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Effect of aggregate properties on the strength and stiffness of lightweight concrete

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Abstract

An experimental program was carried out to obtain the compressive strengths and elastic moduli of cold-bonded pelletized lightweight aggregate concretes. Three types of aggregates were made with different fly ash contents. Experimental data were analyzed statistically. Test results of multivariate analysis of variance (MANOVA) with 95% confidence level ($\alpha = 0.05$) show that the properties of lightweight aggregates and the water/binder ratio are two significant factors affecting the compressive strength and elastic modulus of concrete.

Keywords: Compressive strength; Elastic modulus; Lightweight aggregate concrete; Multivariate analysis

1. Introduction

Civil construction is growing rapidly in Taiwan and the demand for aggregates is much increased. But environmental considerations hinder the supply of natural aggregate. And there are strong objections to opening of pits as well as to quarrying. Therefore, the production and the use of artificial aggregates becomes necessary.

Lightweight aggregate is an artificial aggregate that can be produced from a wide variety of raw materials and production procedures. The properties and the characteristics of lightweight aggregates vary within wide limits [1]. Aggregates generally constitute about 70 to 80% by volume of Portland cement concrete. Due to the large volume fraction it occupies in concrete, aggregates exert a major influence on the elastic modulus of concrete and can be expected to have an important influence on other properties as well [2]. Yang and Huang demonstrated that the compressive strength of concrete is mainly affected by the properties and volume fraction of aggregate [3]. Lydon pointed out that for some lightweight aggregates, the compressive strength depends on the type of aggregate and increases with increase in density [4]. The essential characteristic of lightweight aggregate is its high internal porosity, which results in a low apparent specific gravity. Since the lightweight particles of coarse aggregate are relatively weak, their strength may be the limiting factor affecting concrete strength [5]. The influence of aggregate characteristics on the quality of concrete has also been pointed out by many other researchers [6–8]. The interaction of the paste matrix and the lightweight aggregates is different from that of normal concrete [9]. With a wide range of lightweight aggregates available for concrete, there is a need for a better understanding of the influence of the properties of lightweight aggregates on the compressive strength and elastic modulus of concrete.

In this study, three types of cold-bonded pelletized lightweight aggregates were made of various ratios of cement to fly ash. Three concrete mixtures with various water/binder ratios and volume fractions were designed. A total of 180 concrete cylinders (100 × 200 mm) were cast and tested. It is assumed that multivariated normality, and covariances are equal among groups. And, independence, normality, homogeneity of variances for each dependent variable are taken into account. Experimental data were arranged and analyzed using multivariate analysis (MANOVA) with 95% confidence level ($\alpha = 0.05$) to quantify the influence of the

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lightweight aggregates properties on the compressive strength and elastic modulus of concrete.

2. Experimental program

2.1. Materials and mixture proportions

Type I Portland cement with a specific gravity of 3.15 and fineness of 330 m^2/kg was used in all mixtures. Fine aggregate was river sand with a specific gravity of 2.61, a maximum grain size 4 mm and a moisture content of 1.83%. Three types of cold-bonded pelletized lightweight coarse aggregate were produced with various ratios of cement to fly ash (Class F) as presented in Table 1. Table 2 shows that the saturated surface dry specific gravities for three cold-bonded pelletized aggregates were 1.65, 1.69 and 1.76, respectively. Water absorption was between 20% and 35%. The compressive strength of three cold-bonded pelletized aggregates was 6.01, 7.53, and 8.57 MPa, respectively. The sieve analysis results of the cold-bonded pelletized aggregates are shown in Table 3. Type F superplasticizer (SP) with a specific gravity of 1.2 ($\pm$0.01) and a solid content of 39–41% was used. The pH was 6.0–7.0 and the content of chloride ion was less than 0.2%.

