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ANALYTICAL MODEL OF ULTRASONIC PULSE VELOCITY OF WASTE LCD GLASS CONCRETE

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Key words: concrete, liquid crystal glasses, ultrasonic pulse velocity, prediction model.

ABSTRACT

The purpose of this study is to establish a prediction model for the ultrasonic pulse velocity (UPV) of waste LCD glass concrete and then analyze the results obtained from a series of laboratory tests. The power function is used to perform the nonlinear-multivariate regression analysis of the UPV prediction model, with parameters such as water-binder ratio (w/b), curing age (t) and waste glass content (G). According to the relative regression analysis, the UPV prediction model is developed. The calculated results are in accord with the laboratory-measured data, which are the concrete UPV of various mix proportions. The regression analysis results show that a good agreement is obtained using the proposed prediction model. Therefore, the predicted results for UPV are highly accurate for waste LCD glass applied in concrete. Additionally, the proposed prediction model exhibits a good predictive capacity when it is adapted to calculate the UPV of high-performance recycled liquid crystal glass concrete (HPGC), as performed in a previous study. However, further study is needed as regards applying the proposed prediction model to other ranges of mixture parameters.

I. INTRODUCTION

Ultrasonic pulse velocity (UPV) is a non-destructive technique that involves measuring the speed of a wave through material in order 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. However, it is difficult to accurately evaluate the compressive strength of concrete with this method, since the UPV values are affected by a number of factors, such as mix proportions, aggregate type, age of concrete, moisture content and other factors. However, the factors which might significantly affect the strength of the concrete have little influence on the UPV. As a result, a strength estimated with the pulse velocity method is not a broad-spectrum technique. Therefore, the derived relations can be used for structures made with the same materials at any time during its service period (Lin et al., 2003; Trtnik et al., 2009; Yusuf and Jimoh, 2014).

Glass contains large amounts of silicon and calcium, and it is classified as a Portland material. Its physical properties, such as unit weight, compressive strength, elasticity modulus, thermal expansion coefficient and heat transfer coefficient, are notably close to those of concrete. Therefore, the adding of crushed waste glass to concrete as a fine aggregate can effectively reduce the air content and unit weight of concrete and improve its performance (Topcu and Canbaz, 2004; Wang et al., 2007; Huang, 2009). As a result, the material costs can be reduced, as well as lead to a decrease in the CO_2 emissions, thus making this recycling process the preferred method for sustainable development.

Previous studies have generally focused on investigating the workability and strength properties of recycled concrete, and there has been less discussion of the property prediction model based on the UPV of various concrete materials. Therefore, based on the results of previous studies on concrete with various mixture ratios of waste LCD glass (Huang, 2009), the relationships between the UPV and the influencing factors, such as waste glass content, water-binder ratio and age, were chosen as the focus for this study. The findings will help in the establishing of a database and hardened property prediction model of waste glass concrete, as well as serve as a reference for mixture ratio applications in the future.

II. CHARACTERISTICS OF GLASS AND WASTE LCD GLASS CONCRETE

Ismail and AL-Hashmi (2009) used recycled glass to par-

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Table 1. Chemical properties of LCD glass sand.

	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	Na_2O	MgO	TiO_2	P_2O_5
LCD glass	62.48%	16.76%	9.41%	2.70%	1.37%	0.64%	0.20%	0.01%	0.01%

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	–	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	–	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	–	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

tially replace the fine aggregate content (maximum particle diameter of 20 mm and bulk density of 1545 kg/m^3). Their study showed that the mechanical properties of concrete, such as compressive strength and flexural strength, decreased when the waste glass content was increased. Other studies have reported the same trend (Park et al., 2004; Topcu and Canbaz, 2004; Terro, 2006; Wang and Chen, 2008; Kou and Poon, 2009; Wang, 2009; Wang, 2011; Lin et al., 2012).

On the other hand, because glass sand has a smaller particle size than normal-weight sand, it can fill the gaps in the normal-weight sand and reduce the internal pores in the concrete. Therefore, when the content of waste glass sand increases, the UPV also increases. However, as the water-binder ratio and the mixing water content increase, the concrete is prone to pores, which affects the velocity of compressive stress wave passes. Therefore, the UPV tends to decline with an increased water-binder ratio (Huang, 2009).

As shown in the previous study, when recycled glass, waste glass or waste LCD glass are primarily used to replace the aggregate, the compressive strength or flexural strength of the concrete decreases as the admixture portion level increases. However, the UPV increases accordingly.

In addition, the compressive strength, flexural strength and UPV of the concrete with waste glass exhibit similar behavior to that of general concrete. For example, the compressive strength, flexural strength and UPV increase with curing time. Besides, after a certain age, the increasing trend will level out. Similarly, the compressive strength, flexural strength and UPV decrease when the water-binder ratio increases.

III. EXPERIMENTAL PROGRAM

In this study, the results from experiments conducted using various mixture ratios of self-compacting waste LCD glass concrete form the basis of the discussion of the relationships between the multiple factors influencing the UPV, such as waste glass content, water-binder ratio and age, in order to establish predictive analysis models for the evaluation of the UPV. The details of material types, mixture ratios and the physical properties of the aggregate and glass sand are described in previous studies (Huang, 2009; Wang and Huang, 2010a, 2010b).

