Journal of Marine Science and Technology

Volume 12 | Issue 1 Article 5

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Jen-Hui Su
Ph.D. Candidate of Civil Engineering at National Chung -Hsing University, Instructor of Department of Civil Engineering, Feng Chia University., jhsu@fcu.edu.tw

Tsong Yen
President of National Chung -Hsing University, Prof. of Department of Civil Engineering, National Chung-Hsing University.

Recommended Citation
Su, Jen-Hui and Yen, Tsong (2004) "Effects of Earthquake Excitation on the Strength Properties of Newly Poured Concrete," *Journal of Marine Science and Technology*: Vol. 12: Iss. 1, Article 5.
DOI: 10.51400/2709-6998.2218
Available at: https://jmstt.ntou.edu.tw/journal/vol12/iss1/5

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Acknowledgements

The authors would like to thank the National Science Council of the Republic of China for financially supporting this research under Contract No. NSC 89- 211-E-005-065.

EFFECTS OF EARTHQUAKE EXCITATION ON THE STRENGTH PROPERTIES OF NEWLY POURED CONCRETE

Jen-Hui Su* and Tsong Yen**

Key words: earthquake excitation, strength property, newly poured concrete.

ABSTRACT

This study examines the 28-day strength properties of concrete under shaking, such as from an earthquake, during its strength development period. With a concrete strength of 20.59 MPa (3,000 psi), groups of concrete cylinders were made and tested on a shaking table. The peak value of ground acceleration (PGA) level of the simulated earthquake and the cylinder age are the two variables considered. The test results are as follows. If the concrete is older than three days, the earthquake excitation will not significantly reduce its 28-day strength. At younger than two days, earthquake excitation will reduce the strength of the concrete. The largest reduction in strength was approximately 28%. The 28-day concrete strength was partially recovered up to 50% by appropriate curing, if the concrete suffers earthquake excitation within one day after placement. Additionally, earthquake excitation did not greatly affect the 28-day elastic modulus and the ultrasonic pulse velocity, when the concrete was properly cured.

INTRODUCTION

On September 21, 1999, the Chi-Chi earthquake hit central Taiwan. It reached a magnitude of 7.3 on the Richter Scale. Several thousand people were killed; many people were made homeless and many bridges and much property were damaged. This event revealed numerous engineering defects and problems. One of these problems involved newly poured reinforced concrete that suffered severe earthquake exposure before its strength was fully developed. Most engineers do not know the extent to which a severe earthquake affects the 28-day strength [3, 6, 12].

Setting and hardening are the two major steps in the development of concrete strength. Before setting, concrete is viscous, fluid and workable. During setting, it is in a pudding-like state, as a conformable plastic. After setting, it gradually gains strength by hardening [20]. Setting can be separated into initial and final setting. At initial setting, the concrete maintains its fluidity. Thereafter, it begins to lose its plasticity. It will generate discontinuities between the crystals under any disturbance. At final setting, the concrete loses all of its plasticity. The concrete is now in a solid state, gaining a certain amount of strength. However, this strength is not fully developed and any disturbances will cause the concrete to crack and reduce its strength. The concrete ages are about 4-6 hours and 6-10 hours for initial setting time and final setting time, respectively. These times are based on the penetration resistance test method specified by the ASTM C-403 Standard [4]. Concrete usually gains 10-20% of its 28-day strength in one day after placement, 40-60% in three days and 65-80% in seven days [8, 10].

This study chooses the peak value of ground acceleration (PGA) levels of the earthquakes and the age of the concrete as the two main factors in evaluating the effects of earthquake excitation on the strength properties of newly poured concrete. The reduction in the concrete strength, elastic modulus and ultrasonic pulse velocity of newly poured concrete under different earthquake excitation actions is investigated.

EFFECT OF CHANGE ON THE STRENGTH PROPERTY OF CONCRETE

The effect of an earthquake on newly poured concrete has seldom been addressed. The authors were able to find only a few references about the strength properties of concrete. The characteristics of concrete are changing all the time. Before initial setting, concrete is highly fluid. Any crack or fissure induced in it by an earthquake is automatically sealed. An earthquake can typically inflict only slight damage on newly poured concrete. Between initial and final setting the concrete becomes less plastic. Any shaking by an earthquake can cause permanent cracks in the concrete and reduce its strength. At this stage, the concrete is

Paper Submitted 10/24/03, Accepted 12/25/03. Author for Correspondence: Jen-Hui Su. E-mail: jhsu@fcu.edu.tw.
**Ph.D. Candidate of Civil Engineering at National Chung -Hsing University, Instructor of Department of Civil Engineering, Feng Chia University.*
***President of National Chung -Hsing University, Prof. of Department of Civil Engineering, National Chung-Hsing University.*

Table 1. Concrete mix proportion

Concrete Strength (MPa)	W/C ratio	Water (kg/m^3)	Cement (kg/m^3)	Fine Aggr. (kg/m^3)	Coarse Aggr. (kg/m^3)	Coarse Aggr. Dmax (mm)	Slump (mm)
20.59	0.8	220	258	818	1006	19	15

not completely hydrated. Curing can remedy some of the cracks or the reduction of strength. During hardening (at an early age), the intensity of earthquake excitation reduces the concrete's strength. This work seeks to determine the reduction in the 28-day strength properties of newly poured concrete caused by an earthquake.

An earthquake shakes concrete back and forth randomly, in a manner similar to the repeated vibrations applied to newly poured concrete. As stated in Refs. 18 and 19, the concrete is repeatedly vibrated is after normal consolidation. The concrete is allowed to set for a while and then vibrated again. The greatest advantage of repeatedly vibrated concrete is its plasticity. Therefore, the repeated vibration must be intense enough to cause the concrete to enter the plastic state. The concrete maintains its plasticity, filling the pores and expelling air bubbles. Hence, the strength of newly poured concrete may be increased by earthquake excitation. The elastic modulus of concrete is an important parameter in characterizing the force-deformation relationship. A greater elastic modulus corresponds to a smaller elastic deformation. The elastic modulus is strongly related to the strength and density of the concrete and the characteristics of the paste and aggregate. Generally, in the elastic stage, the unit-deformation of the paste exceeds that of the aggregate. The properties of the paste strongly affect the deformation of the concrete. The capillary porosity and the number of fissures also affect the elastic modulus. A greater capillary porosity and number of fissures correspond to a smaller elastic modulus [13]. The concrete mix proportion was maintained constant in this experiment (Table 1), so the only factors that affect the elastic modulus of newly poured concrete after an earthquake are the intensity of the earthquake and the strength, density, paste and number of fissures in the concrete.