Concrete cylindrical specimens with different lightweight aggregates and volume fractions were made and tested for compressive strengths and elastic moduli. The water/binder ratio was kept at 0.30, 0.40 and 0.50, respectively. The volume fraction was defined as the coarse aggregate volume divided by the total concrete volume. Concrete mixtures with volume fraction of 18%, 24%, 30% and 36% coarse aggregates were designed. The details of mix proportions of lightweight concrete are shown in Table 4 and the air content for all mixtures was kept at a constant of 3%.

Table 1
Mix proportions of cold-bonded pelletized lightweight aggregate (wt.%)

Aggregate type	Cement	Fly ash
I	10	90
II	15	85
III	20	80

Table 2
Physical properties of lightweight aggregate

Aggregate type	Specific gravity (SSD)	Specific gravity (OD)	Water absorption (%)	Bulk unit weight (AD) (kg/m^3)	Crushing value (%)	Particle strength (MPa)
I	1.65	1.23	34.4	857	43.9	6.01
II	1.69	1.29	30.5	952	36.1	7.53
III	1.76	1.44	20.8	972	31.6	8.57

Table 3
Sieve analysis results of cold-bonded pelletized aggregates

Aggregate type	Sieve size (mm)	Cumulative mount retained (%)	Cumulative amount passing (%)
I	19.1	0.00	100.00
	12.7	1.72	98.28
	9.52	22.22	77.78
	4.76	100.00	0.00
II	19.1	0.00	100.00
	12.7	7.59	92.41
	9.52	49.49	50.51
	4.76	100.00	0.00
III	19.1	0.00	100.00
	12.7	20.18	79.82
	9.52	68.92	31.08
	4.76	100.00	0.00

2.2. Experimental methods

The specific gravity and water absorption of lightweight aggregate were tested according to ASTM C127. The size distribution was measured using ASTM C136. The compressive strength of aggregate was obtained from the formula of granular mechanics [10]. Lightweight concrete cylinders (100×200 mm) were cast following the ASTM C192. During casting, all of the specimens were compacted by rodding and vibration. During the first 24 h the specimens were left in the molds. Then the specimens were removed and cured in water (25 ± 2 °C) until the time of testing. At 28 days the compressive strengths were tested according to ASTM C39 and the elastic moduli were determined according to ASTM C469. Prior to the tests, specimens were removed from the curing room and left to dry in air for 24 h.

3. Statistical analysis

Analysis of variance is a useful technique for analyzing experimental data. When several sources of variation are acting simultaneously on a set of observations, the variance of the observations is the sum of the variances of the independent sources. The application of the analysis of variance is meaningful particularly in factorial experiments where several independent

Table 4
Mix proportions of lightweight aggregate concretes

w/b[a]	Water (kg/m^3)	Cement (kg/m^3)	SP (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate volume fraction (%)	Coarse aggregate Type I (kg/m^3)	Coarse aggregate Type II (kg/m^3)	Coarse aggregate Type III (kg/m^3)
0.3	171	602	9	1096	18	297	–	–
				939	24	396	–	–
				783	30	495	–	–
				626	36	594	–	–
0.4	202	517	5	1096	18	297	–	–
				939	24	396	–	–
				783	30	495	–	–
				626	36	594	–	–
0.5	226	453	0	1096	18	297	–	–
				939	24	396	–	–
				783	30	495	–	–
				626	36	594	–	–
0.3	171	602	9	1096	18	–	304	–
				939	24	–	406	–
				783	30	–	507	–
				626	36	–	608	–
0.4	202	517	5	1096	18	–	304	–
				939	24	–	406	–
				783	30	–	507	–
				626	36	–	608	–
0.5	226	453	0	1096	18	–	304	–
				939	24	–	406	–
				783	30	–	507	–
				626	36	–	608	–
0.3	171	602	9	1096	18	–	–	317
				939	24	–	–	422
				783	30	–	–	528
				626	36	–	–	634
0.4	202	517	5	1096	18	–	–	317
				939	24	–	–	422
				783	30	–	–	528
				626	36	–	–	634
0.5	226	453	0	1096	18	–	–	317
				939	24	–	–	422
				783	30	–	–	528
				626	36	–	–	634

[a] w/b = (water + SP)/cement.

sources of variations may be present. The main objective of a factorial experiment is to determine the effect of various factors (independent variable) on some characteristic of the material (dependent variable) and to determine the significance of each factor on the material characteristic under consideration [11].

