KCI CONRETE JOURNAL
Vol.14 No.1, March 2002, pp.23-29

Impact Echo Test for the Dynamic Characteristics of a Vibration-Mitigated Concrete Structure

Young-Soo Chung[1)*] and Young-Goo Park[2)]

[1)] *Professor of Civil Engineering, Chung-Ang University, Korea*
[2)] *Engineer of Civil Engineering, Samsung Engineering Co., Ltd., Korea*

(Received December 6, 2001; Accepted February15, 2002)

Abstract

Recent construction activities have given rise to civil petitions associated with vibration-induced damages or nuisances. To mitigate unfavorable effects of construction activities, the measures to reduce or isolate from vibration need to be adopted. In this research, a vibration-mitigated concrete, which is one of the active measures for reducing vibration in concrete structures, was investigated. Concrete was mixed with vibration-reducing materials (i.e. latex, rubber power, plastic resin, and polystyrofoam) to reduce vibration and tested to evaluate dynamic material properties and structural characteristics. Normal and high strength concrete specimens with a certain level of damage were also tested for comparisons. In addition, recycling tires and plastic materials were added to produce a vibration-reducing concrete. A total of 32 concrete bars and eight concrete beams were tested to investigate the dynamic material properties and structural characteristics. Wave measurements on concrete bars showed that vibration-mitigated concrete has larger material damping ratio than normal or high strength concrete. Styrofoam turned out to be the most effective vibration-reducing mixture. Flexural vibration tests on eight flexural concrete beams also revealed that material damping ratio of the concrete beams is much smaller than structural damping ratio for all the cases.

***Keywords:** vibration mitigated concrete, compressive strength, dynamic material property, damping ratio, half-power bandwidth method, impact echo test*

1. Introduction

In order for infrastructure construction to keep up with the economic growth in Korea before the IMF bailout, construction activities have often given rise to civil lawsuits associated with vibration-induced damages or nuisances. The objective of this experimental study is to develop a vibration-mitigated concrete by adding a vibration-reducing material, which can be recycled from obsolete materials such as old tires, plastics, styrofoams, ect. Albeit a possible disadvantage of obtaining low compressive strength concrete with these admixtures exists, it is important to develop a useful vibration-mitigation material which can be contributed not only to reduce vibration-induced damages or nuisances at construction sites, but also to recycle obsolete materials as a part of the environmental protection movement. A further investigation was performed on fundamental frequencies and structural damping ratio of 15×10×240 cm RC flexural beams by the half-power bandwidth method. Damage assessment has been also performed on the basis of fundamental frequencies of intact and cracked RC beams for five load cases.

2. Test plan

This study includes the investigation of dynamic material characteristics and dynamic structural characteristics of a vibration-mitigated concrete, which can be effectively used to assess the possible damage of cracked RC structures. This study consists of two tasks: 1) the investigation of dynamic material properties of 32 round and square concrete bars, and 2) the investigation of dynamic structural properties of intact and cracked RC flexural beams. For comparison, normal and high strength concretes were also included in this experiment. Wave measurements have been performed to investigate dynamic material damping ratios, fundamental frequencies, elastic and shear moduli, Poisson's ratio in accordance with KS F2437(similar to

* *Corresponding author*
Tel.: +82-031-670-3339 ; Fax.: +82-031-675-9563
E-mail address: chung47@cau.ac.kr

ASTM C215).

Type I Portland cement was used in manufacturing of vibration-controlled concrete specimens by adding various vibration-mitigation materials. In the concrete, 19 mm coarse aggregates and standard fine aggregates with the fineness modulus of 2.6 and the unit weight of 1.53 tonf/m^3 were mixed together. In addition, high strength concrete specimens were prepared by using the appropriate mix proportion. For the measurements of dynamic material characteristics based on KS, ASTM and JIS codes, test specimens were made as four different types of concrete bars with the dimensions of 10×20 cm and 10×40 cm for cylinders, and 10×10×20 cm and 10×10×40 cm for rectangular bars as shown in Table 1. Dynamic structural properties were also investigated for flexural RC beams with the dimensions of 15×10×240 cm.