Here, an attempt is made to determine the internal fissures in the newly poured concrete cylinders by measuring their ultrasonic pulse velocity. More or larger fissures correspond to a lower pulse velocity. Reference 5 shows that if the width of the fissure reaches 0.08 mm, the ultrasonic pulse will be totally stopped. Many reports [11, 14, 16, 17] pointed out that the factors that dominate the ultrasonic pulse velocity in concrete are the quality and quantity of the aggregate, the water to cement ratio, the water content, the curing conditions and the age of the concrete. References 7 and 15 stated that the existence of a few pores and fissures does not obviously affect the ultrasonic pulse velocity, but will affect the strength of the concrete. The strength will be reduced owing to the stress concentration effect on the rims of the pores or at the tips of the fissures. The concrete mix proportion was maintained constant in this experiment, so after an earthquake, the factors that affected the ultrasonic pulse velocity of the newly poured experimental concrete were the earthquake intensity, the age of the concrete and the number of fissures.

EXPERIMENTAL PROGRAM

Accordingly, Fig. 1 shows the experimental procedure. This study includes the following tests and analysis.

1) Material Properties

Cement: Type I Portland cement
 Specific gravity = 3.15
Coarse Aggregate: D_{max} = 19 mm
 Saturated surface dry (SSD) bulk specific gravity = 2.61
 Saturated surface dry (SSD) absorption capacity = 1.02%
 Dry -rodded unit weight = 1,508 kg/m^3
Fine Aggregate: Fineness modulus (F.M.) = 2.72
 Saturated surface dry (SSD) bulk specific gravity = 2.62
Concrete Mix Proportion: See Table 1

2) Setting Time Determination

Code C-403 of the ASTM Standard was used to determine the initial and final setting times.

3) Specimen Planning

This study focuses on concrete with the strength of 20.59 MPa (3000 psi). To measure the effects of earthquake excitation on the strength properties of newly poured concrete, this study selected six concrete ages during the concrete strength development period, for example, 4.5 hours (before initial setting), 6.5 hours (between initial and final setting), 12 hours (after final setting), one day, two days and three days (during hardening). The concrete specimens were placed in the specimen molds. The molds are fixed on the shaking table and vibrated with different PGAs (peak value of ground acceleration) to simulate earthquakes (See Picture 1). PGA is mainly attributed to shear wave and surface wave. The earthquake excitation intensities used were 0.05 g, 0.20 g, 0.33 g and 0.45 g. Twenty-four cylinders were prepared for each test age; six cylinders from each group were tested on the shaking table at four different earthquake excitation intensities. Eighteen control set cylinders were prepared. According to six different ages (6.5 hrs, 12 hrs, one day, two days, three days, and 28 days), the eighteen cylinders were divided into six groups. Each group has three cylinders. A total of 162 cylinders were used in these experiments. (See Fig. 1)

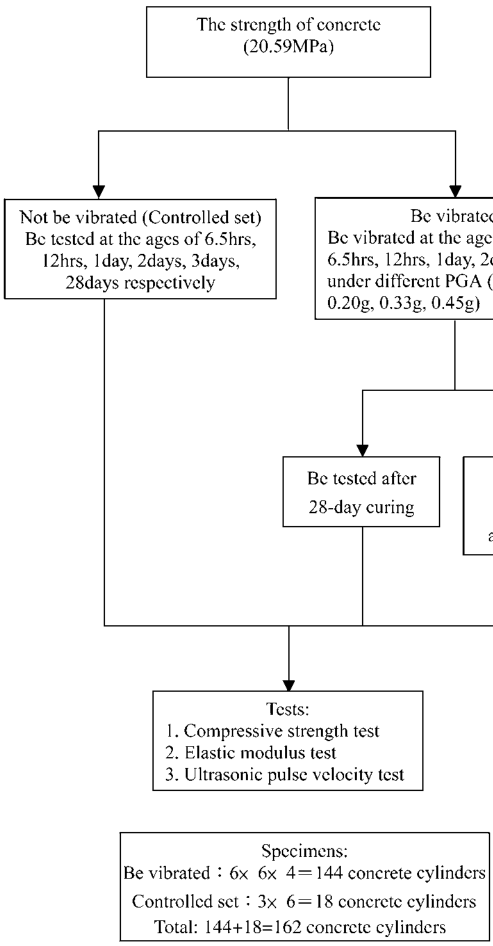


Fig. 1. Procedure of experimental program.

4) Concrete Vibration Test and Measurement of Mechanical Properties

Half of the concrete cylinders (Type A) were tested for compressive strength, elastic modulus and ultrasonic pulse velocity immediately after they were vibrated. The other half of the concrete cylinders (Type B) were tested after 28 days of curing for compressive strength, elastic modulus and ultrasonic pulse velocity. The undisturbed control set concrete cylinders had the same concrete ages as the Type A cylinders (and were called Type C). The 28-day cured concrete (Type D) had the same age as Type B (Table 2). These samples were tested for compressive strength, elastic modulus and ultrasonic pulse velocity. All concrete cylinders (A, C and B, D) were analyzed to determine the effect of varied earthquake excitation intensity on the concrete strength properties.

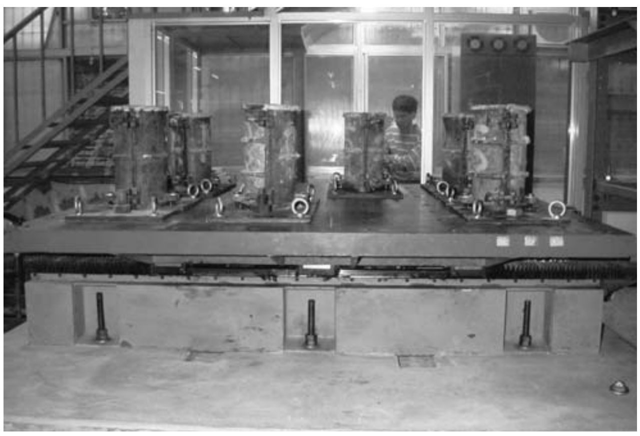
5) Earthquake Simulation

An acceleration sensor was installed on the shaking table to record the history of acceleration to verify that this actuator could produce good simulated earthquakes. The input earthquake acceleration history (real) was compared with the output (simulated) acceleration. Figures 2 to 5 plot the results. Both acceleration histories (real and simulated) are similar, as shown in the figures.