In analyzing the variations in factorial experiments, the first step is to compute the sum of squares (SS) and then the mean squares (MS). When one variable at several levels is investigated, the sum of squares can be written as

$$SS_{total} = \sum \chi^2 - \frac{T^2}{N}$$

where $\sum \chi^2$ is the sum of squares of all observations, T is the grand total of all observations, N is the total number of observations; The mean squares can be determined from the following relationship:

$$MS = \frac{SS}{DOF}$$

where DOF is the degrees of freedom.

Let the different levels of the variable be represented by columns.

$$SS_c = \text{SS between column means} = \sum \frac{T_c^2}{n} - \frac{T^2}{N}$$

where T_c is total of each column, c is the number of columns, n is the number of observations in each column,

$$\mathrm{SS}_{\mathrm{residual}} = \mathrm{SS} \text{ within the columns or the experimental error} = \mathrm{SS}_{\mathrm{total}} - \mathrm{SS}_c$$

The total variation includes two parts: the variation within the columns and the variation between the columns. Each of the variations can be reduced to the mean square when they are divided by the corresponding degree of freedom. The ratio of any two of mean squares provides basic information for the F test of significance. When the F test is applied to the ratio of MS of residual, the difference between the columns will be determined [12].

In this study, statistical method was applied to analyze the experimental data of the compressive strengths and elastic moduli of lightweight aggregate concretes. Three factors such as water/binder ratio, aggregate type and volume fractions were taken into account, each at three, three, and four levels, respectively. This gives 36 possible combinations. One hundred eighty specimens (five specimens per case) were cast and tested. Let independent variable A represent water/binder ratio, independent variable B represent aggregate type, and independent variable C represent volume fraction ratio. The test of multivariate analysis of variance with 95% confidence level ($\alpha = 0.05$) was applied. The total variations in this study results from main factor, interacting factors, and residual error.

4. Results and discussion

Compressive strengths and elastic moduli of lightweight aggregate concretes are given in Tables 5 and 6, respectively. All data are the average of five specimens at the age of 28 days. The test results of multivariate analysis of variance are shown in Table 7 and compressive strength and elastic modulus of concrete is represented by f'_c and E_c, respectively. The variations include A, B, C, $A \times B$, $B \times C$, $A \times C$, and $A \times B \times C$ because full three-factor experiments are considered. It shows that significant difference exists among all cases for the compressive strengths and elastic moduli of lightweight concretes. Ordinarily, the test for interaction is carried out before the test for main factor effects. If interaction effect exists, it is difficult to clarify the factor effect. Therefore, a univariated analysis is more suitable and F test is carried out. The possibility of having type II error has been considered in the following univariated analysis. The main effect of each factor has been investigated to determine which of the above mentioned three factors have significant effect on compressive strength and elastic modulus of lightweight concrete.

Table 5
Compressive strengths of lightweight aggregate concretes (MPa)

Aggregate type	Volume fraction (%)	w/b = 0.3 (A1)	w/b = 0.4 (A2)	w/b = 0.5 (A3)
I (B1)	18 (C1)	41.7	32.6	29.8
	24 (C2)	37.5	29.5	25.7
	30 (C3)	35.0	27.6	23.3
	36 (C4)	31.8	23.0	21.3
II (B2)	18 (C1)	43.9	37.3	27.4
	24 (C2)	41.2	33.4	26.3
	30 (C3)	38.7	30.4	24.6
	36 (C4)	35.6	28.4	21.5
III (B3)	18 (C1)	48.2	38.3	31.2
	24 (C2)	47.4	37.6	29.5
	30 (C3)	45.8	38.9	27.7
	36 (C4)	42.6	37.5	29.7

