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Prediction models of compressive strength and UPV of recycled material cement mortar

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Abstract. With the rising global environmental awareness on energy saving and carbon reduction, as well as the environmental transition and natural disasters resulted from the greenhouse effect, waste resources should be efficiently used to save environmental space and achieve environmental protection principle of "sustainable development and recycling". This study used recycled cement mortar and adopted the volumetric method for experimental design, which replaced cement (0%, 10%, 20%, 30%) with recycled materials (fly ash, slag, glass powder) to test compressive strength and ultrasonic pulse velocity (UPV). The hyperbolic function for nonlinear multivariate regression analysis was used to build prediction models, in order to study the effect of different recycled material addition levels (the function of R_m(F, S, G) was used and be a representative of the content of recycled materials, such as fly ash, slag and glass) on the compressive strength and UPV of cement mortar. The calculated results are in accordance with laboratory-measured data, which are the mortar compressive strength and UPV of various mix proportions. From the comparison between the prediction analysis values and test results, the coefficient of determination R^2 and MAPE (mean absolute percentage error) value of compressive strength are 0.970-0.988 and 5.57-8.84%, respectively. Furthermore, the R^2 and MAPE values for UPV are 0.960-0.987 and 1.52-1.74%, respectively. All of the R^2 and MAPE values are closely to 1.0 and less than 10%, respectively. Thus, the prediction models established in this study have excellent predictive ability of compressive strength and UPV for recycled materials applied in cement mortar.

Keywords: compressive strength; ultrasonic pulse velocity; prediction model; recycled materials; cement mortar

1. Introduction

In recent years, efficient energy saving, carbon reduction, and resource recycling have become the key issues in sustainable development across the world. The production of artificial aggregate appears as a promising alternative to recycle some industrial by-products. Utilization of industrial waste materials, such as fly ash (FA) and ground granulated blast furnace slag (GGBFS) in the production of artificial aggregate has been practiced by some researchers (Gesoğlu *et al*. 2012, Li and Zhao 2003, Bilir *et al*. 2015, Yeonung *et al*. 2015). Taiwan is no exception. For example, the GGBFS produced by the CHC Resources Corporation, the fly ash produced by the Thermal Power Plant of the Taiwan Power Company, and the waste LCD glass powder (sand) derived from Taiwan TFT-LCD (thin film transistor-liquid crystal display) panels, are mixed with concrete to replace partial cement or sand. The resulting economic benefit and engineering properties exceed the mere addition of cement (Public Construction Commission Executive Yuan 2001, Hwang 2007). Therefore, when recycling fly ash, furnace slag, and waste LCD glass powder (sand), the appropriate and economic mix proportion should determined by validation for further application in public works. The efficient utilization of recycled materials in Taiwan can reduce material costs, environmental impacts, and CO_2 emissions. This is an inevitable trend of sustainable development and environmental protection.

Our previous study (Wang *et al*. 2014a, b, Wang *et al*. 2015a, b) discussed the relationships among multiple influential factors, such as waste glass content, water-binder ratio, and age, according to the hardened mechanical properties of compressive strength, bending strength, and ultrasonic pulse velocity, in a series of mix proportion test results of self-compacting waste LCD glass concrete. They used hyperbolic function, exponential function, and power function for nonlinear multivariate regression analysis, and developed a reasonable prediction analysis model. The findings of the present study can serve as a reference for the future design of mixing ratios of waste LCD glass concrete. This study partially replaced cement (replacement ratio of 0%, 10%, 20%, and 30%) with recycled materials, such as fly ash, slag, and glass powder. The volumetric method was used for mix design. The compressive strength and ultrasonic pulse velocity of recycled material cement mortar were discussed. The hyperbolic function was used for multivariate regression analysis on the test results, and prediction models were developed for the compressive

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strength and ultrasonic pulse velocity of recycled material cement mortar. This study is expected to establish recycled material cement mortar database and hardened properties prediction models, which will serve as reference for mixing ratio research in the future.

2. Characteristics of recycled materials

Fly ash is one of the pozzolan materials, and its main constituents are SiO_2 and Al_2O_3 clay. Fly ash can be divided into two classes according to composition and characteristics, namely Class C fly ash (high calcium fly ash) and Class F fly ash (low calcium fly ash), which have different CaO contents. Class F fly ash has lower calcium content, its pozzolanic reaction is slower, and the early strength of concrete is lower. Therefore, ACI specifies that the replacement of Class C fly ash in normal concrete is 15-35%, and that of Class F fly ash is 15-25%. As Class C fly ash is difficult to obtain, Class F fly ash is mostly used (Ćojbašić *et al*. 2005, Papadakis 2000). Taiwan's fly ash is mostly Class F (low calcium) fly ash, and the CaO content is lower than 10%, which is the main combustion product of anthracite and soft coal (Public Construction Commission Executive Yuan 1999). When fly ash is used as the pozzolan concrete admixture, the particle size distribution, morphology, and surface characteristic of fly ash particles have considerable effect on the batched water requirements for fresh concrete workability and strength development rate of hardened concrete. Fly ash has been extensively used due to its advantages of energy saving, carbon reduction, improving of the flowability of concrete material, reducing hydration heat, enhancing long-term strength development, lowering loss rate, improving durability, and saving cost (Mishra and Ravindra 2015, Sakai *et al*. 2005).

The GGBFS (ground-granulated blast-furnace slag) is produced by quickly cooling blast furnace slag to generate a high content of glassiness, which has high activity and cementing properties. The hydration of slag is slower than cement, as it is pulverized and mixed with cement to generate the pozzolanic reaction. The hydroxide ions released during hydration would break and dissolve the vitreous texture, thus consuming the $Ca(OH)_2$, and forming a hydrate C-S-H colloid similar to clinker, which is similar to the properties of hydrate C-S-H colloid formed by the principal constituents of cement. As a result, the cement can be appropriately replaced. If fine blast furnace slag is used as an admixture in concrete, the porosity of cement paste can be reduced, while the workability, compactness, durability, and ultimate strength can be improved. Moreover, the concrete quality can be upgraded, and the scope of material application is expanded. This is conducive to material cost savings and waste resource recycling (Chen and Brouwers 2007a, b, Kolani *et al*. 2012). According to the manufacturing process, GGBFS is a variable material due to the variability of its chemical composition. It offers latent hydraulic properties when mixed with clinker cement, and the hydration of slag is directly related to its hydraulicity: the dissolution of the slag glass fraction is ensured by the hydroxyl ions (OH^-) resulted from the hydrolysis of Portlandite $Ca(OH)_2$ produced by the hydration of clinker (Zhang *et al*. 2011, Gesoğlu *et al*. 2012).

