete would immediately increase and obviously change in the initial curing duration. Thus, it will have more error between the measured and predicted strength, which are calculated by UPV-strength model. Therefore, the tested results of compressive strength of initial curing time, such as 1 day, would be ignored when the values of predicted by UPV-strength model and tested strength are compared. According to the error analysis, the analytic result shows that the *MAPE* value is 16.5%, 12.6% and 15.1% when the water-binder ratio *w/b* is 1.1, 1.3 and 1.5, respectively. The comparison of all water-binder ratio analysis values and testing results suggest that the coefficient of determination should be R^2 = 0.932, which is greater than 0.8, and *MAPE* = 14.7%, as shown in Fig. 9. Therefore, the *MAPE* values of the compressive strength are less than 20%, established by UPV-strength model in this paper, meaning that the model's predictive ability is good.

Table 5 Comparison of predicted and measured values of compressive strength.

w/b	No./age (day)	Experimental compressive strength (MPa)						Predicted compressive strength (Eq. (8)) (MPa)					
		1	3	7	28	56	90	1	3	7	28	56	90
1.1	N11GS0	0.73	1.06	1.56	2.87	4.3	4.76	0.06	0.73	1.33	2.52	3.23	3.75
	N11GS1	0.69	0.98	1.27	2.81	3.9	4.59	0.12	0.82	1.45	2.69	3.43	3.98
	N11GS2	0.52	0.94	1.21	2.71	3.9	4.33	0.18	0.91	1.56	2.86	3.63	4.22
	N11GS3	0.41	0.76	1.11	2.48	3.8	3.99	0.24	1.00	1.68	3.04	3.84	4.45
1.3	N11GS0	0.52	0.95	1.6	2.66	3.6	3.86	0.09	0.65	1.45	2.13	2.70	3.14
	N11GS1	0.49	0.92	1.41	2.61	3.4	3.64	0.14	0.72	1.24	2.67	2.87	3.33
	N11GS2	0.48	0.78	1.31	2.58	3.4	3.55	0.19	0.79	1.34	2.41	3.04	3.52
	N11GS3	0.34	0.78	1.21	2.55	3.3	3.54	0.24	0.87	1.43	2.55	3.22	3.72
1.5	N11GS0	0.44	0.77	1.34	2.44	2.7	2.80	0.17	0.61	1.00	1.78	2.24	2.59
	N11GS1	0.43	0.74	1.05	2.43	2.7	2.76	0.21	0.66	1.08	1.89	2.38	2.74
	N11GS2	0.41	0.66	0.96	2.37	2.6	2.74	0.24	0.72	1.15	2.00	2.51	2.89
	N11GS3	0.35	0.55	0.96	1.94	2.4	2.69	0.28	0.78	1.23	2.12	2.65	3.05

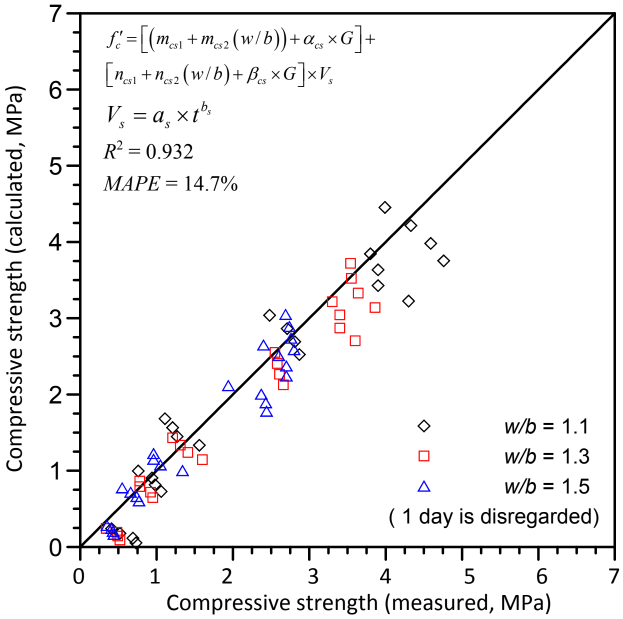


Fig. 9 Comparison of predicted and measured compressive strength.

