

# Vibration Control Using Large Pneumatic Isolation Systems with Damped Concrete Inertia Masses

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## ABSTRACT

The paper discusses an improved method for the vibration isolation of large areas in vibration-sensitive facilities, such as those used for nanotechnology R&D. Although the use of a large inertial mass supported on airsprings is not new, there are size-related drawbacks associated with this approach, most notably those associated with resonance amplification within the inertial mass itself. This resonance amplification is governed largely by the material damping properties of the concrete. The paper presents the results of a study intended to address means by which the concrete damping may be increased, thus reducing the amplification caused by the inertial mass. Methods are shown by which modal damping may be introduced into the concrete masses.

Keywords: vibration isolation, damped concrete

## 1. INTRODUCTION

There is a growing need for low-vibration environments for nanotechnology facilities. In many cases, a quiet site is enough, but in other cases, vibration isolation may be required. In the past, commercially available optical benches supported on legs containing airsprings achieved this isolation; however, this is not an all-purpose solution. Some applications require a very long optical path, and multiple optical tables might lead to beam misalignment. Other applications may require the working surface in the lab to be at floor level, necessitating a pit for the isolation unit. Some payloads require an extraordinarily large isolated mass to improve the performance of additional stages of isolation or to lower the center of gravity of the structure.

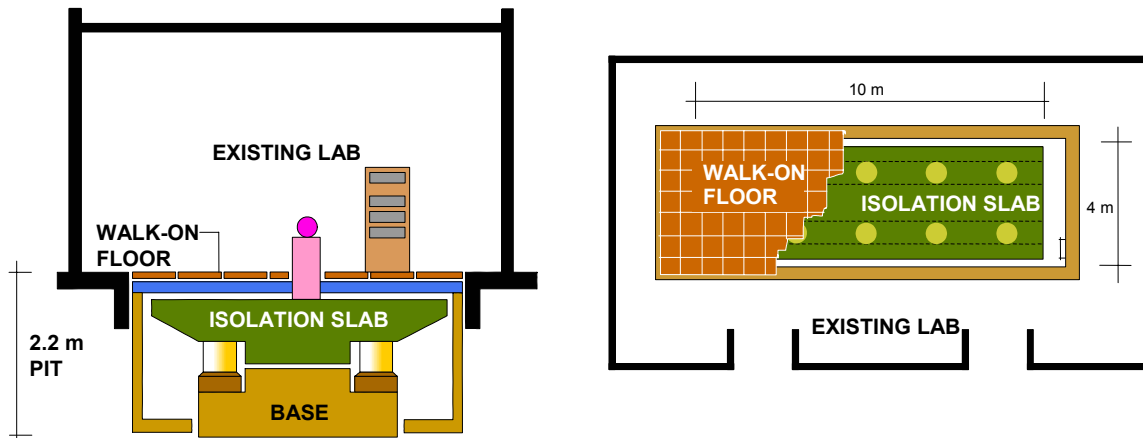
Several R&D lab designs have employed large inertia masses supported on huge airsprings. In many cases where arbitrary size or shape is required for the inertia mass, concrete is the material of choice. However, the material damping of concrete is low enough that isolation is degraded at the internal resonances of the mass. Increasing concrete's damping would improve their performance. This paper reviews several design concepts for these systems and test data from a 4m x 10m prototype system built at the National Institute of Standards and Technology (NIST), in Gaithersburg, MD [Amick, *et al.* (1998)].

The NIST prototype study indicated that an increase in the system damping properties would enhance the feasibility of such a large-scale system. This leads one to consider increased concrete damping as a logical approach. The paper reviews the important issues raised by the NIST prototype study and presents results of a study examining means by which the material damping of concrete may be increased as part of the design process, particularly through use of polymer admixtures. This increase in damping will improve a system's isolation performance at the internal resonance frequencies.

## 2. INERTIAL SLAB ISOLATION SYSTEMS

The NIST prototype, shown conceptually in Figure 1 is representative of an inertial slab isolation system. This particular configuration is becoming known in nanotechnology circles as a "NIST-

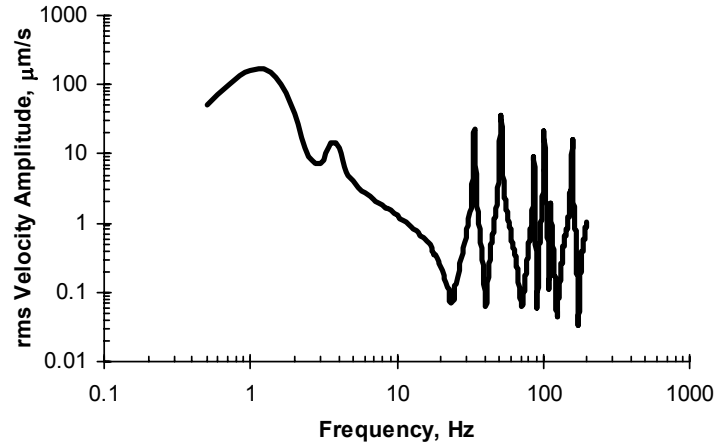
A1” slab, denoting the vibration criterion it was intended to meet for NIST’s Advanced Measurement Laboratory. (A more generic term is “keel-slab”, and the springs need not be directly beneath the slab as shown.) A 4m x 10m prototype was designed and built in one of the existing labs at NIST, and is now used to support development of a force measurement system capable of measuring nanonewtons, one of the metrology requirements of nanotechnology [Amick, *et al.* (1998)].