Table 1 Types of test specimens

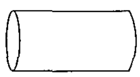
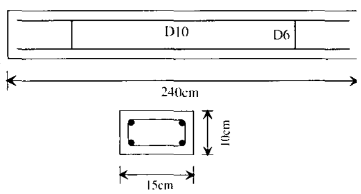
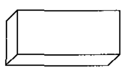
Material dynamic properties		Structural dynamic properties	
Resonance test (KSF 2437)		Free vibration test	
A-Type	ø10×20cm Cylinder	Length	240cm
B-Type	ø10×40cm Cylinder	Width	15cm
C-Type	10×10×20cm Prism	Height	10cm
D-Type	10×10×40cm Prism	Longitudinal : D10	Stirrup : D6
(Cylinder) 			
(Prism) 			

Table 2 shows the mix proportions and compressive strength of vibration-mitigated concrete specimens where polystyrofoam, plastic resin, rubble powder, and latex of 1%, 1%, 2%, and 4% of the cement weight were added, respectively.

3. Test wave measurements

3.1 Dynamic material properties

Dynamic material properties for cylindrical and prismatic concrete specimens were evaluated in accordance with KS F2437 (similar to ASTM C215 and JIS A1127-1976). Wave velocities, dynamic elastic and shear moduli were evaluated using the fundamental frequencies of longitudinal and torsional waves on RC bars with free-free boundary conditions. Then material damping ratios and Poisson's ratios were computed from the measured wave velocities. Material damping ratios were calculated by the polynomial curve fitting method. Fig. 1 shows the schematic diagrams for the generation of longitudinal and torsional waves on test specimens by the impact hammer. Longitudinal waves can be generated by impacting on the surface of one end of the specimen. And, torsional waves can be generated by applying a torque to the specimen by an attached aluminum device shown in Fig. 2.

3.2 Structural dynamic properties

As shown in Fig. 3, both ends of flexural RC beams were bounded to generate a free flexural vibration with minimal constraints. An accelerometer was placed on the bottom surface at the midpoint of flexural RC beams where the

Table 2 Mix proportions and compressive strength of specimens

Specimens		Designation	Comp. strength (MPa)	Slump (cm)	Air (%)	Unit weight (kg/m^3)							
						Coarse agg.	Fine. agg.	Cement	Water	V-M※	Superplasticizer	A.E.	Silica fume
Normal strength concrete		NR	28.3	8	3.4	1,144	717	350	168	-	-	1.12	-
Vibration-mitigated concrete	Poly styrofoam	ST	24.8	8.7	5.0	943.3	742.8	368.58	175	3.72 (1%)	-	1.12	-
	Plastic resin	PR	25.6	9.5	2.6	943.3	742.8	364.86	175	7.41 (2%)	-	1.12	-
	Rubber powder	RP	26.3	8.5	3.0	943.3	742.8	368.58	175	3.72 (1%)	-	1.12	-
	Latex	LT	27.0	8	4.8	943.3	742.8	372.30	161	14.00 (4%)	-	1.12	-
High strength concrete		H35	39.0	3.5	2.5	1,052	766	389	175	-	-	-	-
		H45	48.9	7.5	2.0	1,065.9	741.3	462.8	166.6	-	3.70	-	-
		H70	48.7	-	-	1,037	668	552	160	-	13.8	-	82.6

※ V-M : Vibration-mitigated materials

impact was applied to induce flexural vibrations. A rubber tip was attached at the impact hammer to minimize the high frequency components. The FFT analyzer acquires the time histories of acceleration, performs a Fourier transform in a real time, and determines the transfer function. The magnitude spectrum of the transfer function was used to compute the damping ratio for the resonant-mode by the half-power bandwidth method. The use of transfer function in applying the half-power bandwidth is essential in that the transfer function can eliminate the effects of the impact source.