Table 6
Elastic moduli of lightweight aggregate concretes (GPa)

Aggregate type	Volume fraction (%)	w/b = 0.3 (A1)	w/b = 0.4 (A2)	w/b = 0.5 (A3)
I (B1)	18 (C1)	22.9	20.3	18.2
	24 (C2)	21.5	16.5	15.5
	30 (C3)	20.1	16.5	14.2
	36 (C4)	18.7	13.8	13.3
II (B2)	18 (C1)	22.8	21.4	17.1
	24 (C2)	21.7	18.2	17.0
	30 (C3)	18.9	17.4	15.2
	36 (C4)	18.2	16.1	14.8
III (B3)	18 (C1)	23.1	21.9	19.3
	24 (C2)	21.9	21.4	17.9
	30 (C3)	20.9	20.6	16.3
	36 (C4)	19.8	18.0	15.4

Table 7
MANOVA table for three-factor experiment

Source of variation	Degree of freedom	Univariate (F)		p Value	
		f'_c	E_c	f'_c	E_c
A	2	2430.60	314.13	0.002*	0.033*
B	2	786.09	59.30	0.001*	0.011*
C	3	274.11	136.13	0.007*	0.004*
$A \times B$	4	39.27	9.77	0.013*	0.008*
$A \times C$	6	4.98	2.43	0.002*	0.021*
$B \times C$	6	26.06	4.39	0.023*	0.031*
$A \times B \times C$	12	4.79	2.65	0.008*	0.001*

* $p < 0.05$.

4.1. The simple main effect of A (w/b) on B (aggregate type)

The test results of the simple main effect of A (w/b) on B (aggregate type) are shown in Table 8 and Figs. 1 and 2. They show that the compressive strengths and elastic

Table 8
The simple main effect of w/b on aggregate type

Source of variation	Aggregate type	Degree of freedom	Univariate (F)		p Value	
			f'_c	E_c	f'_c	E_c
w/b	I	2	42.03	28.77	0.003*	0.033*
	II	2	89.55	21.50	0.014*	0.007*
	III	2	355.59	25.32	0.001*	0.016*

* $p < 0.05$.

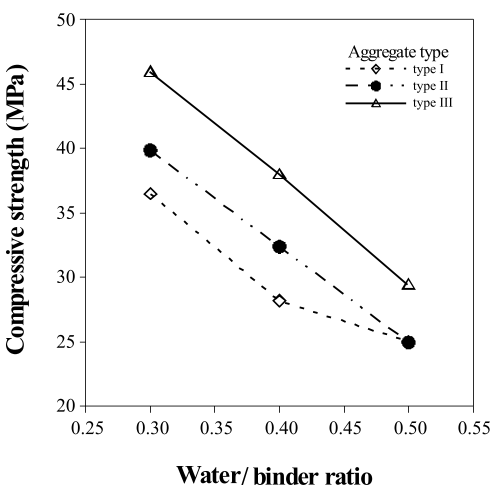

Fig. 1. Effect of water/binder ratio on compressive strength for concrete using different aggregate type.

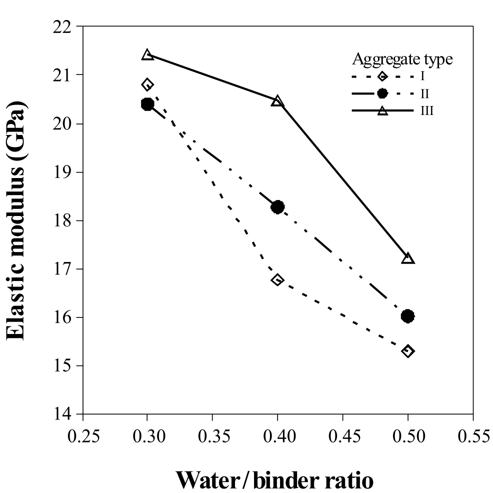

Fig. 2. Effect of water/binder ratio on elastic modulus for concrete using different aggregate type.

moduli of lightweight aggregate concretes with various volume fractions and the same type of aggregate have significant differences among water/binder ratios. Both compressive strengths and elastic moduli of concretes decrease with an increase in w/b ratio.