RESULTS AND DISCUSSION

1. Setting Time of the Concrete

Figure 6 shows the initial and final setting times for 20.59 MPa (3,000 psi) concrete. The initial setting time is around 4.7 hours and the final setting time is



Picture 1

around 6.8 hours. Accordingly, 4.5 hours (before the initial setting), 6.5 hours (between the initial and final settings), 12 hours, one day, two days and three days (during hardening) were selected as the concrete excitation times to simulate earthquakes. Concrete with six different ages was used.

2. Measuring error and quality control of concrete strength

Measuring error may originate from instrumental imperfection or reading bias. The reliability of the testing results can be estimated by calculating the standard deviations of the mutiple-repeat-test data first, which are based on the statistical rules [2, 9]. The calculation procedures can be depicted as follows:

Assume that $Y_1, Y_2, ..., Y_i, ..., Y_n$ are testing samples, and if Y_i has m_i testing data, then the total number of data is M then

$$M = \sum_{i=1}^{n} m_i \tag{1}$$

Let Y_{ij} represent the jth data of Y_i variable and $\overline{Y}_i$ is the mean value of Y_i, then

$$\overline{Y}_i = \frac{1}{m_i}\left(\sum_{j=1}^{m_i} Y_{ij}\right),\ i = 1, 2, ..., n \tag{2}$$

Table 2. Classification of types A, B, C, and D

Type	Condition	Concrete Ages (as vibrated)	PGA (1 g = 9.8 m/s^2)
A	Vibrated Tested immediately after vibration	*4.5 hrs, 6.5 hrs, 12 hrs, 1 day, 2 days, 3 days *:The specimens of concrete aged 4.5 hrs are not tested	0.05 g, 0.20 g, 0.33 g, 0.45 g
B	Vibrated Tested after 28-day curing	4.5 hrs, 6.5 hrs, 12 hrs, 1 day, 2 days, 3 days	0.05 g, 0.20 g, 0.33 g, 0.45 g
C	Not be vibrated (controlled set)	6.5 hrs, 12 hrs, 1 day, 2 days, 3 days	0 g
D	Not be vibrated (controlled set)	28 days	0 g

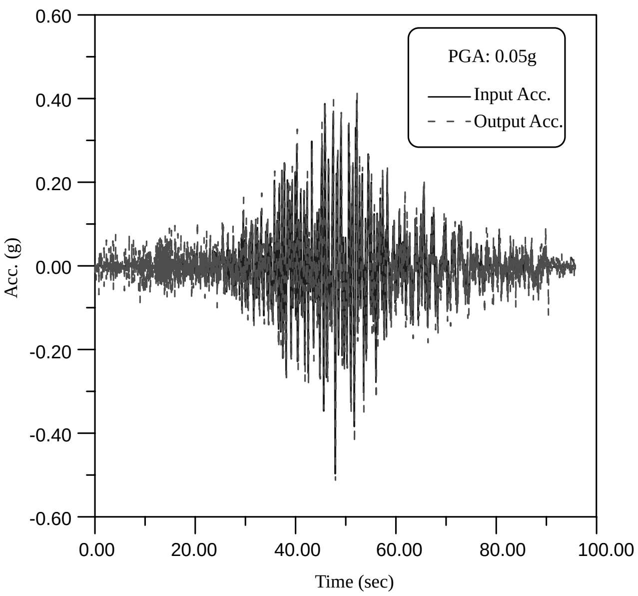


Fig. 2. Input, output acceleration history when PGA is 0.05 g.

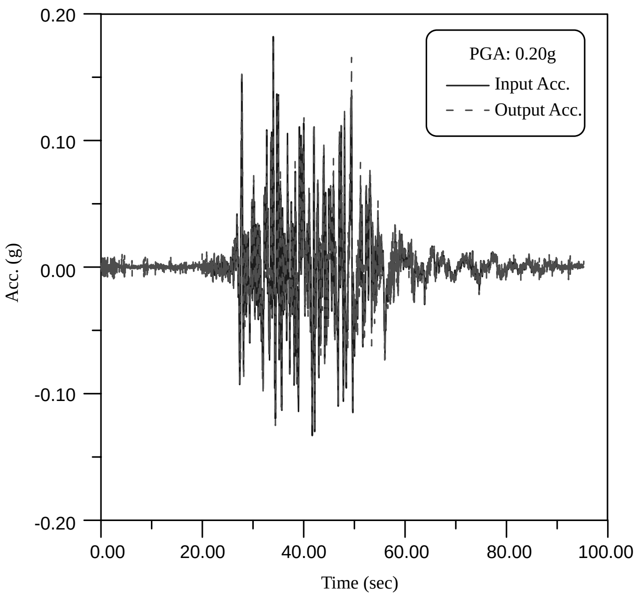


Fig. 3. Input, output acceleration history when PGA is 0.20 g.