Among various types of solid waste, glass has been popularly studied as a substitution for coarse and fine aggregates, and even cement. Glass powder is an amorphous material with high silica content, which is the primary requirement for a pozzolanic material. Hydration and strength development in glass powder modified cement pastes, as well as the mechanical and durability properties of concrete containing glass powder, have been reported in earlier studies (Du and Tan 2013, Schwarz and Neithalath 2008, Schwarz *et al*. 2008, Tan and Du 2013). As the use of waste glass particles as fine aggregates may reduce the flow ability and density of mortar, it may also increase its air content. Except for drying shrinkage, the mechanical properties are compromised due to micro-cracking in the glass sand and the weakened bond with the cement paste; however, durability is enhanced, especially in terms of the resistance to chloride ion penetration. Waste LCD glass is a type of general industrial waste, and can be mixed with cement mortar. This facilitates the pozzolanic reaction in concrete, and its replacement within 30% in the concrete mix results in good strength development. The addition of waste glass to medium and low strength concrete can effectively fill the pores in concrete, thus, providing better durability, surface resistance, acid resistance, salinity tolerance, alkali resistance, chloride ion penetration, and concrete ultrasonic pulse velocity (Shi *et al*. 2005, Shayan and Xu 2004, Wang 2009).

3. Test program

3.1 Test materials

1. Cement: Type I Portland cement produced by the Taiwan Cement Corporation was used, and its fineness was 3500 cm^2/g; its properties conformed to the Type I Portland cement specified in ASTM C150.
2. Mixing water: Conforms to ASTM C94 concrete mixing water.
3. Fine 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, and its fineness was 3140 cm^2/g.
5. Slag: GGBFS was produced by the CHC Resources Corporation, was ground into 4500 cm^2/g, and its properties conformed to ASTM C989.
6. Glass powder: TFT-LCD waste LCD glass sand was ground into 6000 cm^2/g.

3.2 Test variables and method

This study used a standard mix design of cement mortar according to ASTM C109, with a fixed cement-water-sand ratio of 1:0.64:2.75. The volumetric method was used for the design. Recycled materials (fly ash, slag, waste LCD glass powder) were used to replace the cement (0%, 10%, 20%, 30%). A 5 cm×5 cm×5 cm cement mortar specimen was made and solidified. The form was removed after 24 h, and the specimen was cured in saturated limewater. The

Table 1 The physical properties of materials

Items	Specific gravity	Water absorption (%)	F.M	Fineness (cm^2/g)
Fine Aggregate	2.65	2.3	3.1	-
Cement	3.15	-	-	3500
Fly ash	2.18	-	-	3140
Slag	2.8	-	-	4500
Glass	2.54	-	-	6000

Table 2 The chemical properties of the materials Unit: %

Properties	Cement	Fly ash	Slag	Glass
SiO_2	20.22	50.79	33.79	62.48
Al_2O_3	4.96	24.97	13.59	16.67
Fe_2O_3	2.83	7.87	0.36	9.41
CaO	64.51	5.68	41.33	2.7
MgO	2.33	1.72	7.26	-
LOI	2.4	3.1	1.1	-
SO_3	2.46	0.3	0.1	-
Alkalis	0.48	-	-	-
K_2O	-	-	-	0.2
Na_2O	-	-	-	0.64
TiO_2	-	-	-	0.01
P_2O_5	-	-	-	0.01

compressive strength and ultrasonic pulse velocity were tested at the ages of 1, 7, 28, and 56 days according to ASTM C109 and ASTM C597.

The physical properties of materials are as shown in Table 1. The chemical properties of materials are as shown in Table 2. The unit weight of the mix design cement mortar with added recycled materials are as shown in Table 3.

4. Studying and planning the prediction model for compressive strength and UPV

4.1 Development of the compressive strength prediction model

The influence of partial or aggregate replacements, including fly ash, furnace slag, and waste glass, in concrete, under identical conditions on compressive strength increased with age, and the increasing tendency became smooth over time. Our previous study (Wang *et al*. 2014a, b) used a hyperbolic function to calculate the relationship between compressive strength and curing time for waste LCD glass concrete. The results showed that the compressive strength decreased when the waste glass content was increased using an identical mixture ratio, as shown in Eq. (1), where parameters a_c and b_c are the coefficients of the hyperbolic function, and t is the age. Furthermore, a linear function between a_c and G was used. The relationship of b_c and G had the same trend. Thus, Eq. (1) can be rewritten, as shown in Eq. (2). Moreover, parameters m and n versus water-binder ratio w/b also exhibit linear relationships, and Eq. (2) can also be rewritten as Eq. (3).