The cement, fly ash and slag used in this study were local materials in compliance with the Taiwanese specifications CNS61, CNS3036 and CNS12549, respectively. Particulate waste glass sand, which can pass through a No. 8 sieve, was provided by Chi Mei Optoelectronics. Of the waste LC glasses, the SiO_2 ratio was the highest, at about 62.48%, so it acted as a high Si material. Also present in the waste LC glasses, in decreasing order of ratio, were Al_2O_3, Fe_2O_3, CaO and K_2O. The chemical compositions of the LC glasses are shown in Table 1. The fineness modulus of the LC glass sand was 3.37. The water-to-binder ratios were set as 0.28, 0.32 and 0.36, and 4 types of glass sand were added at volume replacement ratios of 0%, 10%, 20% and 30%. Fly ash, water-quenched slag and superplasticizer were added and blended using a simple SCC (self-consolidating concrete) mixing design method to explore the mixing, hardening and durability properties. The compressive strength, flexural strength and

UPV, among other parameters, were measured. The SCGC (self-consolidating glass concrete) mixture proportions are shown in Table 2.

IV. STUDYING AND PLANNING THE PREDICTION MODEL FOR THE ULTRASONIC PULSE VELOCITY

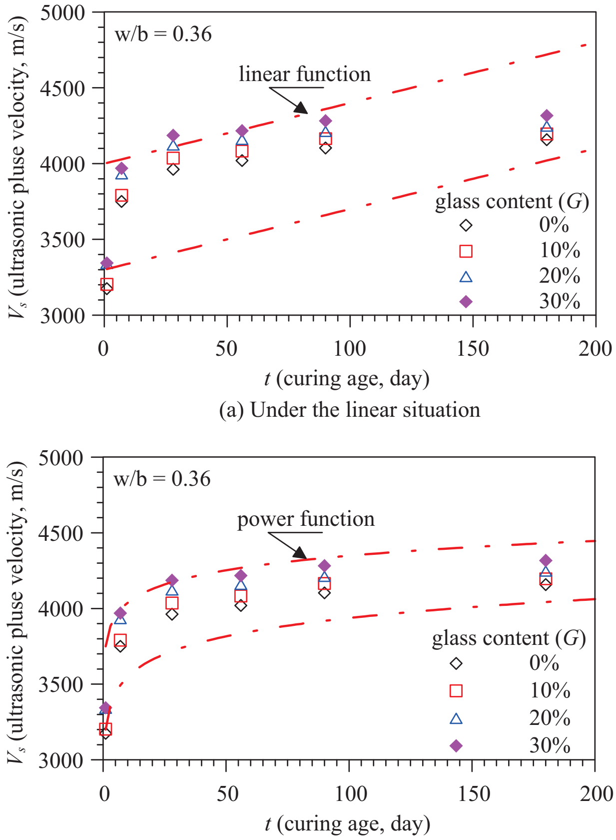
1. Development of Ultrasonic Pulse Velocity Prediction Model

Many authors have studied how UPV can be correlated with concrete strength. An extensive review of their contributions was undertaken. Sheen et al. (2013) used two approaches for their analysis. First, the nonlinear regression method (RM) was used to build up the empirical UPV-strength relationship based on test data. Second, the artificial neural network (ANN), using a combination of pulse velocity and other factors, such as curing time and mixed-composition as inputs of the network, was employed to interpolate the strength. Breysse (2012) further condensed the UPV-strength and rebound number-strength models utilizing three commonly found mathematic models: exponential law, power law and linear law. In this study, the power function was selected to explore the non-linear relationship between the UPV and the age.

Chen et al. (2011), using a mixture design of high-performance recycled liquid crystal glass concrete, found the correlation coefficient (R value) between age and UPV to be over 0.928, meaning the UPV was gradually growing with age. However, during the initial curing stage after mixing, the concrete gradually hardened from its flowing state of the initial setting to its solid stage of the final setting. Therefore, its mechanical properties significantly changed, which meant that a specimen aged for one day has the appropriate compressive strength; therefore, its UPV is considerable, as shown in Fig. 1(a). Although the UPV sharply increased when the final setting of the specimen was reached, the increment of compressive strength was usually smaller than that of the UPV, and there was little difference in the tendency of strength and the UPV to increase.

In addition, before concrete is damaged, the UPV and compressive strength are in an exponentially increasing relationship. Shah et al. (2012) adapted the neural network algorithm to predict the residual strength of damaged concrete. They found that the residual strength could be reasonably predicted and analyzed using the non-linear UPV method. According to the findings on waste LCD glass concrete by Wang (2009), the UPV has the same tendency as the compression strength and the flexural strength to increase with longer age. However, this tendency tended to level out after a certain period of time.

Hence, the sharp rise in the UPV of concrete after the initial setting and the gradually leveling out of the UPV were simulated in the model for predicting the UPV. Fig. 1(b) illustrates the test results of the UPV and age of concrete with different waste glass contents and a water-binder ratio of 0.36. For the same waste glass content, G, the ultrasonic pulse velocity, V_s increased with the age, t, but the tendency to increase leveled out as the age further increased. Therefore, the relationship between the UPV and the age was simulated using a power function, as shown in Eq. (1), where parameters a_s and b_s are the coefficients of the power function and t is the age.



(a) Under the linear situation

(b) After transfer to power function

Fig. 1. Ultrasonic pulse velocity *vs*. curing age.