Table 3. Quality control levels for concrete testing [1]

Quality Control Level	Standard Deviation (MPa)		Coefficient of Variation (%)	
	Site	Laboratory	Site	Laboratory
Excellent	<2.75	<1.38	<3	<2
Very Good	2.75~3.45	1.38~1.73	3~4	2~3
Good	3.45~4.14	1.73~2.07	4~5	3~4
Fair	4.14~4.82	2.07~2.41	5~6	4~5
Poor	>4.82	>2.41	>6	>5

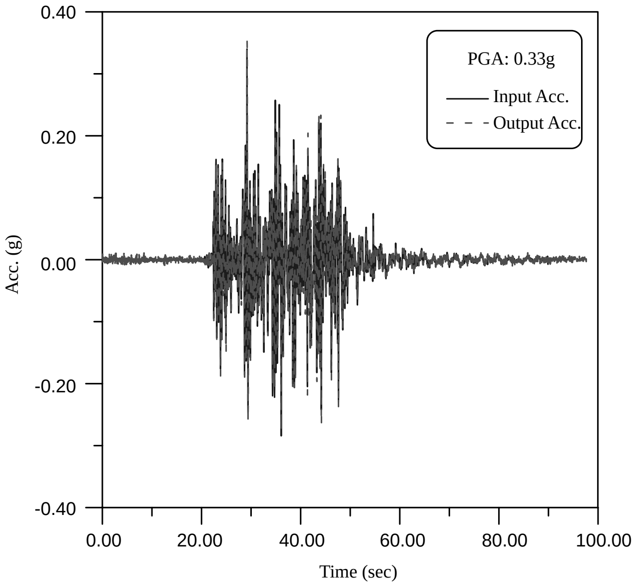


Fig. 4. Input, output acceleration history when PGA is 0.33 g.

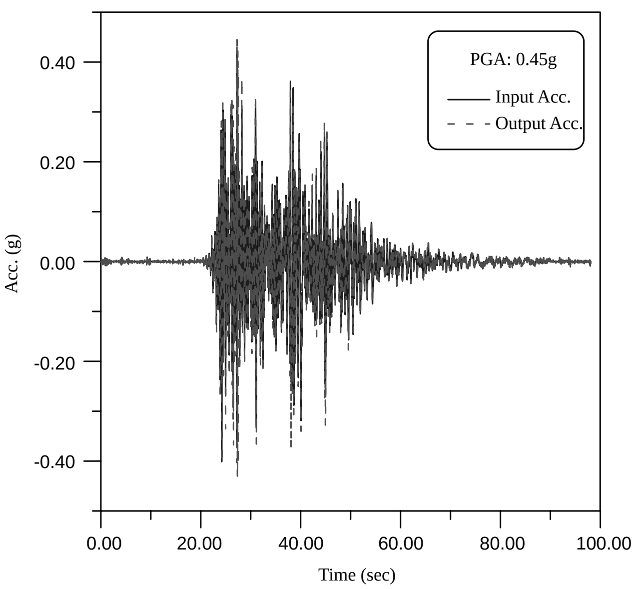


Fig. 5. Input, output acceleration history when PGA is 0.45 g.

The unbiased variance of Y_i is

$$S_i^2 = \frac{\sum_{j=1}^{m_i} (Y_{ij} - \overline{Y}_i)^2}{m_i - 1}, \quad i = 1, 2, 3, \ldots, n \tag{3}$$

The variance of all data is

$$S^2 = \frac{\sum_{i=1}^{n} (m_i - 1) S_i^2}{M - n} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m_i} (Y_{ij} - \overline{Y}_i)^2}{M - n} \tag{4}$$

Where, S is the standard deviation.

Table 3, as suggested by ACI 214 regulation, defines the quality levels of concrete testing and their corresponding extent of standard variation [1]. Comparing the standard deviation calculated with equation (4) and the values in Table 3 reveals the quality of concrete testing, thus allowing us to understand the level of quality control of the laboratory. According to the t-distribution in statistics, the 95% confidence inter-

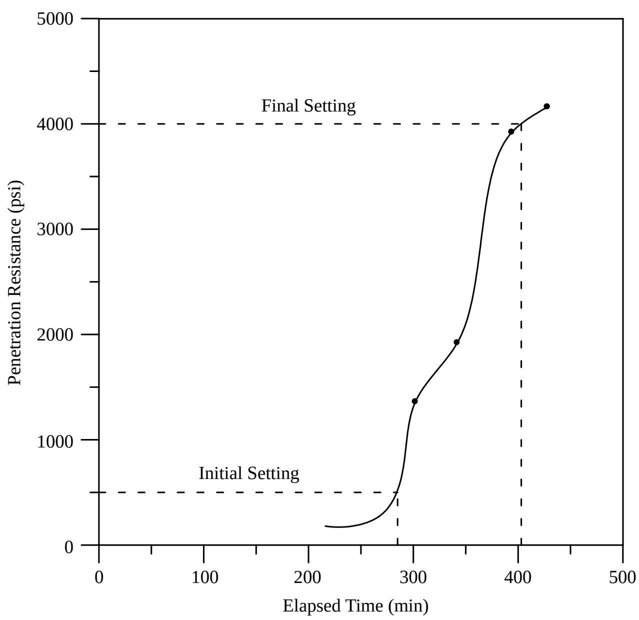


Fig. 6. Setting time of concrete with compressive strength 20.59 MPa.

val of the mean value is $\overline{Y} - t_{\alpha/2}\frac{S}{\sqrt{n}} < \mu < \overline{Y} + t_{\alpha/2}\frac{S}{\sqrt{n}}$. The meaning error is $(t_{\alpha/2}\frac{S}{\sqrt{n}})/\overline{Y}$. Table 4 summarizes the standard deviation of 28-day cylinder strength among the 25 groups. Their standard deviation is 0.51 MPa, which falls into the excellent level shown in Table 3. The mean value is 19.07 MPa. The range of meaning error is ±1.1%.

3. Effect of Earthquake on the Strength of Newly Poured Concrete

3.1 Concrete Strength Comparison between Type A and Type C

Table 5 shows the results of concrete strength immediately after vibration. The strength of Type A cylinders does not significantly decline due to the excitation of concrete aged three days. This finding implies that if the concrete age is older than three days, earthquake excitation will not reduce its strength. Type A cylinders younger than two days old were weakened by earthquake excitation. Concrete aged 6.5 hours was especially vulnerable to earthquake excitation (between the initial and final setting) because the concrete is weakest in this stage.

Figure 7 compares the strength of the vibrated cylinders (Type A) with that of the control-set cylinders (Type C). P_1(%) is defined as the rate of decrease or increase in the compressive strength (elastic modulus or ultrasonic pulse velocity).