Table 3 Unit weight of mix design cement mortar adding recycled materials

No.	Cement	Fly ash	Slag	Glass	Unit：kg/m³ Sand	Water
F0	543	-	-	-	1494	348
F10	462	38	-	-		
F20	408	75	-	-		
F30	353	113	-	-		
S0	543	-	-	-	1494	348
S10	462	-	48	-		
S20	408	-	97	-		
S30	353	-	145	-		
G0	543	-	-	-	1494	348
G10	462	-	-	44		
G20	408	-	-	88		
G30	353	-	-	131		

Table 4 The parameter values for compressive strength prediction model

Material	Fly ash		Slag		Glass	
$R_m(F,S,G)$	$R_m(F,0,0)$		$R_m(0,S,0)$		$R_m(0,0,G)$	
m_s	m_{sf}	2.783	m_{ss}	2.620	m_{sg}	2.572
α_s	α_{sf}	8.071	α_{ss}	7.966	α_{sg}	4.740
n_s	n_{sf}	0.783	n_{ss}	0.822	n_{sg}	0.850
β_s	β_{sf}	0	β_{ss}	0	β_{sg}	0
x	x_f	30.28	x_s	30.38	x_g	30.74
θ	θ_f	-33.20	θ_s	7.30	θ_g	-1.60

$$\frac{f'_c}{f'_{c,28}} = f(t) = \frac{t}{a_c + b_c t} \tag{1}$$

$$\frac{f'_c}{f'_{c,28}} = \frac{t}{(m+\alpha\times G)+(n+\beta\times G)t} \tag{2}$$

$$\frac{f'_c}{f'_{c,28}} = \frac{t}{[(m_1+m_2(w/b))+\alpha\times G]+[(n_1+n_2(w/b))+\beta\times G]\times t} \tag{3}$$

$$f'_{c,28} = [x_1 + x_2(w/b)] + \theta\times G \tag{4}$$

Where α, β, m and n are the parameters related to waste glass content G, and m_1, m_2 and n_1, n_2 are the coefficients related to the water-binder ratio (w/b). The evaluation method for the compressive strength on Day 28 is derived and expressed as Eq. (4).

Fig. 1(a) shows the test results for the compressive strength of cement mortar with added recycled materials versus curing ages for different fly ash contents when the water-binder ratio w/b is 0.64. For identical fly ash content F, while the compressive strength f'_c increases with age t,

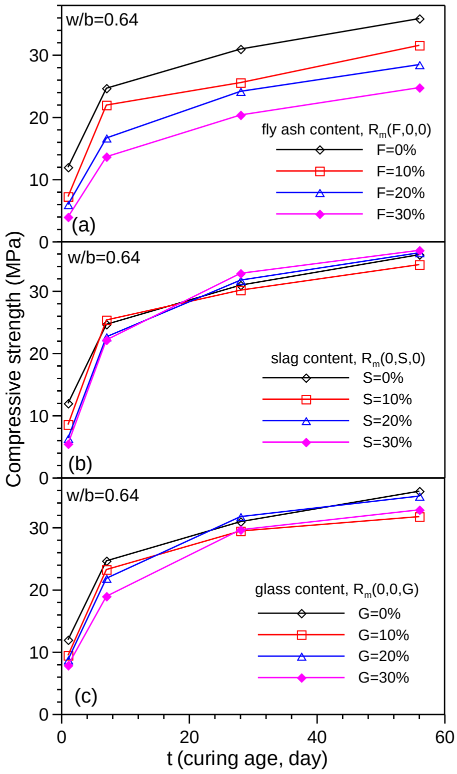
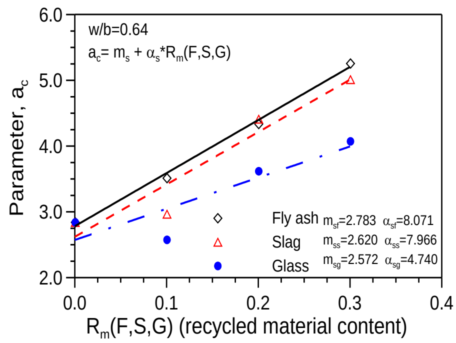
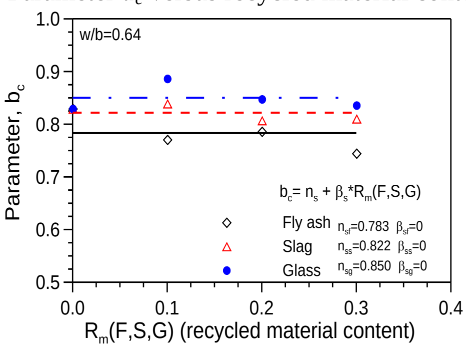


Fig. 1 The relationship between compressive strength and curing age



(a) Parameter a_c versus recycled material content



(b) Parameter b_c versus recycled material content

Fig. 2 Characteristics of parameters of the compressive strength prediction model

the increase becomes smooth as the age further increases. Similar phenomena were observed in other tests for adding slag and glass material, as shown in Figs. 1(b) and 1(c). The relation between compressive strength and age was

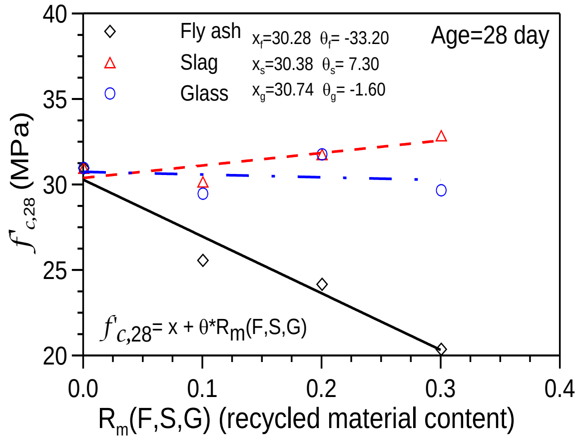


Fig. 3 Compressive strength on day 28 versus recycled material content

simulated using the hyperbolic function. However, as the water-binder ratio w/b is fixed at 0.64, and there are three types of added recycled materials, the parameter of the water-binder ratio w/b can be neglected, and the parameter of glass content G can be substituted for adding recycled materials, respectively. Therefore, the function of $R_m(F, S, G)$ is used as the effect of recycled materials, such as the content of fly ash, slag and glass, respectively. Thus, Eqs. (2) and (4) can be rewritten as Eqs. (5) and (6).

$$\frac{f'_c}{f'_{c,28}} = \frac{t}{[m_s + \alpha_s \times R_m(F,S,G)] + [n_s + \beta_s \times R_m(F,S,G)] \times t} \tag{5}$$

$$f'_{c,28} = x + \theta \times R_m(F,S,G) \tag{6}$$

Where α_s, β_s, m_s and n_s are the parameters related to the content of adding recycled material $R_m(F, S, G)$ for the compressive strength established in this study. In Eqs. (5) and (6), the parameter $R_m(F, S, G)$ is replaced by parameter $R_m(F, 0, 0)$, $R_m(0, S, 0)$ and $R_m(0, 0, G)$ when fly ash, slag, and glass is added in recycled material cement mortar, respectively.