Furthermore, five incremental loads of 250 , 500 , 750 , 1,000 , and 1,250 kgf were applied to produce cracks at the midpoint of flexural RC beams. Flexural vibration tests were performed on the intact and cracked RC beams to find the resonant-mode frequency and the damping ratio corresponding to the resonant-mode. Five incremental loads were selected to have an equal distribution between the crack-initiated load and the failure load for a normal flexural RC beam. Visible damage of cracked RC beams was assessed by deflection and crack width, which were measured by a LVDT and a clip gage, respectively.

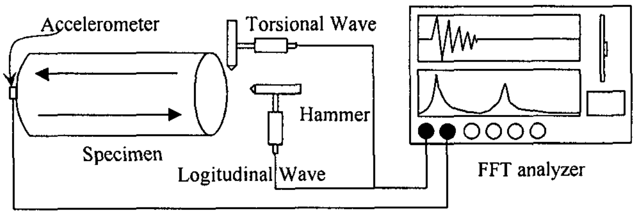


Fig. 1 Wave resonance test

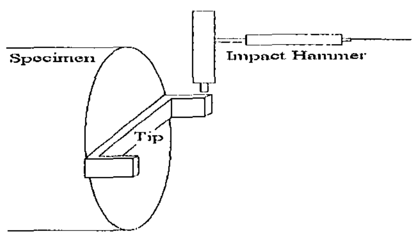


Fig. 2 Experimental configuration of torsional wave measurements

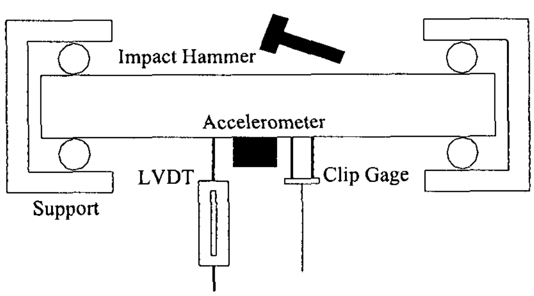


Fig. 3 Schematic diagram of flexural vibration test

3.3 Structural damage

It is well understood that the resonant-mode frequency of a flexural RC beam is dependent on its boundary conditions, material properties, sectional shapes, and so on. Stiffness of a simply-supported cracked RC beam is also one of very important factors for determining the resonant-mode frequency.

In the flexural RC beam test, the structural damage can be determined from the resonant-mode frequency which should be variable with the crack levels. Damage index D_I, an indicator of structural safety, is generally expressed as Equation (1). Equation (1) is a function of the resonant-mode frequency of undamaged and damaged structures.

$$D_I = 1 - \frac{\omega_D^2}{\omega_N^2} \tag{1}$$

where, ω_N is the resonant-mode frequency of the intact structure and ω_N is the resonant-mode frequency of the damaged structure. In Equation (1), the damage index D_I becomes 1.0 at the failure state of the structure.

4. Test results

4.1 Impact echo test for concrete cylinders

4.1.1 Longitudinal wave

The velocity of waves propagating through a concrete specimen is dependent on the water content of a concrete specimen. Therefore, all specimens were dried in the laboratory for at least three days. An impact hammer was applied at the free end of RC beams. Longitudinal wave, which was initiated at one end of a RC beam, was reflected at the other end of a RC beam. The resonant-mode frequency of the longitudinal wave was used to calculate elastic modulus and wave velocity. As shown in Fig. 4, the velocity of a longitudinal wave linearly increases with the compressive strength of concrete specimens. Fig. 5 shows the first fundamental frequency and the magnitude spectrum of the transfer function for the longitudinal waves of test specimens in four different mix proportions. The resonant-mode frequency increases with the compressive strength of test specimens.