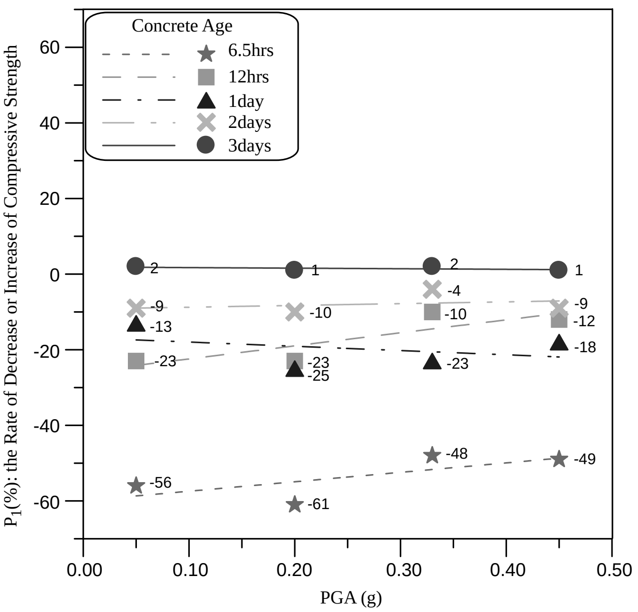


Fig. 7. Comparison of compressive strength of type A and type C (%).

Table 4. Error computation of 28-day compressive strength for type B and type D

Sample (n)	Item	28-day Strength (MPa)	m_i	Mean (MPa)	$(m_i-1)(S_i)^2$
1	A0d28-1	20.45	3	20.69	1.0664
	A0d28-2	20.11			
	A0d28-3	21.51			
2	h4.5A1d28-1	15.90	3	16.57	0.7953
	h4.5A1d28-2	17.15			
	h4.5A1d28-3	16.67			
3	h4.5A2d28-1	19.47	3	18.88	0.5834
	h4.5A2d28-2	18.41			
	h4.5A2d28-3	18.76			
4	h4.5A3d28-1	19.29	3	19.24	0.915
	h4.5A3d28-2	18.54			
	h4.5A3d28-3	19.89			
5	h4.5A4d28-1	19.01	3	19.68	0.7574
	h4.5A4d28-2	20.22			
	h4.5A4d28-3	19.81			
6	h6.5A1d28-1	18.35	3	18.37	0.1865
	h6.5A1d28-2	18.68			
	h6.5A1d28-3	18.07			
7	h6.5A2d28-1	18.69	2	18.44	0.1201
	h6.5A2d28-3	18.20			
8	h6.5A3d28-1	21.71	3	21.49	0.7549
	h6.5A3d28-2	20.80			
	h6.5A3d28-3	21.97			
9	h6.5A4d28-1	19.08	3	19.64	0.5373
	h6.5A4d28-2	19.75			
	h6.5A4d28-3	20.10			
10	h12A1d28-1	18.89	3	18.83	0.1465
	h12A1d28-2	19.06			
	h12A1d28-3	18.57			
11	h12A2d28-1	17.98	3	18.41	0.2918
	h12A2d28-2	18.54			
	h12A2d28-3	18.71			
12	h12A3d28-1	20.64	3	20.69	1.205
	h12A3d28-2	21.49			
	h12A3d28-3	19.94			
13	h12A4d28-1	21.00	3	21.31	0.1749
	h12A4d28-2	21.59			
	h12A4d28-3	21.33			
14	d1A1d28-1	17.32	3	17.34	0.7206
	d1A1d28-2	17.95			
	d1A1d28-3	16.75			
15	d1A2d28-1	18.13	3	17.99	0.2393
	d1A2d28-2	18.25			
	d1A2d28-3	17.60			
16	d1A3d28-1	17.01	3	17.22	0.5683
	d1A3d28-2	17.83			
	d1A3d28-3	16.83			
17	d1A4d28-1	14.27	3	14.83	1.1202
	d1A4d28-2	15.68			
	d1A4d28-3	14.54			
18	d2A1d28-1	19.34	3	19.18	0.1569
	d2A1d28-2	19.35			
	d2A1d28-3	18.86			
19	d2A2d28-1	18.60	3	18.82	0.0773
	d2A2d28-2	18.90			
	d2A2d28-3	18.97			
20	d2A3d28-1	19.36	3	19.72	0.5593
	d2A3d28-2	19.48			
	d2A3d28-3	20.33			
21	d2A4d28-1	19.39	3	19.56	0.6467
	d2A4d28-2	20.19			
	d2A4d28-3	19.09			
22	d3A1d28-1	19.79	3	19.80	0.0131
	d3A1d28-2	19.95			
	d3A1d28-3	19.89			
23	d3A2d28-1	19.09	3	19.44	0.4541
	d3A2d28-2	19.98			
	d3A2d28-3	19.24			
24	d3A3d28-1	20.11	3	20.26	0.2803
	d3A3d28-2	20.69			
	d3A3d28-3	19.99			
25	d3A4d28-1	20.55	3	20.25	0.2081
	d3A4d28-2	20.30			
	d3A4d28-3	19.91			
Σ			74	476.75	12.5787

S = 0.51MPa, $\overline{Y}$ = 19.07MPa, $t_{\alpha/2}\frac{S}{\sqrt{n}} / \overline{Y}$ = 1.1%

Table 5. Results of vibration test: Tested immediately after vibration - compressive strength of concrete (MPa)

Concrete	Type C	Type A			
Age	Control	0.05 g	0.20 g	0.33 g	0.45 g
6.5 hrs	1.03 (100%)	0.45 (44%)	0.40 (39%)	0.54 (52%)	0.53 (51%)
12 hrs	2.02 (100%)	1.56 (77%)	1.55 (77%)	1.82 (90%)	1.78 (88%)
1 day	4.99 (100%)	4.36 (87%)	3.74 (75%)	3.83 (77%)	4.07 (82%)
2 days	7.16 (100%)	6.49 (91%)	6.44 (90%)	6.87 (96%)	6.48 (91%)
3 days	9.20 (100%)	9.37 (102%)	9.31 (101%)	9.41 (102%)	9.30 (101%)

Table 6. Results of vibration test: Tested after 28-day curing - compressive strength of concrete (MPa)