Fig. 2(a) illustrates a linear increasing function between parameter a_c and recycled material content $R_m(F, S, G)$, where parameters m_s and α_s are the interception and slope of the linear function, respectively. Therefore, in the model deduction, parameters m_s and α_s can be rewritten as m_{sf} and α_{sf} when fly ash is added as the recycled material. In addition, as parameter b_c does not affect the various recycled material content $R_m(F, S, G)$, no relationship is found, and it is a horizontal line, as shown in Fig. 2(b). In other words, parameter b_c is equal to n_s and the slope value β_s is equal to 0. Similarly, parameters n_s and β_s can be rewritten as n_{sf} and β_{sf} when fly ash is added as the recycled material. Fig. 3 shows the compressive strengths of 28 day mixtures with different types of added recycled materials. The relationship indicates that the compressive strength on Day 28 ($f'_{c,28}$) and recycled material content $R_m(F, S, G)$ exhibit a linear decreasing function for the added fly ash and glass recycled material; nevertheless, it is a linear increasing relationship for added slag recycled material. Furthermore, parameters x and θ of Eq. (6) can be rewritten as x_f and θ_f when fly ash is added as the recycled material.

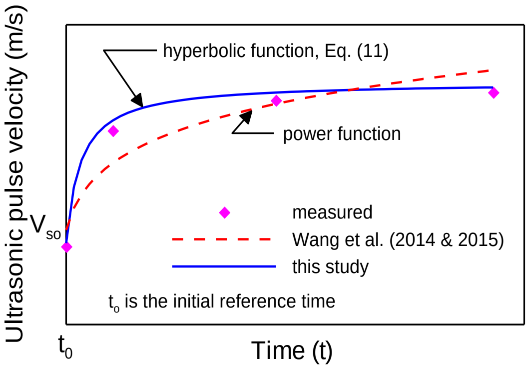


Fig. 4 Characteristics of the UPV versus curing time

Accordingly, the parameters m_s, α_s, n_s, β_s, x and θ of Eqs. (5) and (6) can be rewritten and classified, as shown as Eq. (7), when the fly ash of added recycled material is used. In addition, the previous parameters can be rewritten as Eqs. (8) and (9) when slag and glass are used as recycled materials, respectively. The parameter values of the prediction model are as shown in Table 4, where compressive strength is applied in the regression analysis of the testing results.

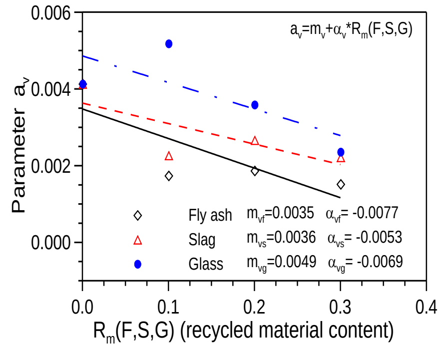
$$\begin{matrix} m_s = m_{sf} & \alpha_s = \alpha_{sf} \\ n_s = n_{sf} & \beta_s = \beta_{sf} \\ x = x_f & \theta = \theta_f \end{matrix} \quad \text{for} \quad R_m(F,S,G) = R_m(F,0,0) = F \quad \text{(fly ash as recycled material)} \tag{7}$$

$$\begin{matrix} m_s = m_{ss} & \alpha_s = \alpha_{ss} \\ n_s = n_{ss} & \beta_s = \beta_{ss} \\ x = x_s & \theta = \theta_s \end{matrix} \quad \text{for} \quad R_m(F,S,G) = R_m(0,S,0) = S \quad \text{(slag as recycled material)} \tag{8}$$

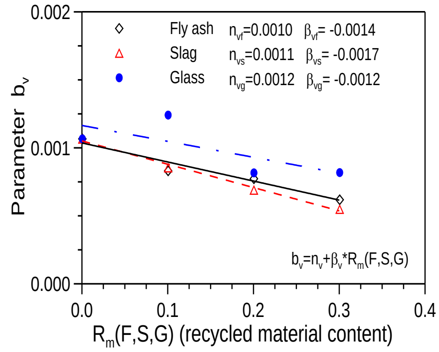
$$\begin{matrix} m_s = m_{sg} & \alpha_s = \alpha_{sg} \\ n_s = n_{sg} & \beta_s = \beta_{sg} \\ x = x_g & \theta = \theta_g \end{matrix} \quad \text{for} \quad R_m(F,S,G) = R_m(0,0,G) = G \quad \text{(glass as recycled material)} \tag{9}$$

4.2 Development of the ultrasonic pulse velocity prediction model

Chen *et al*. (2011) used a mixture design of high-performance recycled liquid crystal glass concrete, and found the correlation coefficient (R value) between age and UPV to be over 0.928, meaning the UPV was gradually growing with age. In addition, Wang *et al*. (2014b) found that the UPV tends to increase with increasing waste glass content and maintenance 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, indicating that the sharp rise in the UPV of the concrete, after the initial setting and the



(a) Parameter a_v versus recycled material content



(b) Parameter b_v versus recycled material content

Fig. 5 Characteristics of parameters of the UPV prediction model

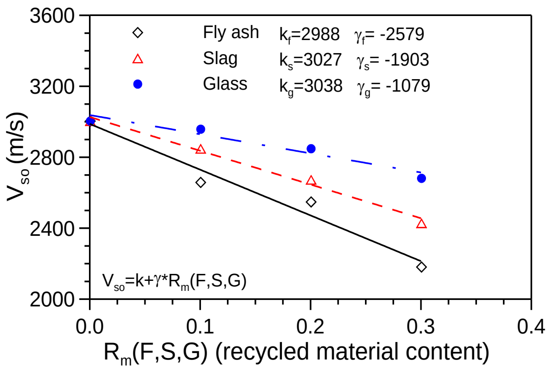


Fig. 6 The UPV value of initial reference time versus recycled material content

gradually smoothing properties of the UPV, should be simulated in a prediction model. Hence, Wang *et al*. (2015b) suggested a power function to establish the UPV of self-compacting waste LCD glass concrete, as shown in Eq. (10), where parameters a_s and b_s are the coefficients of the power function and t is the age.