4.2. The simple main effect of A (w/b) on C (volume fraction)

The test results of the simple main effect of A (w/b) on C (volume fraction) are shown in Table 9 and Figs. 3 and 4. They show that the compressive strengths and elastic moduli of lightweight aggregate concretes with a fixed volume fraction and different type of aggregate have significant differences among water/cement ratios. Both compressive strengths and elastic moduli of concrete also decrease with an increasing w/b ratio.

From the previous discussion, it is clear that the water/binder ratio is still a key factor to determine the compressive strength and elastic modulus of lightweight aggregate concrete.

4.3. The simple main effect of B (aggregate type) on A (w/b)

The test results of the simple main effect of B (aggregate type) on A (w/b) are shown in Table 10 and Figs. 5 and 6. They show that the compressive strengths and elastic moduli of lightweight aggregate concretes with various volume fractions (w/b = 0.4 and 0.5) have significant differences among aggregate types. The compressive strength and elastic modulus of concrete is

Table 9
The simple main effect of w/b on volume fraction of aggregate

Source of variation	Volume fraction (%)	Degree of freedom	Univariate (F)		p Value	
			f'_c	E_c	f'_c	E_c
w/b	18	2	104.65	65.46	0.001*	0.011*
	24	2	54.52	29.26	0.037*	0.033*
	30	2	36.56	22.45	0.009*	0.012*
	36	2	17.82	34.65	0.002*	0.003*

* $p < 0.05$.

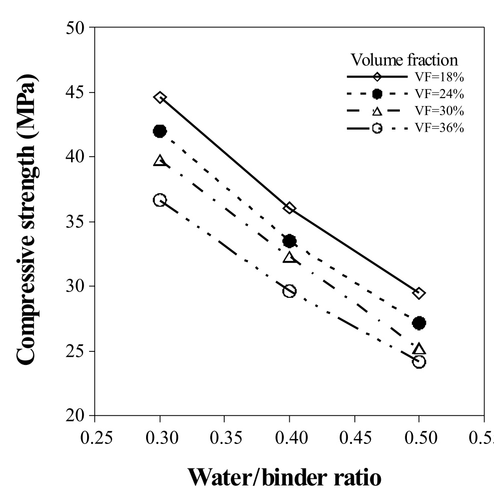

Fig. 3. Effect of water/binder ratio on compressive strength for concrete with various volume fractions.

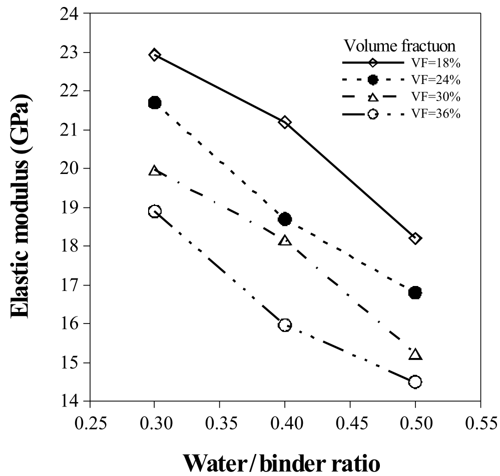

Fig. 4. Effect of water/binder ratio on elastic modulus for concrete with various volume fractions.

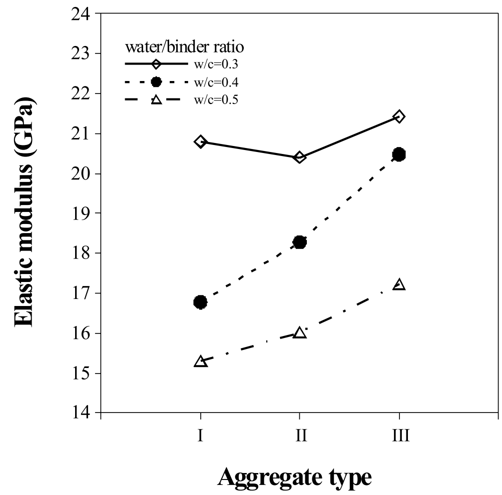

Fig. 6. Effect of aggregate type on elastic modulus for concrete with various water/binder ratios.