4.1.2 Torsional wave

As shown in Fig. 2, a torsional wave was generated using the aluminum bar attached at one end of a test specimen. Two accelerometers were attached at the other end of a test specimen. When an impact hammer was applied at the aluminum bar as shown in Fig. 2, a torsional wave was propagated in a circular motion. Simultaneously, a flexural wave was also propagated in vertical motion. Torsional and flexural waves were generated at the same time. However, the torsional wave alone can be extracted by removing the component of a flexural wave. A series of two adjacent peaks at equal space of Fig. 6 shows the superposed spectrum of the torsional wave and the flexural wave. Fig. 6 and Fig. 7 show the spectrum curves of the waves obtained by one accelerometer and two accelerometers, respectively. Fig. 8 shows the spectrum curve of only the torsional wave which was computed by the half of the difference between magnitudes of Fig. 6 and Fig. 7. Similar to Fig. 5, Fig. 9 shows the resonant-mode frequency and the magnitude spectrum of the transfer function for the torsional waves of test specimens. The resonant-mode frequency increases with the increment of the compressive strength of test specimens. The torsional wave velocity also increases with the compressive strength as shown in Fig. 10.

4.1.3 Dynamic material properties

Elastic modulus, shear modulus and Poisson's ratio can be obtained by the resonant-mode frequencies of longitudinal and torsional waves. Elastic modulus and shear modulus increase with the compressive strength of concrete as shown in Fig. 11. However, Poisson's ratio is not proportional to the magnitude of compressive strength of concrete as tabulated in Table 3.

Concrete material properties can be nondestructively obtained by the wave measurements, but they are more or less affected by water content, air temperature, humidity, and others. Thus, it is necessary to establish the relationship between wave velocity and concrete strength through testing a large number of concrete specimens to obtain more reliable results.

Fig. 12 shows the relationship between the damping ratio and compressive strength of concrete. As shown in Fig. 13 for the bar specimens, a larger damping ratio was obtained by adding vibration-reducing materials such as polystyrofoam, plastic resins, rubber powder, and latex compared to those with normal and high strength. Similar results were obtained for other test specimens as well. The increase of damping ratio due to the addition of the vibration-reducing mixtures decrease the concrete density and compressive strength of concrete.

4.2 Flexural vibration test for RC beams

Eight flexural RC beams were made as shown in Table 1

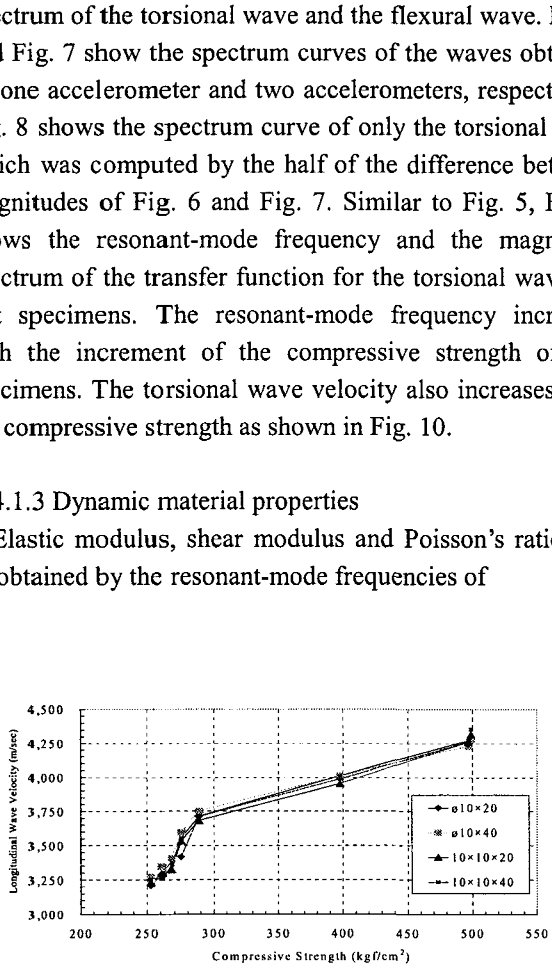
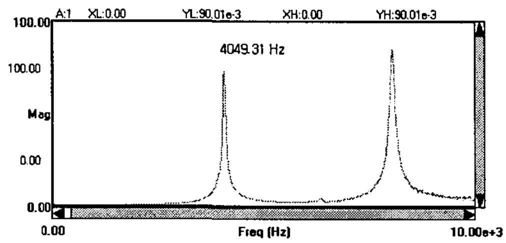