Concrete	Type D	Type B			
Age	Control	0.05 g	0.20 g	0.33 g	0.45 g
4.5 hrs	20.69 (100%)	16.57 (80%)	18.88 (91%)	19.24 (93%)	19.68 (95%)
6.5 hrs	20.69 (100%)	18.37 (89%)	18.44 (89%)	21.49 (104%)	19.64 (95%)
12 hrs	20.69 (100%)	18.83 (91%)	18.41 (89%)	20.69 (100%)	21.31 (103%)
1 day	20.69 (100%)	17.34 (84%)	17.99 (87%)	17.22 (83%)	14.83 (72%)
2 days	20.69 (100%)	19.18 (93%)	18.82 (91%)	19.72 (95%)	19.56 (95%)
3 days	20.69 (100%)	19.88 (96%)	19.44 (94%)	20.26 (98%)	20.25 (98%)

Table 7. Results of vibration test: Tested immediately after vibration - elastic modulus of concrete (MPa)

Concrete	Type C	Type A			
Age	Control	0.05 g	0.20 g	0.33 g	0.45 g
12 hrs	4644 (100%)	3668 (79%)	3250 (70%)	4459 (96%)	4225 (91%)
1 day	7894 (100%)	7498 (95%)	7340 (93%)	6947 (88%)	7105 (90%)
2 days	9029 (100%)	8759 (97%)	8668 (96%)	8852 (98%)	8668 (96%)
3 days	10012 (100%)	10110 (100%)	9911 (99%)	10012 (100%)	9812 (98%)

$$P_1(\%) = \frac{Type\ A - Typ\ C}{Type\ C} \times 100\% \tag{5}$$

Where

Type A = Compressive strength (elastic modulus or ultrasonic pulse velocity) of concrete tested immediately after vibration.

Type C = Compressive strength (elastic modulus or ultrasonic pulse velocity) of the controlled set.

The trend lines in Fig. 7 show that reduction in strength declines as the PGA increases when the concrete is aged for 6.5 hours because of the plasticity of the concrete at this age. Strong earthquake excitation can expel the air bubbles from the cylinders and make the cylinders denser. The reduction in strength decreases as the density of the concrete increases. When the concrete is aged 12 hours, the reduction in strength also decreases as PGA increases. This result is consistent with the conclusions in Refs. 18 and 19 that repeated vibration with enough force increases the strength of the concrete.

When the concrete is aged one day, the reduction in strength increases as PGA increases because the concrete is hardening, but it does not yet have enough strength. The paste-aggregate bond is destroyed more badly when the PGA is greater. When the concrete is aged two days, its strength exceeds that of concrete aged one day, but it still cannot bear a large earthquake excitation. The strength of the concrete is therefore reduced but does not change too greatly with the increase in PGA. Therefore, the line in the chart becomes flatter and straighter.

3.2 28-day Strength Comparison between Type B and Type D

Table 6 shows the results of concrete strength after 28-day curing. The table indicates that the 28-day strength is not significantly reduced when the excitation due to the earthquake occurs as the concrete is aged for three days. This finding implies that if the concrete is older than three days, the earthquake excitation will not reduce the 28-day strength. The 28-day strength of Type B cylinders of younger than two days declined under excitation, especially for excitation at 0.05 g of concrete aged 4.5 hours (before the initial setting). The strength decreased most at 4.5 hours, by about 20% because the concrete strength is lowest in this stage. However, this result is inconsistent with the view that the strength does not decline if the concrete is vibrated before the initial setting, because the initial setting time of cement is less than 4.5 hours at about 2-4 hours. At 4.5 hours, the C-H-S gel has been produced, and the concrete already has some strength.

Figure 8 compares the 28-day strength of vibrated cylinders (Type B) with that of the control-set cylinders (Type D). P_2(%) is defined as the rate of decrease or increase of 28-day compressive strength (28-day elastic modulus or 28-day ultrasonic pulse velocity).

$$P_2(\%) = \frac{Type\ B - Typ\ D}{Type\ D} \times 100\% \qquad (6)$$

Where

Type B = The 28-day compressive strength (28-day elastic modulus or 28-day ultrasonic pulse velocity) of concrete tested after 28-day curing.

Type D = The 28-day compressive strength (28-day elastic modulus or 28-day ultrasonic pulse velocity) of the controlled set.

The trend lines in Fig. 8 show that the 28-day strength reduction for Type B cylinders is generally similar to that described in Section 3.1. When the concrete is younger than 12 hours, the reduction in 28-day strength decreases as PGA increases. The largest strength reduction was by about 20%. When the concrete is one-day old, the reduction in 28-day strength increases with PGA. The largest reduction in strength was by about 28%. When the concrete is two days old,

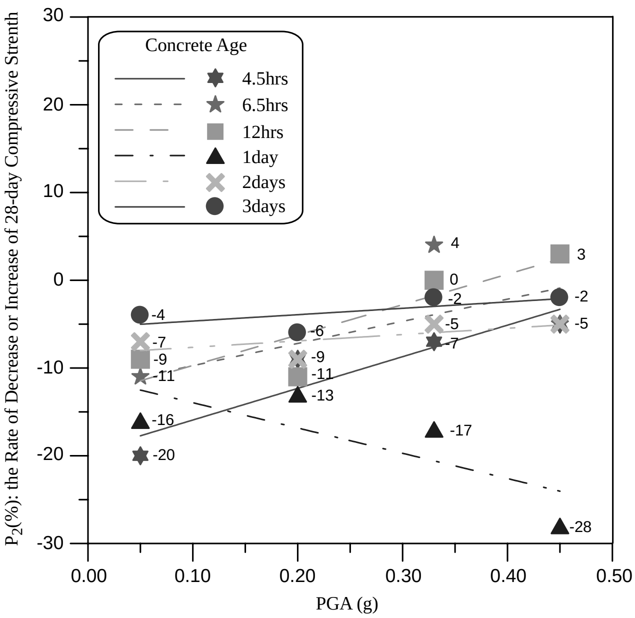


Fig. 8. Comparison of 28-day cmpressive strength of type B and type D (%).