5. Conclusions

From this study, some points can be drawn as follows:

(1) A compressive strength prediction model, established and based on UPV, was constructed by a linear relationship of UPV-strength. This model is not only function of UPV but also function of water-binder ratio, waste glass content and age. Therefore, this model can be used in preliminary compressive strength prediction by using factors of mixed proportion, such as water-binder ratio, waste glass content and curing age;

(2) Compared with the experimental and predicted result, estimated by UPV-strength model, the statistical analysis shows that the coefficients of determination R^2 and *MAPE* were obtained in the range of 0.916 to 0.951 and 12.6% to 15.1% for the compressive strength, respectively. As the result, the values of R^2 and *MAPE* are more than 0.90 and less than 20%, respectively. Therefore, the predicted compressive strength by using UPV-strength model proposed in this paper exhibits reasonable predictive capabilities;

(3) The UPV-strength model of WGCLSM concrete in this study assumes that the compressive strength increased with UPV by a linear relationship and the UPV increased with curing age by a power function. Therefore, the applicability of the prediction model, which was established using deduction and tendency of testing results, to other mixing conditions, should be further studied and validated.

References

[1] ACI (American Concrete Institute). 2011. *Controlled Low Strength Materials (CLSM)*. USA: ACI.

[2] Taha, R. A., Alnuaimi, A. S., Al-Jabri, K. S., and Al-Harthy, A. S. 2007. "Evaluation of Controlled Low Strength Materials Containing Industrial By-products." *Building and Environment* 42 (9): 3366-72.

[3] Türkel, S. 2006. "Long-Term Compressive Strength and Some Other Properties of Controlled Low Strength Pozzolanic Cement and Class C Fly Ash." *Journal of Hazardous Materials* 137 (1): 261-6.

[4] Türkel, S. 2007. "Strength Properties of Fly Ash-Based Controlled Low Strength Materials." *Journal of Hazardous Materials* 147 (3): 1015-9.

[5] Khan, S. R. M., Noorzaei, J., Kadir, M. R. A., Waleed, A. M. T., and Jaafar, M. S. 2007. "UPV Method for Strength Detection of High Performance Concrete." *Structural Survey* 25 (1): 61-73.

[6] Sheen, N. Y., Huang, J. L., and Le, D. H. 2013. "Predicting Strength Development of RMSM Using Ultrasonic Pulse Velocity and Artificial Neural Network." *Computers and Concrete* 12 (6): 785-802.

[7] Demirboğa, R., Türkmen, I., and Karakoç, M. B. 2004. "Relationship between Ultrasonic Velocity and Compressive Strength for High-Volume Mineral-Admixtured Concrete." *Cement and Concrete Research* 34: 2329-36.

[8] Yusuf, I. T., and Jimoh, Y. A. 2014. "Correlation of Pundit Ultrasonic Pulse Velocity with Strength of Palm Kernel Shell Concrete." *Annals of Faculty Engineering Hunedoara-International Journal of Engineering* 2: 51-7.

[9] Lin, Y., Lai, C. P., and Yen, T. 2003. "Prediction of Ultrasonic Pulse Velocity (UPV) in Concrete." *ACI Materials Journal* 100 (1): 21-8.

[10] Mahure, N. V., Vijh, G. K., Sharma, P., Sivakumar, N., and Ratnam, M. 2011. "Correlation between Pulse Velocity and Compressive Strength of Concrete." *International Journal of Earth Sciences and Engineering* 4 (6): 871-4.

[11] Lawson, I., Danso, K. A., Odoi, H. C., Adjei, C. A., Quashie, F. K., Mumuni, I. I., and Ibrahim, I. S. 2011. "Non-destructive Evaluation of Concrete Using Ultrasonic Pulse Velocity." *Research Journal of Applied Sciences, Engineering and Technology* 3 (6): 499-504.

[12] Wang, C. C., Wang, H. Y., Chen, S. H., and Huang, C. 2014. "Analytical Model of Ultrasonic Pulse Velocity of Waste LCD Glass Concrete." *Journal of Marine Science and Technology*. (under review)

[13] Wang, H. Y., and Chen, J. S. 2008. "Study of Thin Film Transition Liquid Crystal Display (TFT-LCD) Optical Waste Glass Applied in Early-High-Strength Controlled Low Strength Materials." *Computer and Concrete* 5 (5): 491-501.