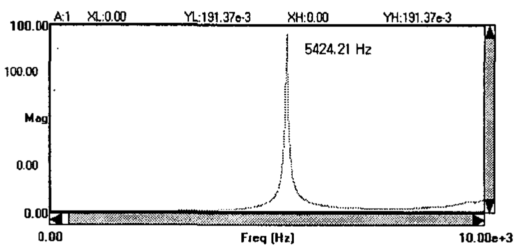
Fig. 4 Longitudinal wave velocity

Table 3 Poisson's ratio of concrete specimen

Specimen designation	A-Type	B-Type	C-Type	D-Type
NR	0.33	0.26	0.22	0.24
ST	0.25	0.29	0.22	0.24
PR	0.29	0.28	0.23	0.25
RP	0.29	0.27	0.23	0.26
LT	0.24	0.26	0.24	0.26
H35	0.21	0.26	0.22	0.26
H45	0.24	0.29	0.24	0.26
H70	0.23	0.25	0.22	0.24



(a) Amplitude spectrum of transfer function for the specimen ST-D type



(b) Amplitude spectrum of transfer function for the specimen H45-D type

Fig. 5 Amplitude spectrum of transfer function for the longitudinal-wave resonance test

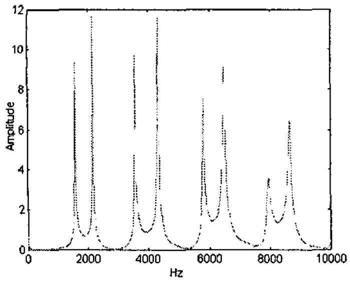


Fig. 6 Amplitude spectrum of torsional waves

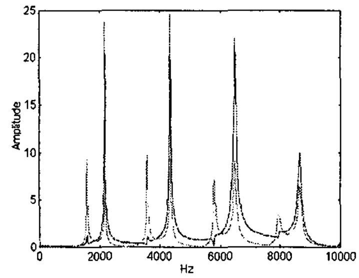


Fig. 7 Amplitude spectrum of torsoinal and flexural waves

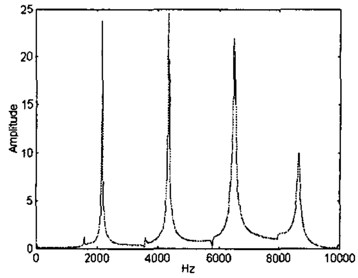
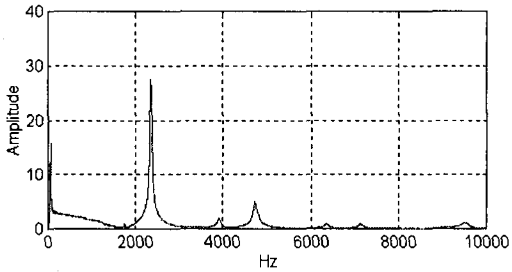
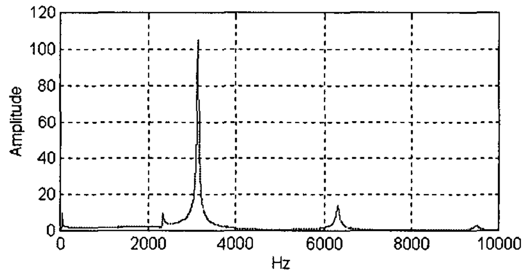