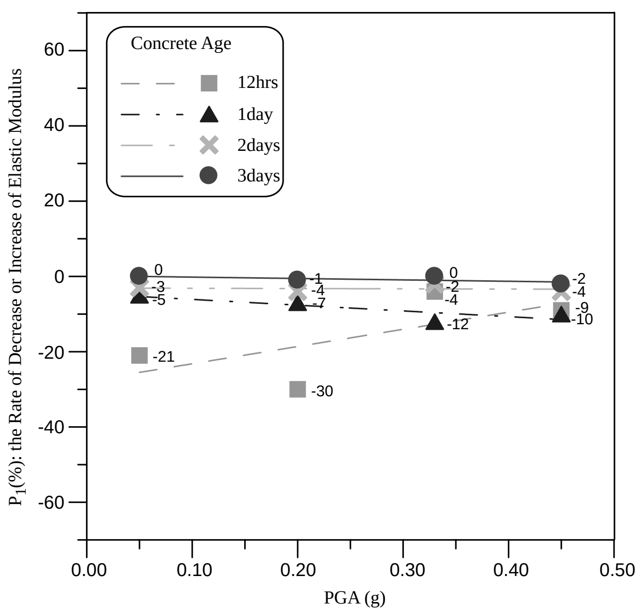


Fig. 9. Comparison of elastic moduli of type A and type C (%).

Table 8. Results of vibration test: Tested after 28-day curing - elastic modulus of concrete (MPa)

Concrete Age	Type D Control	Type B 0.05 g	Type B 0.20 g	Type B 0.33 g	Type B 0.45 g
4.5 hrs	21463 (100%)	20174 (94%)	20388 (95%)	20605 (96%)	20819 (97%)
6.5 hrs	21463 (100%)	19960 (93%)	20175 (94%)	21035 (98%)	21034 (98%)
12 hrs	21463 (100%)	20173 (94%)	20605 (96%)	21036 (98%)	21257 (99%)
1 day	21463 (100%)	20262 (94%)	19951 (93%)	19571 (91%)	19496 (91%)
2 days	21463 (100%)	21058 (98%)	21285 (99%)	20619 (96%)	21306 (99%)
3 days	21463 (100%)	21376 (100%)	21298 (99%)	21121 (98%)	21280 (99%)

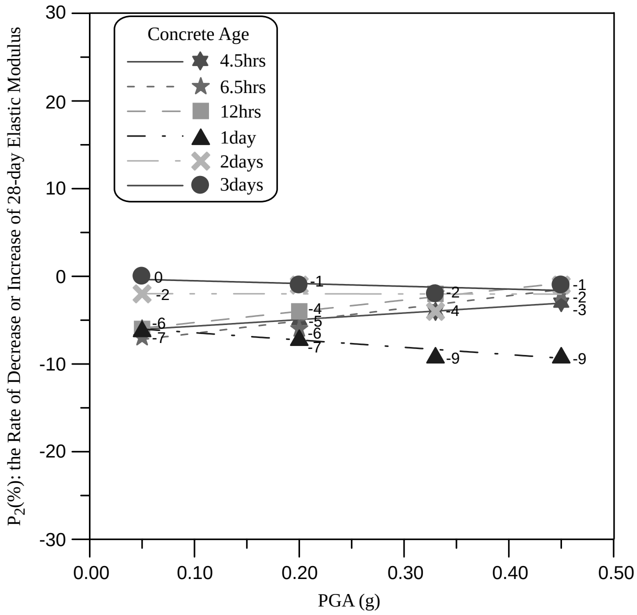


Fig. 10. Comparison of 28-day elastic moduli of type B and type D (%).

the 28-day strength was reduced with the increasing of PGA, but not greatly as PGA increases. The largest strength reduction was by about 9%. The strength plot therefore becomes flatter and straighter.

Tables 5 and 6 indicate that the 28-day strength was partially restored when the concrete age was less than one day. Therefore, if the concrete suffers an earthquake within one day after placement and is then cured properly after shaking, its strength could be restored to approximately 50%.

4. Effect of Earthquake on the Elastic Modulus of Newly Poured Concrete

4.1 Elastic Modulus Comparison between Type A and Type C

Table 7 plots the results of elastic modulus tested immediately after vibration. The table indicates that the elastic modulus of Type A cylinders does not decrease significantly when an earthquake affects concrete aged two or three days. Therefore, if the concrete is older than two days, excitation will not reduce the elastic modulus. The elastic modulus of Type A cylinders made of concrete aged less than one day declined under excitation because the concrete had not formed completely at those ages.

Figure 9 compares the elastic moduli of the vibrated cylinders (Type A) and the control-set cylinders (Type C). Figure 9 shows that the reduction in the elastic modulus of Type A was generally similar to that described in Section 3.1.

4.2 28-day Elastic Modulus Comparison between Type B and Type D

Table 8 plots the results of elastic modulus after 28-day curing. The table indicates that the 28-day elastic modulus does not decrease significantly because an earthquake breaks the concrete bonds and the C-S-H gels fill the cracks after proper curing. Therefore, if newly poured concrete suffers an earthquake and is then cured properly, its 28-day elastic modulus will not be significantly impacted.

Figure 10 compares the 28-day elastic moduli of vibrated cylinders (Type B) and the control-set cylinders (Type D). Figure 10 shows that the reduction in the

Table 9. Results of vibration test: Tested immediately after vibration - ultrasonic pulse velocity of concrete (m/s)

Concrete	Type C	Type A			
Age	Control	0.05 g	0.20 g	0.33 g	0.45 g
6.5 hrs	1889 (100%)	1328 (70%)	1301 (69%)	1573 (83%)	1514 (80%)
12 hrs	2629 (100%)	2335 (89%)	2283 (87%)	2420 (92%)	2356 (90%)
1 day	3225 (100%)	3026 (94%)	2728 (85%)	2751 (85%)	2893 (90%)
2 days	3479 (100%)	3316 (95%)	3340 (96%)	3352 (96%)	3135 (90%)
3 days	3613 (100%)	3642 (101%)	3597 (100%)	3577 (99%)	3553 (98%)

Table 10. Results of vibration test: Tested after 28-day curing - ultrasonic pulse velocity of concrete (m/s)

Concrete	Type D	Type B			
Age	Control	0.05 g	0.20 g	0.33 g	0.45 g
4.5 hrs	3989 (100%)	3776 (95%)	3812 (96%)	3967 (99%)	3949 (99%)
6.5 hrs	3989 (100%)	3824 (96%)	3732 (94%)	3956 (99%)	3932 (99%)
12 hrs	3989 (100%)	3831 (96%)	3896 (98%)	3968 (99%)	3963 (99%)
1 day	3989 (100%)	3816 (96%)	3773 (95%)	3752 (94%)	3735 (94%)
2 days	3989 (100%)	3937 (99%)	3943 (99%)	3815 (96%)	3938 (99%)
3 days	3989 (100%)	3956 (99%)	3922 (98%)	3944 (99%)	3941 (99%)

28-day elastic modulus was similar to that described in Section 3.2.