[14] Wang, H. Y., Chen, J. S., Wang, S. Y., Chen, Z. C., and Chen, F. L. 2007. "A Study on the Mix Proportion and Properties of Wasted LCD Glass Applied to Controlled Low Strength Materials Concrete (CLSM)." Presented at TCI 2007 Concrete Technology Conference and Exhibition, Taiwan.

[15] Wang, H. Y. 2009. "A study of the Engineering Properties of Waste LCD Glass Applied to Controlled Low Strength Materials Concrete." *Construction and Building Materials* 23: 2127-31.

[16] Chen, J. S. 2008. "A Study on the Mix Proportion and Properties of Wasted LCD Glass Applied to Controlled Low Strength Materials Concrete (CLSM)." Master dissertation, National Kaohsiung University of Applied Sciences.

[17] Chen, S. H., Chang, C. S., Wang, H. Y., and Huang, W. L. 2011. "Mixture Design of High Performance Recycled Liquid Crystal Glasses Concrete (HPGC)." *Construction and Building Materials* 25: 3886-92.

[18] Ravindrarajah, R. S. 1992. "Strength Evaluation of High-Strength Concrete by Ultrasonic Pulse Velocity Method." *Non-destructive Testing-Australia* 29 (1): 6-9.

[19] Price, W. F., and Haynes, J. P. 1996. "In-situ Strength Testing of High Strength Concrete." *Magazine of Concrete Research* 4 (176): 189-97.

[20] Phoon, K. K., Wee, T. H., and Loi, C. S. 1999. "Development of Statistical Quality Assurance Criterion for Concrete Using Ultrasonic Pulse Velocity Method." *ACI Materials Journal* 96 (5): 568-73.

[21] Ben-Zeitun, A. E. 1986. "Use of Pulse Velocity to Predict Compressive Strength of Concrete." *International Journal of Cement Composites and Lightweight Concrete* 8 (1): 51-9.

[22] Sturrup, V., Vecchio, F., and Caratin, H. 1984. "Pulse Velocity as a Measure of Concrete Compressive Strength." *ACI Special Publication* 82: 201-8.

[23] Anderson, D. A., and Seals, R. K. 1981. "Pulse Velocity As a Predictor of 28- and 90-Day Strength." *Journal Proceedings* 78 (2): 116-22.

[24] Solís-Carcaño, R., and Moreno, E. 2008. "Evaluation of Concrete Made with Crushed Limestone Aggregate Based on Ultrasonic Pulse Velocity." *Construction and Building Materials* 22 (6): 1225-31.

[25] Chang, T. P., Lin, H. C., Chang, W. T., and Hsiao, J. F. 2006. "Engineering Properties of Lightweight Aggregate Concrete Assessed by Stress Wave Propagation Methods." *Cement and Concrete Composites* 28 (1): 57-68.

[26] Lin, Y., Kuo, S. F., Hsiao, C., and Lai, C. P. 2007. "Investigation of Pulse Velocity-Strength Relationship of Hardened Concrete." *Materials Journal* 104 (4): 344-50.

[27] Trtnik, G., Kavcic, F., and Turk, G. 2009. "Prediction of Concrete Strength Using Ultrasonic Pulse Velocity and Artificial Neural Networks." *Ultrasonics* 49 (1): 53-60.

[28] Bogas, J. A., Gomes, M. G., and Gomes, A. 2013. "Compressive Strength Evaluation of Structural Lightweight Concrete by Non-destructive Ultrasonic Pulse Velocity Method." *Ultrasonics* 53 (5): 962-72.

[29] Breysse, D. 2012. "Nondestructive Evaluation of Concrete Strength: An Historical Review and a New Perspective by Combining NDT Methods." *Construction and Building Materials* 33: 139-63.

[30] Wang, C. C., Chen, T. T., Wang, H. Y., and Huang, C. 2014. "A Predictive Model for Compressive Strength of Waste LCD Glass Concrete by Nonlinear-Multivariate Regression." *Computers and Concrete* 13 (4): 531-45.

[31] Lewis, C. D. 1982. *Industrial and Business Forecasting Method.* London: Butterworth Scientific Publishers.

[32] Mousavi, S. M., Aminian, P., Gandomi, A. H., Amir, A. H., and Bolandi, H. 2012. "New Predictive Model for Compressive Strength of HPC Using Gene Expression Programming." *Advances in Engineering Software* 45 (1): 105-14.