Table 10
The simple main effect of aggregate type on w/b

Source of variation	w/b	Degree of freedom	Univariate (F)		p Value	
			f_c'	E_c	f_c'	E_c
Aggregate type	0.3	2	34.78	1.19	0.044*	0.312
	0.4	2	42.43	10.75	0.031*	0.018*
	0.5	2	17.03	4.81	0.001*	0.005*

*$p < 0.05$.

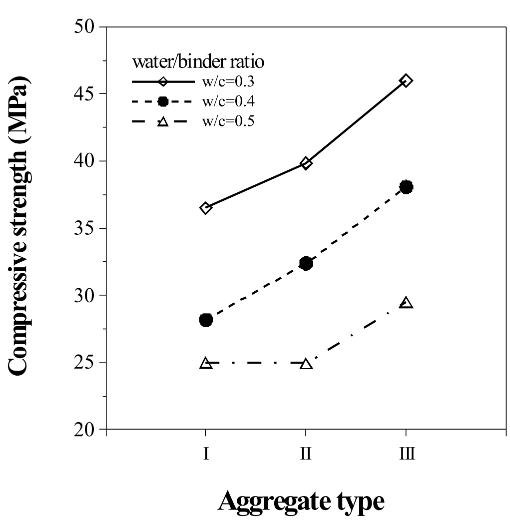

Fig. 5. Effect of aggregate type on compressive strength for concrete with various water/binder ratios.

I < II < III. The series of compressive strength of concrete with water/binder of 0.3 is still I < II < III, but no difference exists in elastic moduli of concrete with different aggregate types. It indicates that the moduli of lightweight aggregate concretes are independent of the aggregate types even with various volume fractions.

4.4. The simple main effect of B (aggregate type) on C (volume fraction)

The test results of the simple main effect of B (aggregate type) on C (volume fraction) were shown in Table 11 and Figs. 7 and 8. They show that the compressive strengths and elastic moduli of lightweight aggregate concretes with a volume fraction of 24%, 30%, 36% and different w/b ratios have significant difference among aggregate types. The compressive strength and elastic modulus of concrete is I < II < III. But no difference exists in compressive strengths and elastic moduli of concretes with a volume fraction of 18% and different aggregate types. For concretes with a volume fraction of 18%, the compressive strengths and elastic moduli are independent of the aggregate type, which are controlled by the cement paste. This is because there is only a small quantity of lightweight aggregates in the concrete.

From the previous discussion, it seems that the property of lightweight aggregate is a key factor affect-

Table 11
The simple main effect of aggregate type on volume fraction ratio

Source of variation	Volume fraction (%)	Degree of freedom	Univariate (F)		p Value	
			f_c'	E_c	f_c'	E_c
Aggregate type	18	2	1.41	0.33	0.258	0.719
	24	2	3.80	3.49	0.033*	0.042*
	30	2	5.93	4.00	0.006*	0.028*
	36	2	13.12	3.70	0.001*	0.036*

*$p < 0.05$.

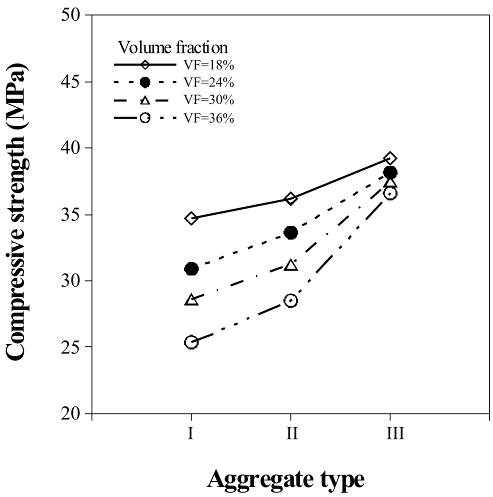

Fig. 7. Effect of aggregate type on compressive strength for concrete with various volume fractions.