$$V_s = a_s \times t^{bs} \tag{10}$$

Although the prediction model (Eq. (10)) can reasonably establish the relation between UPV and curing time, the power function does not accurately simulate the characteristic of the UPV when it is rapidly raised and quickly transferred to the tendency of the horizontal level in the initial stage. Thus, it will have a relatively large amount of errors if the trend of UPV versus curing time becomes smooth over time. Therefore, it is more suitable to simulate by the hyperbolic function, as shown in Fig. 4. Furthermore, the relationship between UPV and curing time must be considered when the final setting is achieved; consequently, the hyperbolic function will be shifted by the UPV value (V_{s0}) of the initial maintenance stage (or the initial reference time, t_0) when the model is deduced, as shown in Fig. 4 and expressed by Eq. (11), where parameters a_v and b_v are the coefficients of the hyperbolic function. In other words, at the initial maintenance stage after mixing the mortar or concrete, it gradually becomes hardened from the flowing state of the initial setting to the solid stage of the final setting. Thus, its mechanical properties significantly changed. The compressive strength and UPV suddenly increased during the initial curing period. Therefore, a hyperbolic function and translation of coordinate axes from the virgin point are combined and proposed. It will be more reasonable to predict the behavior of UPV. Hence, the initial reference time (t_0) is reflected to the initial point of translated axes. The age of first time to test for experiment is often adopted as initial reference time. In this study, the initial reference time is 1 day.

Fig. 5(a) illustrates a linear decreasing function between parameter α_v and recycled material content $R_m(F, S, G)$, as shown in Eq. (12), and parameters m_v and α_v are the interception and slope of the linear function, respectively. Therefore, in model deduction, parameters m_v and α_v can be rewritten as m_{vf} and α_{vf} when fly ash is added as the recycled material (i.e., $R_m(F, 0, 0)$). Similarly, parameter b_v has the same tendency, as shown in Fig. 5(b) and expressed as Eq. (13). Hence, parameters n_v of interception and β_v of slope can also be rewritten as n_{vf} and β_{vf} when fly ash is added as the recycled material (i.e., $R_m(F, 0, 0)$. Fig. 6 shows the relationship of UPV value on reference time (V_{s0}) and recycled material content $R_m(F, S, G)$. The UPV value of reference time (V_{s0}) and recycled material content $R_m(F, S, G)$ exhibit a linear decreasing function for different types of added recycled materials, as shown in Eq. (14). Therefore, parameters k and γ of Eq. (14) can also be rewritten as k_f and γ_f when fly ash is added as the recycled material. Eqs. (11) to (14) are combined, and the UPV prediction model is described, as shown in Eq. (15).

$$V_s = V_{s0} + \frac{(t - t_0)}{a_v + b_v(t - t_0)} \tag{11}$$

$$a_v = m_v + \alpha_v \times R_m(F, S, G) \tag{12}$$

$$b_v = n_v + \beta_v \times R_m(F, S, G) \tag{13}$$

$$V_{s0} = k + \gamma \times R_m(F, S, G) \tag{14}$$

$$V_S = [k + \gamma \times R_m(F,S,G)] + \frac{(t\text{-}t_0)}{(m_v + \alpha_v \times R_m(F,S,G)) + (n_v + \beta_v \times R_m(F,S,G)) \times (t\text{-}t_0)} \tag{15}$$

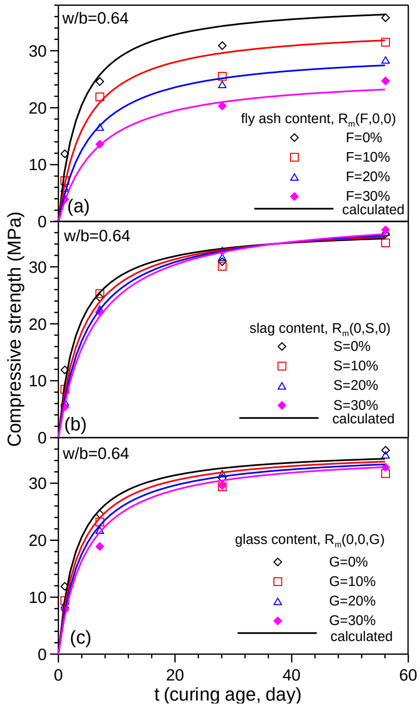


Fig. 7 Comparison of predicted model and tested results for compressive strength

Where α_v, β_v, m_v and n_v are the parameters related to the content of adding recycled material $R_m(F, S, G)$ for the UPV established in this study. In Eqs. (12) to (15), parameter $R_m(F, S, G)$, instead of $R_m(F, 0, 0)$, $R_m(0, S, 0)$ and $R_m(0, 0, G)$, is used when fly ash, slag, and glass are added in recycled material cement mortar, respectively. Correspondingly, parameters m_v, α_v, n_v, β_v, k and γ of Eq. (15) can be rewritten and classified, as shown as Eq. (16), when the fly ash of added recycled material is used. In addition, the previous parameters can be rewritten as Eqs. (17) and (18) when slag and glass are used as the recycled materials, respectively. The parameter values of the prediction model are as shown in Table 5, while UPV is applied in the regression analysis of the testing results.