Fig. 8 Amplitude spectrum of torsional wave only



(a) Amplitude spectrum of transfer function for specimen ST-D type



(b) Amplitude spectrum of transfer function for specimen H45-D type

Fig. 9 Amplitude spectrum from trosional-wave resonance test

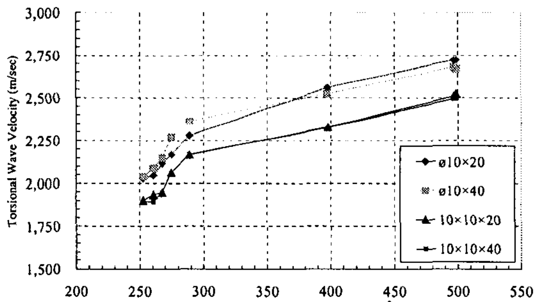


Fig. 10 Relationship of torsional-wave velocity and compressive strength

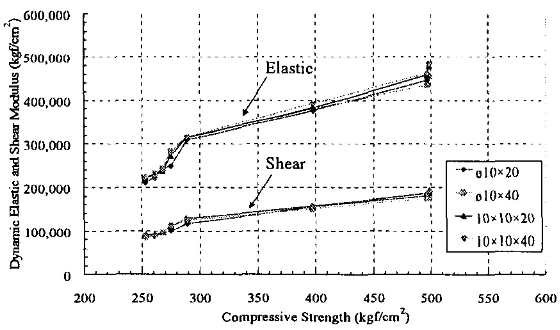


Fig. 11 Relationship of elastic and shear modulus and concrete strength

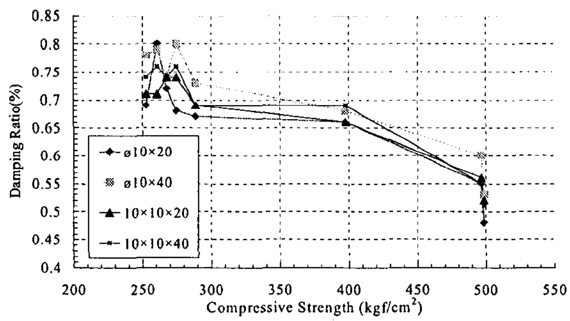


Fig. 12 Relationship of damping ratio and compressive strength

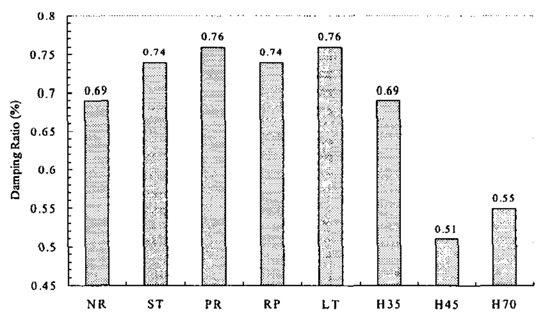


Fig. 13 Material damping ratio for A-type bar

Table 4 Resonant-mode frequencies and structural damping ratios for five increamental loads

Specimens		NR	ST	PR	RP	LT	H35	H45	H70
Mat. damping ratio (%) / Load(newton)		0.69	0.74	0.76	0.74	0.76	0.69	0.51	0.55
1st Resonance frequency(Hz) / Damping (%)	0	40.49 / 3.05	31.63 / 2.15	37.51 / 1.62	40.89 / 1.39	43.42 / 1.85	42.67 / 1.54	48.66 / 1.08	47.78 / 1.17
	2,452	38.61 / 3.15	31.41 / 2.28	37.04 / 1.69	37.52 / 1.60	41.38 / 1.93	40.69 / 1.56	44.16 / 1.78	47.15 / 1.32
	4,904	38.61 / 3.66	30.88 / 2.43	36.53 / 1.74	36.32 / 1.95	40.26 / 1.99	39.05 / 1.57	42.57 / 2.15	42.48 / 1.71
	7,355	38.61 / 3.79	29.83 / 2.89	36.17 / 1.89	35.35 / 1.95	39.45 / 2.03	38.13 / 1.71	41.01 / 2.36	42.01 / 1.69
	9,807	38.09 / 3.79	28.85 / 2.90	35.81 / 1.95	32.54 / 2.03	39.02 / 2.25	37.80 / 1.79	40.63 / 2.37	41.49 / 1.74
	12,259	37.17 / 4.23	23.50 / 3.54	32.36 / 2.22	27.11 / 2.05	38.20 / 2.29	35.44 / 1.92	40.21 / 4.47	41.19 / 1.85

and 2. And, their structural damping ratios were obtained on the damage level of each of five incremental loads.