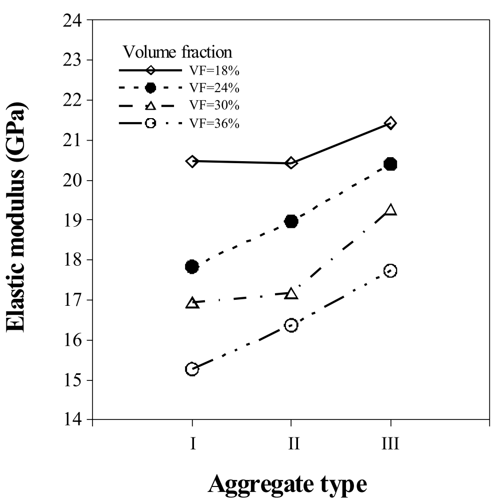

Fig. 8. Effect of aggregate type on elastic modulus for concrete with various volume fractions.

ing the compressive strength and elastic modulus of lightweight aggregate concrete with high volume fraction of aggregates in the mixture.

4.5. The simple main effect of C (volume fraction) on A (w/b)

The test results of the simple main effect of *C* (volume fraction) on *A* (w/b) are shown in Table 12 and Figs. 9 and 10. They show that the compressive strengths and elastic moduli of lightweight aggregate concretes with different aggregate types and the same w/b ratio have significant different values depending on the various volume fractions. The compressive strengths and elastic moduli of concretes decrease with an increase in volume fraction. Consequently the compressive strength and elastic modulus of lightweight aggregate concrete are affected by the volume fraction.

Table 12
The simple main effect of volume fraction on w/b

Source of variation	w/b	Degree of freedom	Univariate (F)		p Value	
			f'_c	E_c	f'_c	E_c
Volume fraction	0.3	3	7.44	29.19	0.001*	0.001*
	0.4	3	3.95	14.65	0.014*	0.001*
	0.5	3	9.14	20.56	0.023*	0.003*

$^* p < 0.05$.

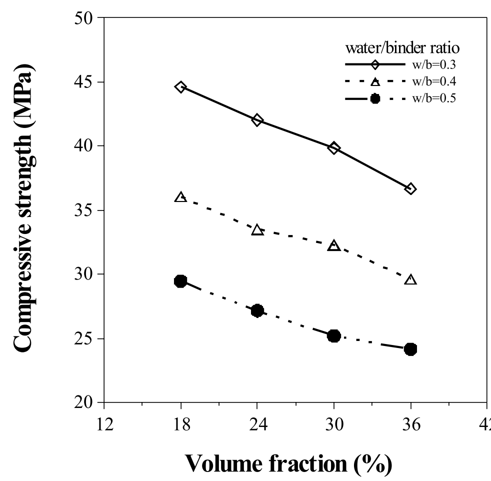

Fig. 9. Effect of volume fraction on compressive strength for concrete with various water/binder ratios.

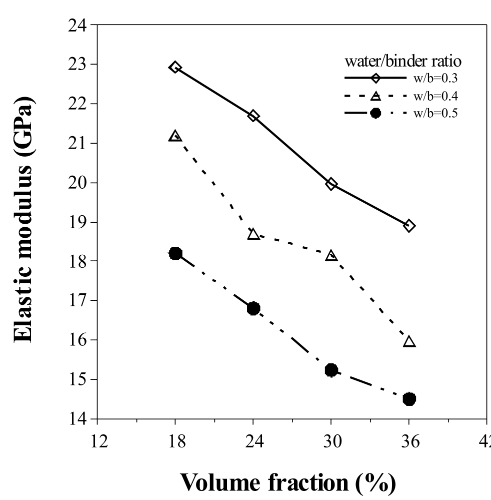

Fig. 10. Effect of volume fraction on elastic modulus for concrete with various water/binder ratios.