$$\begin{array}{ll} m_v = m_{vf} & \alpha_v = \alpha_{vf} \\ n_v = n_{vf} & \beta_v = \beta_{vf} \\ k = k_f & \gamma = \gamma_f \end{array} \quad \begin{array}{c} \text{for} \\ R_m(F,S,G) = R_m(F,0,0) = F \\ \text{(fly ash as recycled material)} \end{array} \tag{16}$$

$$\begin{array}{ll} m_v = m_{vs} & \alpha_v = \alpha_{vs} \\ n_v = n_{vs} & \beta_v = \beta_{vs} \\ k = k_s & \gamma = \gamma_s \end{array} \quad \begin{array}{c} \text{for} \\ R_m(F,S,G) = R_m(0,S,0) = S \\ \text{(slag as recycled material)} \end{array} \tag{17}$$

$$\begin{array}{ll} m_v = m_{vg} & \alpha_v = \alpha_{vg} \\ n_v = n_{vg} & \beta_v = \beta_{vg} \\ k = k_g & \gamma = \gamma_g \end{array} \quad \begin{array}{c} \text{for} \\ R_m(F,S,G) = R_m(0,0,G) = G \\ \text{(glass as recycled material)} \end{array} \tag{18}$$

Table 5 The parameter values for UPV prediction model

Material	Fly ash		Slag		Glass	
$R_m(F,S,G)$	$R_m(F,0,0)$		$R_m(0,S,0)$		$R_m(0,0,G)$	
m_v	m_{vf}	0.0035	m_{vs}	0.0036	m_{vg}	0.0049
α_v	α_{vf}	-0.0077	α_{vs}	-0.0053	α_{vg}	-0.0069
n_v	n_{vf}	0.0010	n_{vs}	0.0011	n_{vg}	0.0012
β_v	β_{vf}	-0.0014	β_{vs}	-0.0017	β_{vg}	-0.0012
k	k_f	2988	k_s	3027	k_g	3038
γ	γ_f	-2579	γ_s	-1903	γ_g	-1079

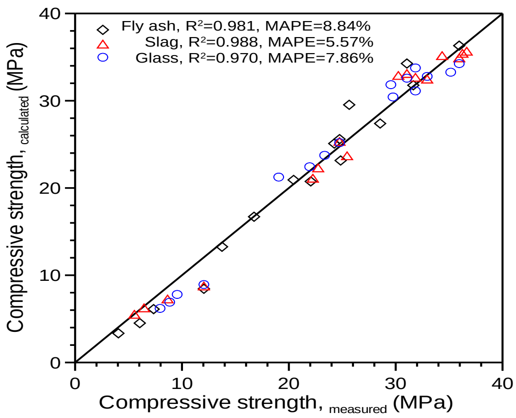


Fig. 8 Comparison of predicted model and measured compressive strength

5. Comparison between the predictive analysis and the test result

5.1 Compressive strength

As shown in Fig. 7(a), the multivariate recycled material cement mortar compressive strength prediction model (Eq. 5), which considers age *t* and fly ash as the recycled material, was used to compare the test results of adding fly ash content from 0% to 30%. The analysis results suggested that the compressive strength prediction model based on the hyperbolic function can accurately evaluate compressive strength, and compressive strength decreases with increased fly ash content. Furthermore, while the prediction analysis results of other recycled materials (slag and glass) have the same trends, as shown in Figs. 7(b) and 7(c), the tendency of compressive strength varied slag content is slightly different. The test results showed that the compressive strength decreases as the slag content increases during the initial curing time; however, the trends are changed after certain curing time. It is noteworthy that a cross point will occur at certain curing times for curves of compressive strength versus curing age. In addition, the relationship between compressive strength and curing time is significantly changed for different fly ash content; nevertheless, the variation is smaller than fly ash content and not obvious for slag and glass content. However, as all model parameters are regressed based on test results, the analysis results of the prediction model have the same tendency for all the recycled materials, as shown in Fig. 7. Hence, the proposed compressive strength prediction model

Table 6 Comparison of predicted and measured values of compressive strength

Material type	No.	Tested compressive strength (MPa) (days)				Predicted compressive strength (MPa) (days)				R^2	MAPE
		1	7	28	56	1	7	28	56		
Fly ash $R_m(F,0,0)$	F0	12.00	24.70	31.00	35.90	8.41	24.88	32.97	34.86	0.981	8.84%
	F10	7.30	22.00	25.60	31.60	7.48	22.16	29.35	31.03		
	F20	6.00	16.70	24.20	28.50	6.56	19.43	25.74	27.21		
	F30	4.00	13.70	20.40	24.80	5.64	16.70	22.12	23.39		
Slag $R_m(0,S,0)$	S0	12.00	24.70	31.00	35.90	8.82	25.39	33.18	34.96	0.988	5.57%
	S10	8.60	25.40	30.20	34.30	7.34	23.75	32.95	35.23		
	S20	6.40	22.70	31.80	36.20	6.32	22.36	32.74	35.49		
	S30	5.50	22.20	32.90	36.60	5.58	21.18	32.54	35.73		
Glass $R_m(0,0,G)$	G0	12.00	24.70	31.00	35.90	8.98	25.24	32.63	34.30	0.970	7.86%
	G10	9.50	23.30	29.50	31.80	7.85	23.79	31.89	33.81		
	G20	8.80	21.90	31.80	35.10	6.96	22.48	31.17	33.32		
	G30	7.90	19.00	29.70	32.90	6.25	21.30	30.48	32.84		

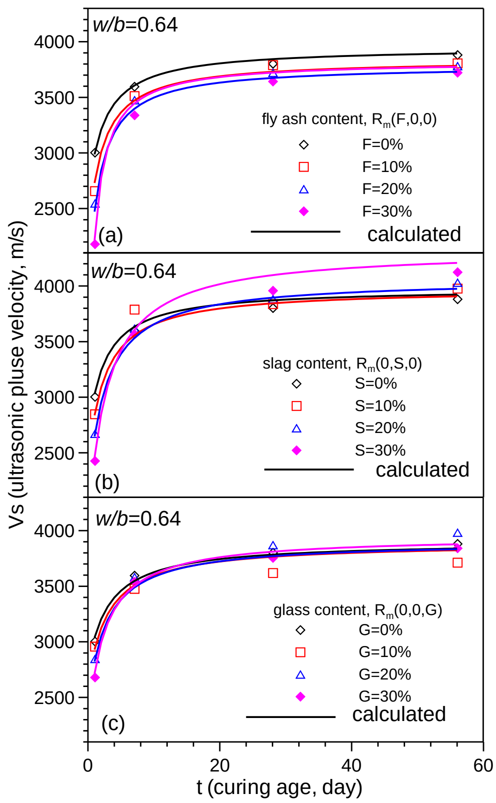


Fig. 9 Comparison of predicted model and tested results for UPV

can be used to reasonably estimate the compressive strength of cement mortar for different types of recycled materials. A comparison of the predicted values of compressive strength using the model and actual experimental values are as shown in Table 6.