4.2.1 Structural damping ratio

As shown in Fig. 14, crack widths are steadily increased until the load of 500 kgf(4.9 KN) but rapidly increased until the load reaches 750 kgf(7.43 KN).

The vibration-mitigated concrete shows a steeper increase in the crack width than normal and high strength concrete. This can be explained by the fact that the bonding strength of vibration-mitigated concretes is smaller than the strengths of normal and high strength concrete due to higher void ratio of vibration-mitigated concrete. Similar results were obtained in flexural deflection measurements in Fig. 15. Table 4 and Fig. 16 show that damping ratios of RC beams increase with the increasing damage level, and resonant-mode frequencies decrease with the increasing damage level.

In general, the resonant-mode frequency of RC beam is known to be dependent on boundary conditions, material properties, sectional shapes, and so on. In the case of this simple RC beam test, it is observed that the resonant- mode frequency is strongly dependent on the sectional modulus, which is an important factor for structural stiffness. Damping ratio may increase due to the possible friction at the interface of concrete crack. Similarly, a larger material

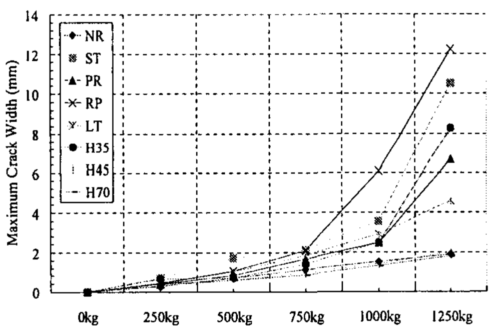


Fig. 14 Maximum crack width at middle point of beam specimen

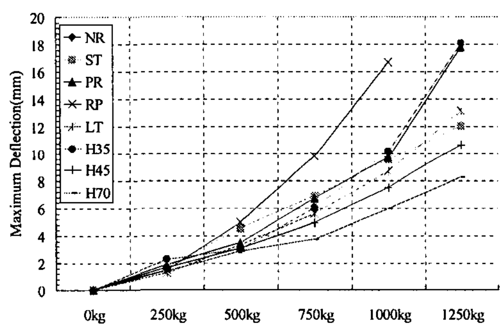


Fig. 15 Maximum deflection at middle point of beam specimen

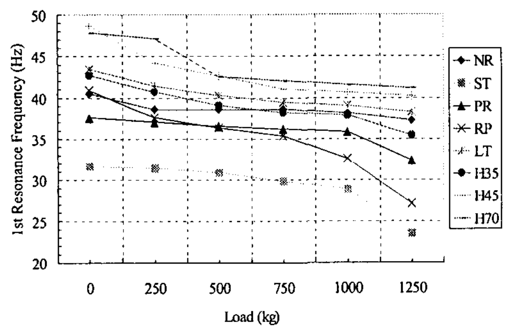


Fig. 16 Resonant-mode frequencies for 5 incremental loads

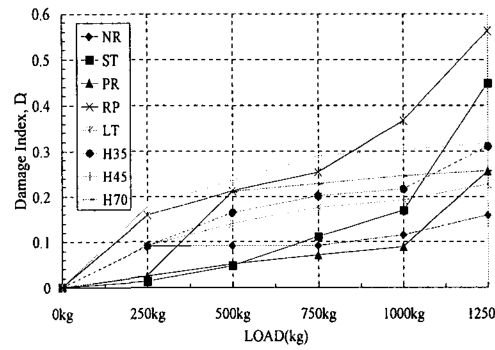


Fig. 17 Damage indices (D_I) for 5 incremental loads

damping ratio was obtained for vibration-mitigated concrete as shown in Fig. 13. However, it was observed from flexural vibration test on eight concrete beams that material damping ratio was smaller than structural damping ratio in concrete structure.