4.6. The simple main effect of C (volume fraction) on B (aggregate type)

The test results of the simple main effect of *C* (volume fraction) on *B* (aggregate type) are shown in Table 13 and Figs. 11 and 12. They show that the compressive strengths and elastic moduli of lightweight aggregate concretes with types I and II aggregates and different w/b ratios have significant difference among volume fractions. The compressive strengths and elastic moduli of concretes decrease with an increase in volume fraction. The elastic modulus of concrete with type III aggregate has the same trend as those of concretes with types I and II aggregates, but there is no difference in concrete compressive strength. It indicates the compressive strengths of lightweight aggregate concretes are independent of the volume fraction of type III aggregate.

To sum up, the compressive strengths and elastic moduli of lightweight aggregate concretes decrease with an increase in aggregates volume fraction and increase (except the volume fraction ratio of 18%) with an increase of aggregate strength. The strength of lightweight aggregate directly affects the compressive strength of concrete because the aggregate compressive strength is much lower than the strength of cement paste. When the volume fraction of lightweight aggregate is 18%, concrete elastic modulus and the compressive strength are controlled by the cement paste.

Table 13
The simple main effect of volume fraction on aggregate type

Source of variation	Aggregate type	Degree of freedom	Univariate (*F*) f'_c	Univariate (*F*) E_c	*p* Value f'_c	*p* Value E_c
Volume fraction	I	3	6.93*	8.69*	0.001*	0.001*
	II	3	3.11*	8.63*	0.036*	0.002*
	III	3	0.29	5.60*	0.833	0.002*

*$p < 0.05$.

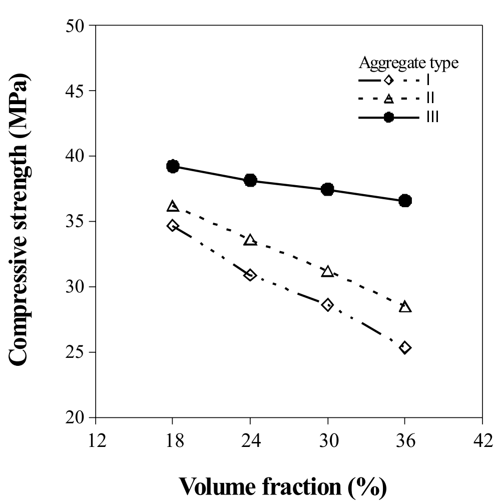

Fig. 11. Effect of volume fraction on compressive strength for concrete using different aggregate type.

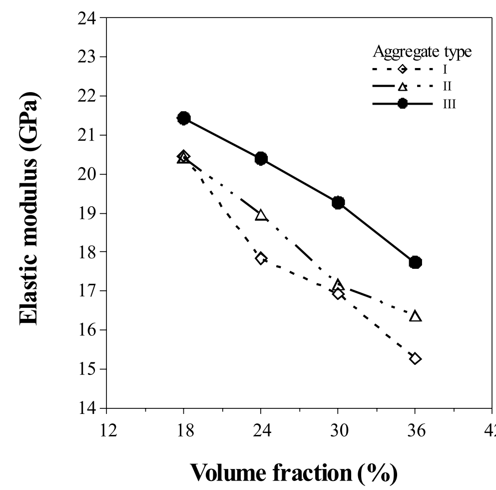

Fig. 12. Effect of volume fraction on elastic modulus for concrete using different aggregate type.

5. Conclusions

The following conclusions can be drawn based on the results of this study:

(1) The water/binder ratio and the properties of lightweight aggregate are two important factors determining the compressive strength and elastic modulus of lightweight aggregate concrete.
(2) When aggregate volume fraction is 18%, the compressive strengths and elastic moduli of the concrete are independent of the aggregate type, being mainly controlled by the water to cement ratio of the paste.

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