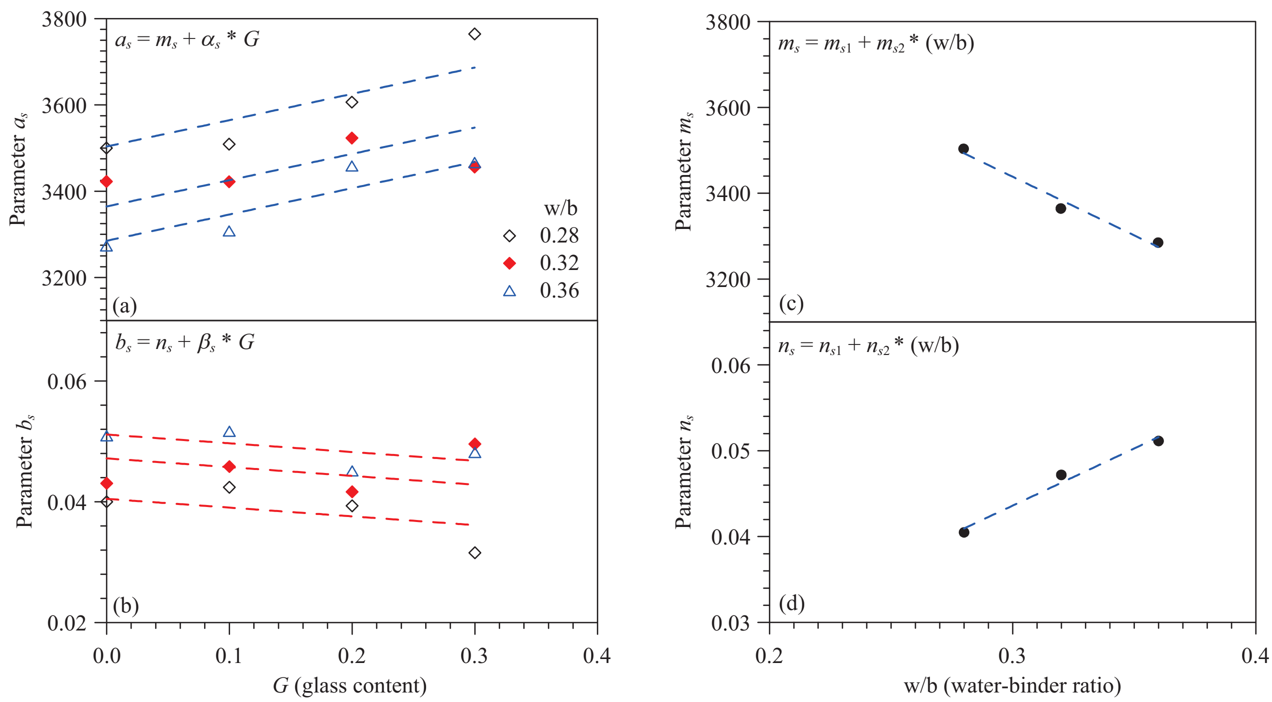
$$V_s = a_s \times t^{b_s} \tag{1}$$

2. Determine Parameters of the Ultrasonic Pulse Velocity Prediction Model

Under identical age conditions, the UPV tended to increase with increases in the amount of waste glass; similar phenomena were observed in other tests with various water-binder ratios. Table 3 shows the parameters, a_s and b_s, of the various water-binder ratios. Fig. 2(a) shows the relationship between parameter a_s and glass content G (various water-binder ratios). We found that under identical conditions, parameter a_s increased with the waste glass content. Moreover, for different water-binder ratios, the trend was to a linear relationship of mutual parallel lines, as shown in Fig. 2(a). Therefore, when parameter a_s and the waste glass content G are in a linearly

Table 3. Values of parameters a_s and b_s for different mixtures.

w/b	G	a_s	b_s
0.28	0	3500	0.040
	0.1	3509	0.042
	0.2	3606	0.039
	0.3	3764	0.032
0.32	0	3420	0.043
	0.1	3422	0.046
	0.2	3523	0.042
	0.3	3456	0.050
0.36	0	3273	0.051
	0.1	3307	0.052
	0.2	3458	0.045
	0.3	3466	0.048



(a) (b) Parameters a_s and b_s *vs*. glass content.

(c) (d) Parameters m_s and n_s *vs*. water-binder ratio

Fig. 2. The characteristic of parameters of UPV prediction model.

increasing relationship, the deduction model can be described as shown in Eq. (2), where parameters m_s and α_s are the linear-relationship interception and slope, respectively. Furthermore, the relationship between parameter m_s and the water-binder ratio, w/b, is a linearly decreasing relationship, as shown in Fig. 2(c) and expressed as in Eq. (3).