4.2.2 Structural damage assessment

In the previous researches, it is widely noted that structural damage can be assessed by the damage index of Equation (1). Damage indices are increased by the damage level, which can be generally computed by fundamental frequencies of cracked RC beams. Fig. 17 indicates that damage indices increase with increasing loads and the increasing trend is steeper for the vibration-mitigated concrete than for normal and high strength concrete. Specially, the increasing trend of damage index for the vibration-mitigated concrete has an abrupt change around the cracking load of 750kgf(7.4 KN). As expected, the damage level of RC beams can be obtained from fundamental frequencies which were detected by the wave measurements.

These test results show that wave measurements could be widely used for the integrity assessment of RC structures. In addition, Fig. 18 reveals that damping ratios are generally increased with damage index.

5. Conclusions

For the development of vibration-mitigated concrete to reduce vibration-induced damages or nuisances at various construction sites, the wave measurements have been carried out for 32 concrete bars and eight flexural RC beams. Dynamic material and structural properties of vibration-mitigated concretes were investigated as well as those for normal and high strength concrete. The results show following conclusions :

1) Material damping ratio of concrete is increased by adding more vibration-mitigation agent. Larger damping ratio for vibration-mitigated concretes is obtained than the damping ratios of normal and high strength concrete. This can be explained by more and larger voids generated by adding vibration-mitigation materials into concrete.
2) Structural damping ratio is increased by the possible friction at the interface of concrete cracks for cracked concretes. However, we could not get larger material damping ratio for vibration-mitigated concretes than normal and high strength concretes. Damping ratios and the first fundamental frequencies of RC flexural beams were gradually increased and decreased, respectively, by expanding the damage level as per five incremental loads. Thus, it could confirm the possible relationship between structural damping ratio and damage level.
3) Pertinent wave measurements can be widely used for the integrity assessment of RC structures in a nondestructive way.

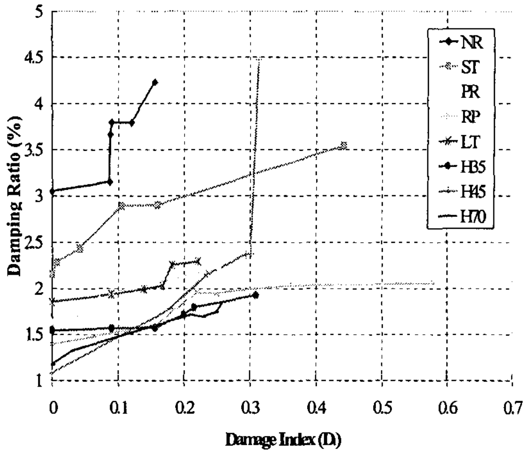


Fig. 18 Relationship of damping ratio and damage index

ACKNOWLEDGEMENTS

This study was partially supported by the Research Equipment Procurement Program of Chung-Ang University in 1998 and by the KOSEF under Grant NO. 981-1202-005-1. The supports are gratefully acknowledged.

REFERENCES

1. Baek, Y.S., Sim, J.S., and Chung, Y.S., "*Research of Prediction and Protection Technology for Vibration Pollution*," Specific Research Assignment 2nd Middle Term Report, Korea Science and Engineering Foundation, 1996.
2. Chung, Y.S., Choi, W.S., and Lee, D.H., "Experimental Study on Dynamic Characteristics of Vibration-Controlled Concrete Beam," *Journal of the Korea Concrete Institute*, Vol. 9, No. 9, 1997.
3. Korea Industrial Standard, *Resonance Vibration Testing for Dynamic Modulus, Shear Modulus and Poisson's Ratio of Concrete*, Korea Industry Promotion Government Office, 1990.
4. Chung, Y.S., Park, Y.G., Joh, S.H., and Lee, K.M., "Experimental Study on Dynamic Characteristics of a Vibration-Controlled Concrete Beam," *Proc. of SMiRT-15*, Vol. 6, 1999, pp.131-138.