To validate the accuracy of the prediction model analysis results, this study employed two indices: the MAPE (mean absolute percentage error) (Lewis 1982) value and R^2 (coefficient of determination) to determine the error between the model analysis results and the measured

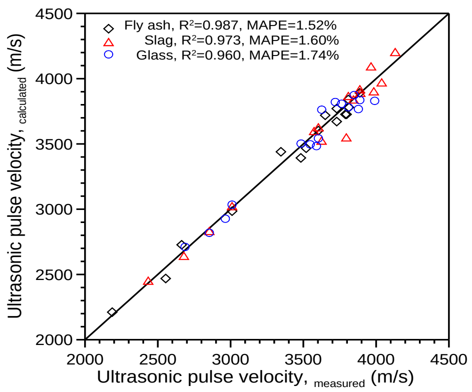


Fig. 10 Comparison of predicted model and measured UPV

Table 7 Comparison of predicted and measured values of UPV

Material type	No.	Tested UPV (m/sec) (days)				Predicted UPV (m/sec) (days)				R^2	MAPE
		1	7	28	56	1	7	28	56		
Fly ash $R_m(F,0,0)$	F0	3007	3600	3806	3885	2988	3605	3843	3894	0.987	1.52%
	F10	2661	3516	3794	3810	2730	3470	3729	3783		
	F20	2551	3480	3726	3786	2472	3395	3674	3729		
	F30	2184	3343	3647	3726	2214	3442	3722	3773		
Slag $R_m(0,S,0)$	S0	3007	3600	3806	3885	3027	3631	3871	3923	0.973	1.60%
	S10	2851	3792	3841	3981	2836	3554	3844	3907		
	S20	2676	3622	3888	4035	2646	3529	3895	3975		
	S30	2431	3571	3962	4128	2456	3602	4097	4207		
Glass $R_m(0,0,G)$	G0	3007	3600	3806	3885	3038	3545	3784	3839	0.960	1.74%
	G10	2961	3481	3623	3716	2930	3505	3765	3823		
	G20	2851	3587	3875	3987	2822	3486	3770	3833		
	G30	2684	3544	3759	3846	2714	3499	3810	3877		

value. The coefficient of the determined R^2 was obtained from regression analysis using the model for the predicted compressive strength analysis value and the test results; with fly ash as recycled material R^2=0.981; with slag as recycled material, R^2=0.988, and with glass as recycled material, R^2=0.970. The analytic results showed that the MAPE values are 8.84%, 5.57%, and 7.86% when fly ash, slag, and glass are used as recycled materials, respectively. The comparison of all analysis values and testing results suggested that all of the coefficients of determination R^2 are greater than 0.8, and the MAPE value is lower than 10%, as shown in Fig. 8. Lewis (1982) suggested that if the MAPE is less than 10%, the model has excellent predictive ability; if the MAPE is in the range of 10-20%, the model has good predictive ability; and if the MAPE is more than 50%, the prediction results of the model are not accurate. Therefore, the compressive strength prediction model, as reported in this paper, has excellent prediction abilities.

5.2 Ultrasonic pulse velocity

As shown in Fig. 9, the UPV prediction model (Eq. (15)) was applied to analyze the UPV and the test results of cement mortar with the replacement of recycled materials, such as fly ash, slag, and glass. The UPV prediction model based on the hyperbolic function can accurately evaluate the relationships between UPV and curing time for different types of recycled materials. Similarly, the trend of UPV and curing time has the same phenomena as compressive strength; hence, a cross point may occur for the predicted curve. A comparison of the predicted values of UPV using the model and the actual experimental values is as shown in Table 7.

Furthermore, the coefficient of determination R^2 was obtained from regression analysis using the model for the predicted UPV analysis value and the test results; with fly ash as recycled material, R^2=0.987; with slag as recycled material, R^2=0.973, and with glass as recycled material, R^2=0.960. The analytic results showed that the MAPE values are 1.52%, 1.60%, and 1.74% when fly ash, slag, and glass are used as recycled materials, respectively. The comparison of all analysis values and test results suggested that all coefficients of determination R^2 are greater than 0.8, and the MAPE value is lower than 10%, as shown in Fig. 10 and Table 7. Therefore, the UPV prediction model has excellent prediction abilities.

6. Conclusions

1. Both compressive strength and UPV prediction models were developed in this study, which simultaneously considered multiple variables, including material types of fly ash, slag, and glass, recycled material content, and curing time. They combined the compressive strength and UPV characteristics of recycled material cement mortar based on the hyperbolic function. The proposed models could provide good reference for mix proportion designs of adding recycled material cement mortar for future engineering applications.

2. Compared with the experimental results, statistical analysis showed that the coefficient of determination R^2 and MAPE values for compressive strength are in the range of 0.970-0.988 and 5.57-8.84%, respectively. Similarly, the R^2 and MAPE values for UPV are in the range of 0.960-0.987 and 1.52-1.74%, respectively. All of the R^2 and MAPE values are closely to 1.0 and less than 10%, respectively. Thus, the proposed prediction models of compressive strength and UPV exhibited excellent predictive capabilities for recycled materials applied in cement mortar.