Similarly, Fig. 2(b) shows the relationship between parameter b_s and glass content G (various water-binder ratios). We found that the relationship between parameter b_s and the waste glass content was a linearly decreasing one, as shown in Fig. 2(b) and as expressed in Eq. (4), where parameters n_s and β_s are the linear-relationship interception and slope, respectively. The relationship between parameter n_s and the water-binder ratio, w/b, was a linearly increasing one, as shown in Fig. 2(d) and expressed as Eq. (5).

$$a_s = m_s + \alpha_s \times G \quad (2)$$

$$m_s = m_{s1} + m_{s2} \times (\mathrm{w/b}) \quad (3)$$

$$b_s = n_s + \beta_s \times G \quad (4)$$

$$n_s = n_{s1} + n_{s2} \times (\mathrm{w/b}) \quad (5)$$

$$V_s = \left(m_{s1} + m_{s2} \times (\mathrm{w/b}) + \alpha_s \times G\right) \times t^{\left(n_{s1} + n_{s2} \times (\mathrm{w/b}) + \beta_s \times G\right)} \quad (6)$$

Table 4. Comparison of predicted values of UPV by the model with actual experimental values.

w/b	No.	Tested ultrasonic pulse velocity (m/s)						Predicted ultrasonic pulse velocity (m/s)					
	Age (day)	1	7	28	56	90	180	1	7	28	56	90	180
0.28	SC28G0	3396	3952	4023	4136	4173	4217	3494	3783	4004	4119	4200	4321
	SC28G10	3413	3969	4055	4199	4220	4292	3555	3839	4054	4167	4246	4364
	SC28G20	3493	4053	4175	4266	4275	4308	3616	3893	4104	4214	4291	4405
	SC28G30	3701	4070	4251	4298	4324	4356	3677	3948	4153	4260	4335	4446
0.32	SC32G0	3329	3849	4035	4062	4137	4190	3384	3703	3948	4077	4168	4303
	SC32G10	3329	3868	4063	4120	4195	4241	3445	3759	4000	4126	4215	4348
	SC32G20	3418	3968	4128	4181	4213	4279	3506	3815	4051	4175	4262	4392
	SC32G30	3303	4051	4162	4218	4282	4343	3567	3870	4102	4223	4308	4435
0.36	SC36G0	3175	3750	3962	4020	4103	4158	3275	3621	3889	4031	4131	4281
	SC36G10	3203	3791	4036	4082	4165	4196	3336	3678	3943	4082	4180	4328
	SC36G20	3341	3933	4122	4160	4212	4247	3397	3735	3995	4132	4229	4374
	SC36G30	3344	3969	4186	4217	4282	4317	3458	3791	4047	4182	4277	4419

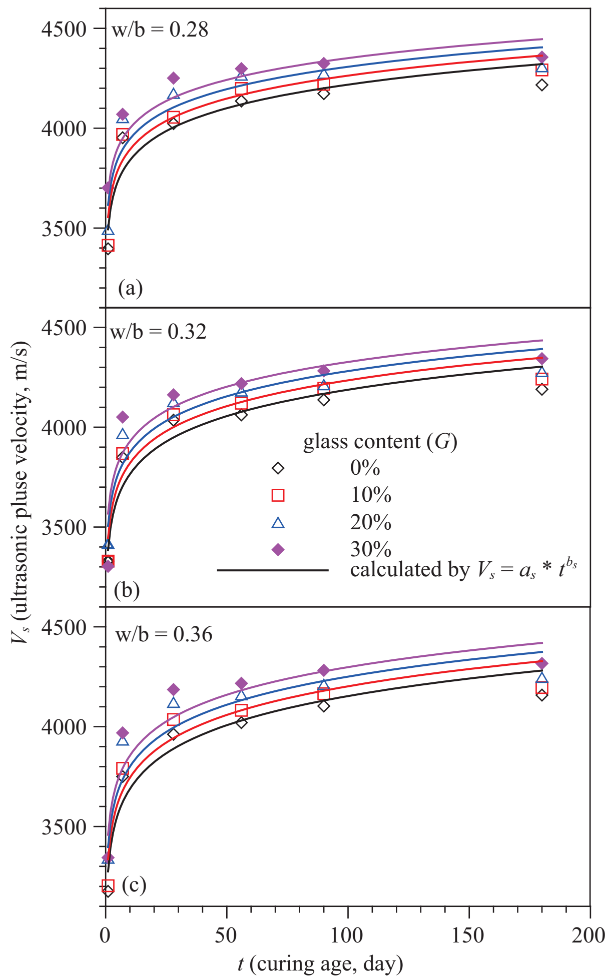


Fig. 3. Comparison of predicted model and test results for UPV

where α_s, β_s, m_s and n_s are the parameters relating to the waste glass content (G); and m_{s1}, m_{s2} and n_{s1}, n_{s2} are the coefficients of the water-binder ratio (w/b). Eqs. (1) to (5) were combined, and the UPV prediction model is described as shown in Eq. (6). When the prediction model of the waste glass concrete UPV was applied in the regression analysis of the test results, the model parameters were $\alpha_s = 610$, $\beta_s = -0.0145$, $m_{s1} = 4258.7$, $m_{s2} = -2732.5$, $n_{s1} = 0.0037$ and $n_{s2} = 0.1331$. More information on this model can be found in the authors' previous study (Wang et al., 2014b).

V. COMPARISON BETWEEN THE PREDICTIVE ANALYSIS AND TEST RESULTS OF ULTRASONIC PULSE VELOCITY

1. Ultrasonic Pulse Velocity

Figs. 3(a) to 3(c) show the test results for the UPV of self-compacting waste LCD glass concrete in which the fine aggregate (sandy soil) has been replaced by waste LCD glass in weight percentages of G of 0%, 10%, 20% and 30%, respectively, in different water-binder ratios. As shown in the figures, the velocity analysis value of the prediction model (Eq. (6)) could be both overrated and underrated, but the result of the overall analysis was reasonable. The comparison of the predicted values of UPV by the model with the actual experimental values is shown in Table 4.