5. Effect of Earthquake on the Ultrasonic Pulse Velocity of Newly Poured Concrete

5.1 Ultrasonic Pulse Velocity Comparison between Type A and Type C

Table 9 plots the results of the ultrasonic pulse velocity tested immediately after vibration. The table indicates that the ultrasonic pulse velocity of Type A cylinders does not decrease significantly when an earthquake excites concrete aged three days. This finding implies that if the concrete is older than three days, excitation will not reduce the ultrasonic pulse velocity. The ultrasonic pulse velocity for Type A cylinders aged less than two days old decreased under excitation.

Figure 11 compares the ultrasonic pulse velocity comparisons of vibrated cylinders (Type A) and the control-set cylinders (Type C). Figure 11 shows that the reduction in the ultrasonic pulse velocity of Type A was similar to that described in Section 3.1, proving the accuracy of Section 3.1.

5.2 28-day Ultrasonic Pulse Velocity Comparison between Type B and Type D

Table 10 plots the results of ultrasonic pulse velocity after 28-day curing. The 28-day ultrasonic pulse velocity does not decrease significantly because the earthquake breaks the concrete bonds and the C-S-H gel fills the cracks after proper curing. This result is consistent with Refs. 7 and 15, which claimed that the existence of small cracks and pores do not affect the ultrasonic pulse velocity significantly. Therefore, if

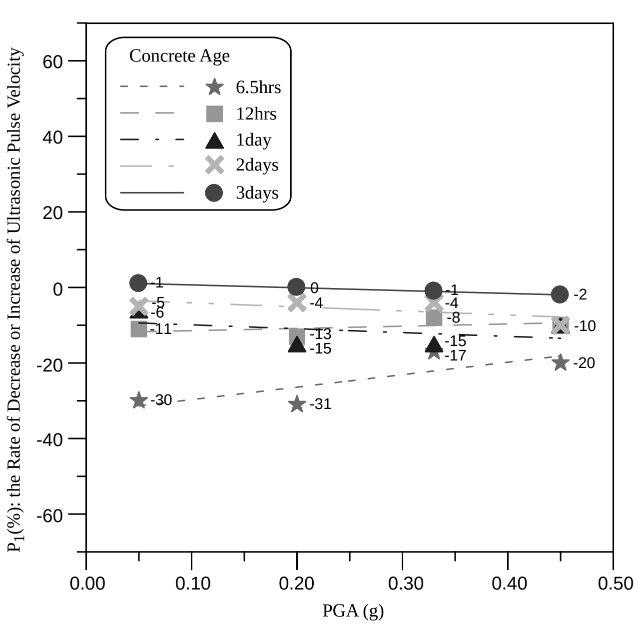


Fig. 11. Comparison of ultrasonic pulse velocities of type A and type C (%).

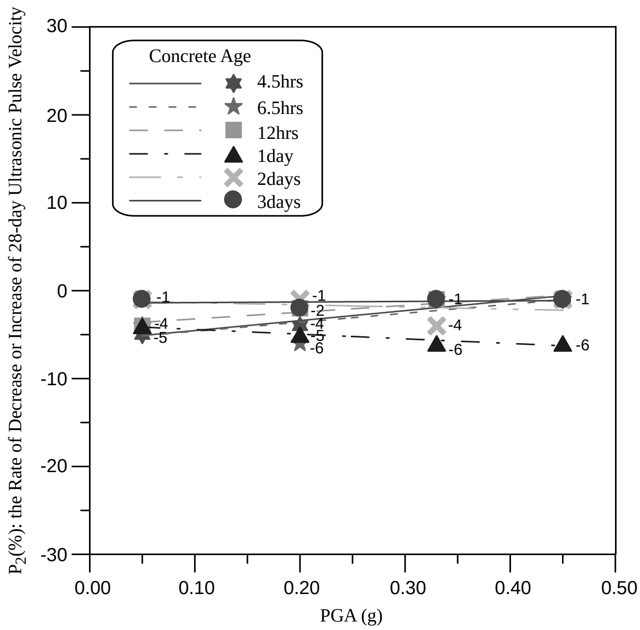


Fig. 12. Comparison of 28-day ultrasonic pulse velocities of type B and type D (%).

newly poured concrete suffers an earthquake and is cured properly, then its 28-day ultrasonic pulse velocity will not be strongly affected.

Figure 12 compares the 28-day ultrasonic pulse velocities of the vibrated cylinders (Type B) and the control-set cylinders (Type D). Figure 12 shows that the reduction in the 28-day ultrasonic pulse velocity was similar to that described in Section 3.2.

CONCLUSION

Important findings of the preceding discussion are as follows:

1. If the concrete is older than three days, earthquake excitation will not significantly reduce its 28-day strength.
2. If the concrete experiences earthquake excitation before it has aged 12 hours, the reduction in 28-day strength decreases as PGA increases. The greatest reduction in strength was by about 20%.
3. If the concrete experiences earthquake excitation when aged one day, the reduction in 28-day strength increases with PGA. The greatest reduction in strength was by about 28%.
4. If the concrete experiences earthquake excitation when aged two days, the 28-day strength is reduced but the strength does not change so much as PGA increases. The greatest reduction in strength was by about 9%.
5. The 28-day concrete strength was partially recovered up to 50% by appropriate curing, if the concrete suffers earthquake excitation within one day after placement.
6. The 28-day elastic modulus and the ultrasonic pulse velocity were not strongly affected by earthquake excitation if the concrete was properly cured.
7. The reduction in the ultrasonic pulse velocity of Type A cylinders was similar to the reduction in strength when the concrete was aged less than 12 hours, proving that a strong earthquake excitation can expel air bubbles out of the cylinders and make the cylinders denser.

ACKNOWLEDGEMENT

The authors would like to thank the National Science Council of the Republic of China for financially supporting this research under Contract No. NSC 89-211-E-005-065.

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