3. The parameters of the compressive strength model are regressed based on test results; hence, the same tendencies between test results and model analysis occur. However, as based on test results, when a proper curing time is reached, a cross point may occur in the predicted curves of compressive strength and curing time if the trend is changed. The UPV model has the same tendency. Future study can apply the proposed prediction models to other mixing conditions for further validation.

References

Bilir, T., Gencel, O. and Topcu, I.B. (2015), "Properties of mortars containing fly ash as fine aggregate", *Constr. Build. Mater.*,

93(9), 782-786.
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)", *Constr. Build. Mater.*, **25**(10), 3886-3892.
Chen, W. and Brouwers, H.J.H. (2007a), "The hydration of slag, part 1: Reaction models for alkali-activated slag", *J. Mater. Sci.*, **42**(2), 428-443.
Chen, W. and Brouwers, H.J.H. (2007b), "The hydration of slag, part 2: Reaction models for blended cement", *J. Mater. Sci.*, **42**(2), 444-464.
Ćojbašić, L., Stefanović, G., Sekulić, Ž. and Heckmann, S. (2005), "Influence of the fly ash chemical composition on the Portland cement and fly ash mixture hydration mechanism", *FACTA Universit.*, **3**(1), 117-125.
Du, H. and Tan, K.H. (2013), "Use of waste glass as sand in mortar: Part II-alkali-silica reaction and mitigation methods", *Cement Concrete Compos.*, **35**(1), 118-126.
Gesoğlu, M., Güneyisi, E. and Öz, H.Ö. (2012), "Properties of lightweight aggregates produced with cold-bonding pelletization of fly ash and ground granulated blast furnace slag", *Mater. Struct.*, **45**(10), 1535-1546.
Gesoğlu, M., Güneyisi, E., Mahmood, S.F., Öz, H.Ö. and Mermerdaş, K. (2012), "Recycling ground granulated blast furnace slag as cold bonded artificial aggregate partially used in self-compacting concrete", *J. Hazard. Mater.*, **235**, 352-358.
Hwang, C.L. (2007), *Pozzolan Concrete Manual*, Sinotech Engineering Consultants Inc., Taipei, Taiwan.
Kolani, B., Buffo-Lacarrière, L., Sellier, A., Escadeillas, G., Boutillon, L. and Linger, L. (2012), "Hydration of slag-blended cements", *Cement Concrete Compos.*, **34**(9), 1009-1018.
Lewis, C.D. (1982), *Industrial and Business Forecasting Methods*, Butterworth Scientific Publishers, London, U.K.
Li, G.Y. and Zhao, X.H. (2003), "Properties of concrete incorporating fly ash and ground granulated blast-furnace slag", *Cement Concrete Compos.*, **25**(3), 293-299.
Mishra, A.K. and Ravindra, V. (2015), "On the utilization of fly ash and cement mixtures as a landfill liner material", *J. Geosynt. Ground Eng.*, **1**(17), 1-7.
Papadakis, V.G. (2000), "Effect of fly ash on Portland cement systems part II: High-calcium fly ash", *Cement Concrete Res.*, **30**(10), 1647-1654.
Public Construction Commission Executive Yuan (1999), *Public Works Fly Ash Concrete Manual*, Taiwan.
Public Construction Commission Executive Yuan (2001), *Public Works Blast Furnace Fly Ash Concrete Stone Manual*, Taiwan.
Sakai, E., Miyahara, S., Ohsawa, S., Lee, S.H. and Daimon, M. (2005), "Hydration of fly ash cement", *Cement Concrete Res.*, **35**(6), 1135-1140.
Schwarz, N. and Neithalath, N. (2008), "Influence of a fine glass powder on cement hydration: Comparison to fly ash and modeling the degree of hydration", *Cement Concrete Res.*, **38**(4), 429-436.
Schwarz, N., Cam, H. and Neithalath, N. (2008), "Influence of a fine glass powder on the durability characteristics of concrete and its comparison to fly ash", *Cement Concrete Compos.*, **30**(6), 486-496.
Shayan, A. and Xu, A. (2004), "Value-added utilization of waste glass in concrete", *Cement Concrete Res.*, **34**(1), 81-89.
Shi, C.J., Wu, Y.Z., Riefler, C. and Wang, H. (2005), "Characteristics and pozzolanic reactivity of glass powders", *Cement Concrete Res.*, **35**(5), 987-993.
Tan, K.H. and Du, H. (2013), "Use of waste glass as sand in mortar: Part I-fresh, mechanical and durability properties", *Cement Concrete Compos.*, **35**(1), 109-117.
Wang, C.C., Chen, T.T., Wang, H.Y. and Huang, C. (2014a), "A predictive model for compressive strength of waste LCD glass concrete by nonlinear-multivariate regression", *Comput. Concrete*, **13**(4), 531-545.
Wang, C.C., Wang, H.Y. and Huang, C. (2014b), "Predictive models of hardened mechanical properties of waste LCD glass concrete", *Comput. Concrete*, **14**(5), 577-597.
Wang, C.C., Wang, H.Y., Chen, C.H. and Huang, C. (2015a), "Prediction of compressive strength using ultrasonic pulse velocity for CLSM with waste LCD glass concrete", *J. Civil Eng. Architect.*, **9**(5), 691-700.
Wang, C.C., Wang, H.Y., Chen, S.H. and Huang, C. (2015b), "Analytical model of ultrasonic pulse velocity of waste LCD glass concrete", *J. Mar. Sci. Technol.*, **23**(5), 732-740.
Wang, H.Y. (2009), "A study of the effects of LCD glass sand on the properties of concrete", *Waste Manage.*, **29**(1), 335-341.
Yeonung, J., Park, H., Jun Y.B., Jeong, J.H. and Oh, J.E. (2015), "Microstructural verification of the strength performance of ternary blended cement systems with high volumes of fly ash and GGBFS", *Constr. Build. Mater.*, **95**, 96-107.
Zhang, T.S., Yu, Q., Wei, J.X. and Li, J.X. (2011), "Investigation on mechanical properties, durability and micro-structural development of steel slag blended cements", *J. Therm. Anal. Calorim.*, **110**(2), 633-639.

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