In addition, to determine the error between the model analysis results and the measurements, the MAPE (mean absolute percentage error) of Eq. (7) was used. A value of less than 10% indicated that the developed prediction model performed with a good accuracy. If the MAPE was in the range of 20%-50%, then the model error was still reasonable. An error over 50% (Lewis, 1982) indicated an incorrect model with too great an error factor. The analytical result showed that when the water-binder ratios, w/b, were 0.28, 0.32 and 0.36, the MAPE values were 1.8%, 2.1% and 2.2%, respectively. According to the error analysis, the MAPE values of the developed model as reported in this paper were all less than 10%, meaning that the model's predictive ability was excellent.

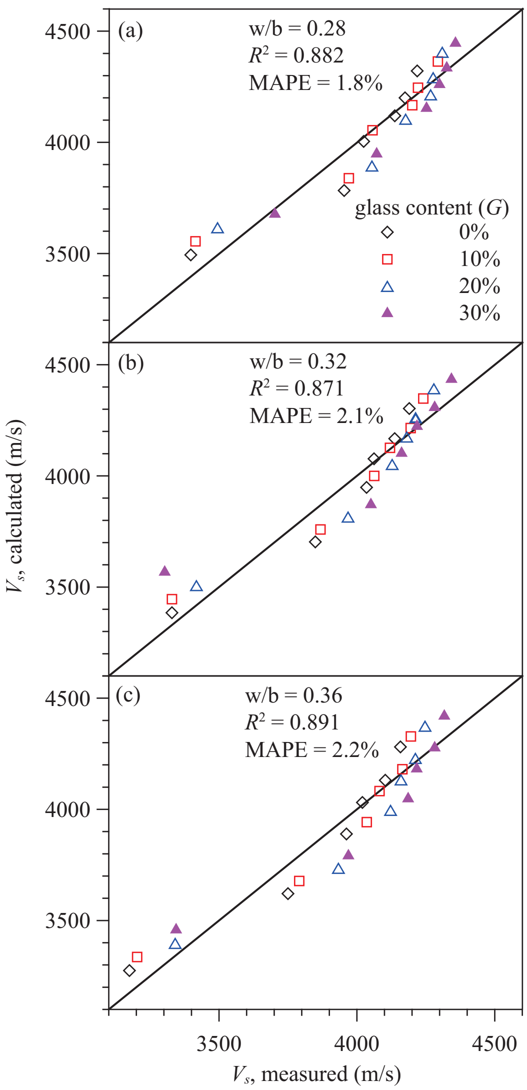


Fig. 4. Comparison of predicted and measured UPV with different w/b.

$$\text{MAPE} = \frac{1}{k}\sum_{i=1}^{k}\left|\frac{y_i - \hat{y}_i}{y_i}\right| \tag{7}$$

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

As shown in Figs. 4(a) to 4(c), the coefficient of determination, R^2, obtained from the regression analysis using the model for the predicted UPV analysis value and the test result also showed excellent accuracy, when the w/b was 0.28 and $R^2 = 0.88$; 0.32 and $R^2 = 0.87$; and 0.36 and $R^2 = 0.89$. Notably, Mousavi et al. (2012) studied high-performance concrete and found that when comparing the analytical result of a prediction model and the experimental value, if the coefficient of determination R^2 value was greater than 0.8, there was an excellent correlation. However, the values of R^2 and MAPE for all data were more than 0.90 and less than 5%. Furthermore, the

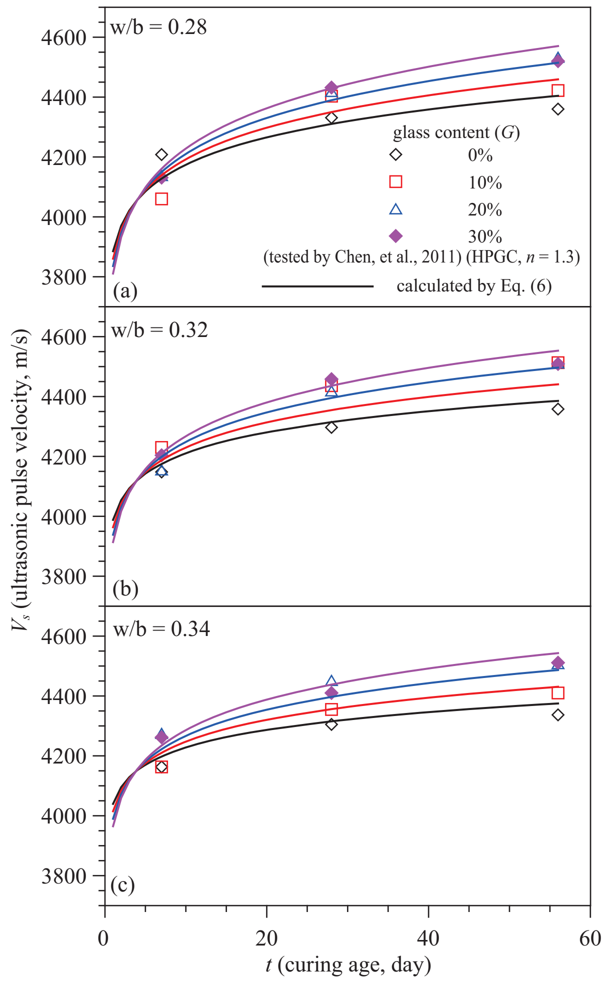


Fig. 5. Comparison of predicted model and test results for UPV (test results from Chen et al., 2011).

established model could well predict the UPV of high-performance recycled liquid crystal glass concrete (HPGC), as in Chen et al. (2011). Figs. 5(a) to 5(c) illustrate the relationship between the predicted and observed UPV with various testing ages. Fig. 6 shows the comparison of the predicted and measured UPV with different water-binder ratios. It was obvious that the UPV calculated from the prediction model was highly reasonable, based on the excellent coefficient of determination, R^2, (0.92) and MAPE (0.8%) for mixtures prepared with water-binder ratios of 0.28, 0.32 and 0.34, respectively. (Note that the collected model parameters were $\alpha_s = -248.4$, $\beta_s = 0.0467$, $m_{s1} = 3165.4$, $m_{s2} = 2571.4$, $n_{s1} = 0.0840$ and $n_{s2} = -0.1889$ for HPGC concrete.)

2. Relationship of Compressive Strength and Ultrasonic Pulse Velocity

Previous researchers have made use of the ultrasonic pulse velocity (UPV) of concrete to predict compressive strength. These research works often involved the development of the relationship between the UPV and compressive strength. Previous studies have concluded that, for concrete with a

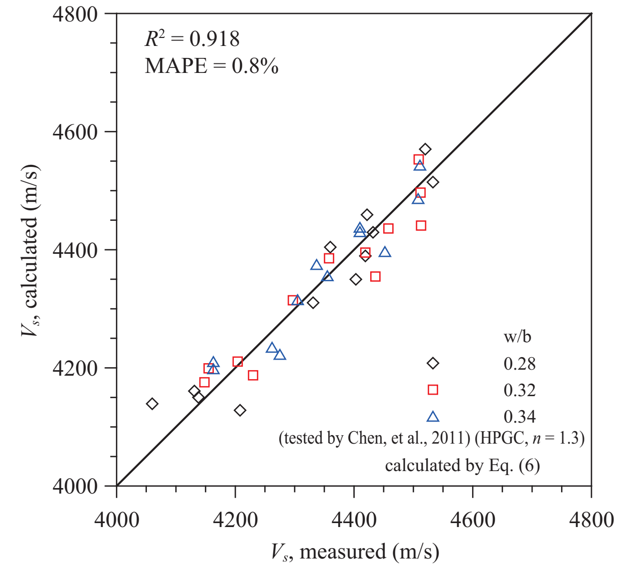


Fig. 6. Comparison of predicted and measured UPV with different w/b (test results from Chen et al., 2011).

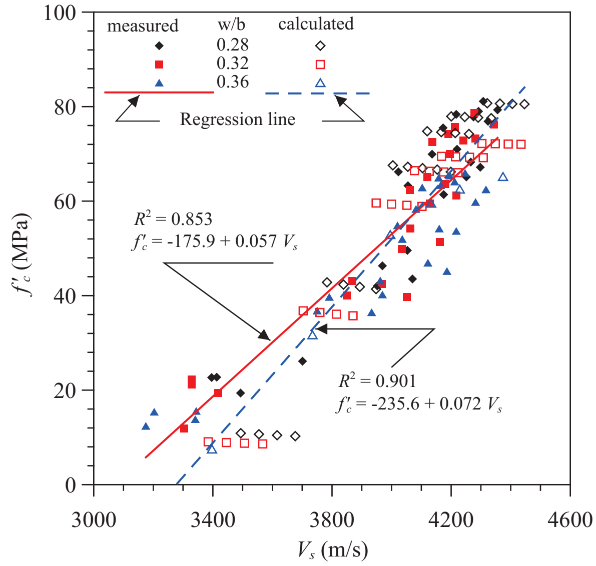


Fig. 7. Relationship between compressive strength and UPV.

particular mix proportion, there was a good correlation between the UPV and the compressive strength. No clear rules have been presented to describe how the relationship between the UPV and the compressive strength of concrete changes according to the mix proportions. Therefore, there has been a high degree of uncertainty when one tries to make use of the UPV to predict the strength of concrete in different mix proportions. The method now used to predict the UPV of hardened concrete based on its mix proportions is well established. In addition, it is known that the compressive strength of concrete corresponds with the mix proportions (Mahure et al., 2011). Lawson et al. (2011) and Mahure et al. (2011) developed theoretical UPV strength models with a high correlation for normal concrete at different curing times. In the present study, the relationship between the compressive strength and the UPV was also investigated.

Fig. 7 illustrates the relationship between the compressive strength and the UPV for concrete with different waste glass contents with water-binder ratios of 0.28, 0.32 and 0.36, respectively. The predicted results using Eq. (6) were notably similar to the test results, and a good linear relationship was found. The prediction analysis of the compressive strength was calculated by Eqs. (8) and (9), as proposed in the authors' previous study. The details of the prediction model and the related parameters are described in the reference (Wang et al., 2014a). (Note that the collected model parameters were α = 1.48, β = 0, m_1 = 4.30, m_2 = 2.58, n_1 = 1.07, n_2 = –1.09, θ = –5.10, x_1 = 124.2 and x_2 = –214.3).

$$\frac{f'_c}{f'_{c,28}} = \frac{t}{\left[\left(m_1 + m_2\left(w/b\right) + \alpha \times G\right) + \left[\left(n_1 + n_2\left(w/b\right)\right) + \beta \times G\right] \times t\right]} \quad (8)$$

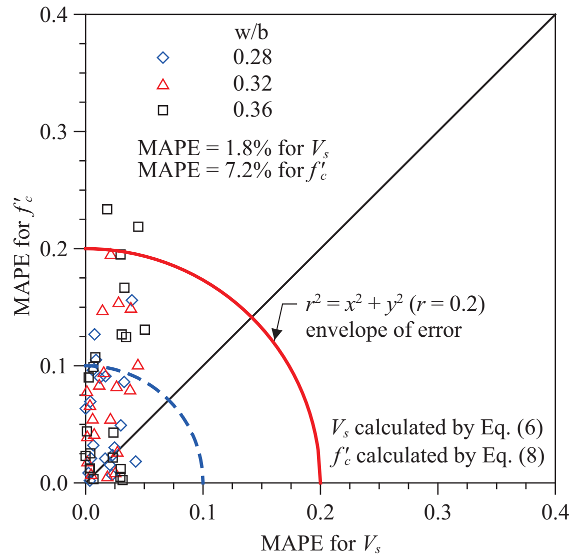


Fig. 8. Comparison of MAPE values for compressive strength and UPV.

$$f'_{c,28} = [x_1 + x_2(\mathrm{w/b})] + \theta \times G \quad (9)$$

Moreover, most of the MAPE values of the developed correlations between the compressive strength and the UPV were around 0.2; in particular, the ultrasonic pulse velocity MAPE value was below 5%, as shown in Fig. 8. The MAPE values were 7.2% and 1.8% for the compressive strength and UPV, respectively. Similarly, the established model could also predict both the compressive strength and UPV of high-performance recycled liquid crystal glass concrete (HPGC), as tested by Chen et al. (2011). The MAPE values were 9.5% and 0.8% for the compressive strength and UPV, respectively, as shown in Fig. 9. Therefore, the proposed compressive strength and

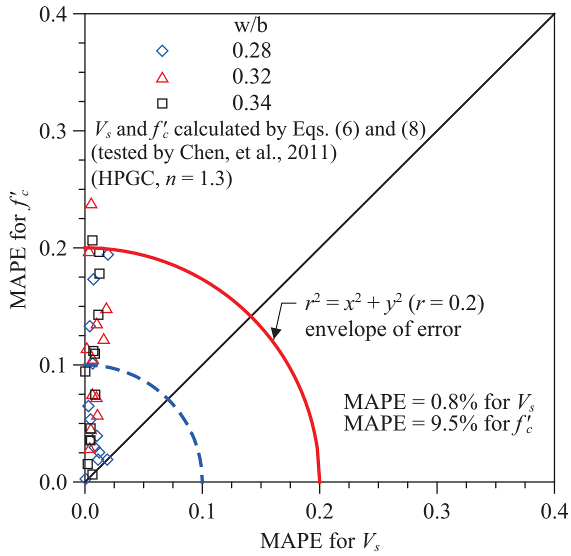


Fig. 9. Comparison of MAPE values for compressive strength and UPV (test results from Chen et al., 2011).

UPV analysis models were proven to have good predictive capabilities. (Note that the collected model parameters are $\alpha = -3.36$, $\beta = 0$, $m_1 = 2.05$, $m_2 = 10.28$, $n_1 = 1.00$, $n_2 = -0.74$, $\theta = -25.93$, $x_1 = 83.74$ and $x_2 = -105.0$ for HPGC concrete).

In addition, the linear relationship of the compressive strength versus the UPV for the measured and analyzed data is shown in Fig. 7 and expressed as Eqs. (10) and (11), respectively. Although the two lines were slightly different, the difference was not significant. The MAPE average values were 8.3% and 9.3% for the compressive strength, as established by Eqs. (10) and (11), respectively. It is worth mentioning that the UPV calculated from Eq. (6) and the test results of the compressive strength of initial curing time on the first day were ignored when the values of the predicted and tested strengths were compared. Thus, if the relationship of the compressive strength and UPV is developed, the compressive strength will be a reasonable estimate of a nondestructive UPV test.

$$f'_c = -175.9 + 0.057 \times V_s \text{ (regressed by tested data)} \quad (10)$$

$$f'_c = -235.6 + 0.072 \times V_s \text{ (regressed by analyzed data)} \quad (11)$$

VI. CONCLUSIONS

1. An ultrasonic pulse velocity (UPV) prediction model, taking into consideration multiple variables, including water-binder ratio, waste glass content and age simultaneously, was developed in this study. It combined the UPV characteristics of waste glass concrete based on a power function. The proposed model will provide a good reference for mix proportion designs for the adding of waste LCD glass to concrete for future engineering applications.
2. As compared with the experimental results, the statistical analysis showed that the coefficient of determination R^2 and the MAPE (mean absolute percentage error) were in the range of 0.87 to 0.89 (larger than 0.80) and 1.8% to 2.2% (less than 10%) for the UPV, respectively. Therefore, the proposed prediction models of UPV exhibited good predictive capabilities.
3. This prediction model was also successfully applied to the calculation of the UPV of high-performance recycled liquid crystal glass concrete (HPGC), as tested by Chen et al. (2011). The coefficient of determination, R^2, was in the range of 0.89 to 0.94, and the MAPE was between 0.7% and 0.9%.
4. The prediction analysis results of the compressive strength and the UPV were notably similar to the test results, showing there to be a good linear relationship. Moreover, when the prediction analysis accuracy of the compressive strength and the UPV were compared, most MAPE values were below 10%. Therefore, the proposed compressive strength and UPV analysis models had good predictive capabilities.

REFERENCES

Breysse, D. (2012). Nondestructive evaluation of concrete strength: An historical review and a new perspective by combining NDT methods. Construction and Building Materials 33, 139-163.

Chen, S. H., C. S. Chang, H. Y. Wang and W. L. Huang (2011). Mixture design of high performance recycled liquid crystal glasses concrete (HPGC). Construction and Building Materials 25, 3886-3892.

Huang, W. L. (2009). A study on waste LCD glass applied in self-compacting concrete. Master Thesis, Graduate Institute of Civil Engineering, National Kaohsiung University of Applied Sciences, Kaohsiung, Taiwan.

Kou, S. C. and C. S. Poon (2009). Properties of self-compacting concrete prepared with recycled glass aggregate. Cement and Concrete Composites 31, 107-113.

Lawson, I., K. A. Danso, H. C. Odoi, C. A. Adjei, F. K. Quashie, I. I. Mumuni and I. S. Ibrahim (2011). Non-destructive evaluation of concrete using ultrasonic pulse velocity. Research Journal of Applied Sciences, Engineering and Technology 3(6), 499-504.

Lewis, C. D. (1982). Industrial and Business Forecasting Method. London: Butterworth Scientific Publishers, London.

Lin, K. L., H. S. Shiu, J. L. Shie, T. W. Cheng and C. L. Hwang (2012). Effect of composition on characteristics of thin film transistor liquid crystal display (TFT-LCD) waste glass-metakaolin -based geopolymers. Construction and Building Materials 36, 501-507.

Lin, Y., C. P. Lai and T. Yen (2003). Prediction of ultrasonic pulse velocity (UPV) in Concrete. ACI Materials Journal 100(1), 21-28.

Mahure, N. V., G. K. Vijh, P. Sharma, N. Sivakumar and M. Ratnam (2011). Correlation between pulse velocity and compressive strength of concrete. International Journal of Earth Sciences and Engineering 4(6), 871-874.

Mousavi, S. M., P. Aminian, A. H. Gandomi, A. H. Amir and H. Bolandi (2012). New predictive model for compressive strength of HPC using gene expression programming. Advances in Engineering Software 45, 105-114.

Park, S. B., B. C. Lee and J. H. Kim (2004). Studies on mechanical properties of concrete containing waste glass aggregate. Cement and Concrete Research 34, 2181-2189.

Shah, A. A., S. H. Alsayed, H. Abbas and Y. A. Al-Salloum (2012). Predicting residual strength of non-linear ultrasonically evaluated damaged concrete using artificial neural network. Construction and Building Materials 29, 42-50.

Sheen, N. Y., J. L. Huang and D. H. Le (2013). Predicting strength development of RMSM using ultrasonic pulse velocity and artificial neural network. Computers and Concrete 12(6), 785-802.

Terro, M. J. (2006). Properties of concrete made with recycled crushed glass at elevated temperatures. Building and Environment 41, 633-639.

Topcu, I. B. and M. Canbaz (2004). Properties of concrete containing waste glass. Cement and Concrete Research 34, 267-274.

Trtnik, G., F. Kavcic and G. Turk (2009). Prediction of concrete strength using ultrasonic pulse velocity and artificial neural networks. Ultrasonics 49, 53-60.

Wang, C. C., T. T. Chen, H. Y. Wang and C. Huang (2014a). A predictive model for compressive strength of waste LCD glass concrete by nonlinear-multivariate regression. Computers and Concrete 13(4), 531-545.

Wang, C. C., H. Y. Wang and C. Huang (2014b). Predictive models of hardened mechanical properties of waste LCD glass concrete. Computers and Concrete 14(5), 577-597.

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, 2127-2131.

Wang, H. Y. (2011). 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. Construction and Building Materials 25, 791-797.

Wang, H. Y. and J. S. Chen (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, 491-501.

Wang, H. Y. and W. L. Huang (2010a). A study on the properties of fresh self-consolidating glass concrete (SCGC). Construction and Building Materials 24, 619-624.

Wang, H. Y. and W. L. Huang (2010b). Durability of self-consolidating concrete is using waste LCD glass. Construction and Building Materials 24, 1008-1013.

Wang, H. Y., J. S. Chen, S. Y. Wang, Z. C. Chen and F. L. Chen (2007). A study on the mix proportion and properties of wasted LCD glass applied to controlled low strength materials concrete (CLSM). Proceeding of TCI 2007 Conference on Concrete Engineering, Taipei, Taiwan, Republic of China, I5-1-I5-12. (in Chinese)

Yusuf, I. T. and Y. A. Jimoh (2014). Correlation of pundit ultrasonic pulse velocity with strength of palm kernel shell concrete. ANNALS of Faculty Engineering Hunedoara-International Journal of Engineering 2, ISSN: 1584-2673, 51-57.