**Figure 1. Conceptual section and plan views of NIST-A1 isolation system. [from Amick, et al. (1998)]**

The vibration isolation characteristics of these systems depend upon two sets of dynamic properties: (1) the large mass acting as a rigid body supported on the airsprings, with six degrees of freedom at relatively low frequencies (generally designed to be less than 5 Hz); and (2) the resonance frequencies associated with deformations of the large mass itself, associated with its bending and torsional vibratory modes (generally greater than 35 Hz). These will be referred to as “rigid body” and “internal” resonances, respectively.

When struck with a hammer, the NIST prototype keel-slab produces a velocity spectrum similar to that shown in Figure 2, the exact shape of which depends upon excitation, directional component, and measurement locations. The broad hump at low frequencies represents the highly damped response of the airspring suspension system. The sharper peaks at frequencies between 34 and 120 Hz represent the first five internal bending and torsional resonance frequencies of the large concrete mass. These peaks are much sharper than those of the airsprings, indicating much lower modal damping of the concrete.



**Figure 2. Velocity spectrum resulting from hammerblow, measured at center of prototype NIST-A1 slab [after Amick, *et al.* (1998)]**

When designing a large pneumatic isolation system for these applications, a designer's concern is generally limited to frequencies below 200 Hz. The room-sized isolation system shown in Figure 1 consists of a 4m x 10m x 600mm thick concrete slab with an additional keel that is 300mm thick. The mass is supported in a pit by ten pneumatic vibration isolation springs. The system has airspring resonance frequencies of 1.4 Hz and 3 Hz, and provides attenuation at frequencies above 5 Hz.

Figure 3 shows the SRSS combination<sup>1</sup> (of all three directional components) of vibrations measured in the pit, on the base below the isolation system (open symbols), and at two locations on the inertial mass (closed symbols). At frequencies above 5 Hz, the gap between the base curve and those measured on the inertial mass is a measure of the attenuation provided by the isolation system. At frequencies above 10 Hz, the attenuation is more than an order of magnitude, but peaks in the inertial mass curves cause the attenuation to diminish considerably at frequencies near 30, 50 and 100 Hz. These three peaks correspond to the three modeshapes given in Figure 4.

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<sup>1</sup>  $SRSS(f)^2 = X(f)^2 + Y(f)^2 + Z(f)^2$ , where X, Y and Z are the amplitude spectra in three orthogonal directions.

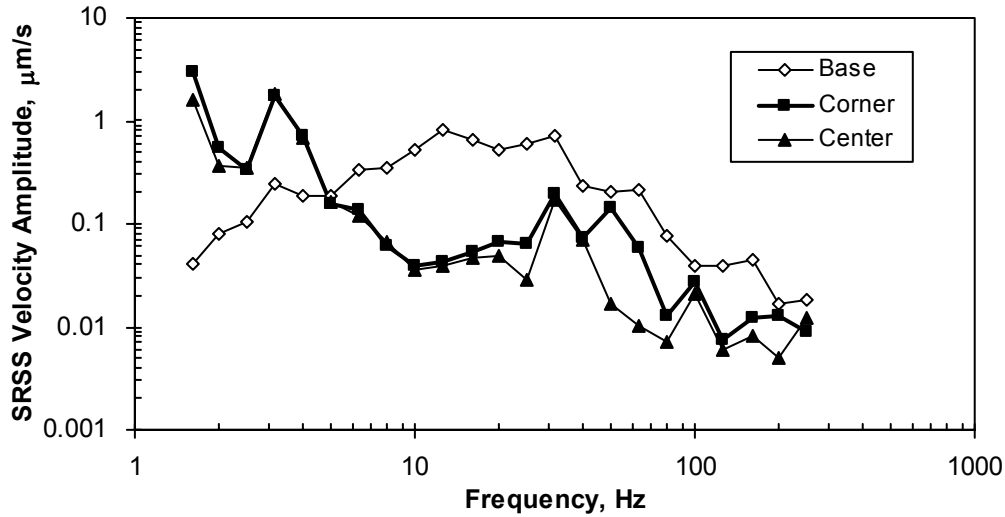


Figure 3. SRSS representation of vibrations below prototype NIST slab (open symbols) and at two locations atop it (closed symbols) [after Amick, *et al.* (1998)]

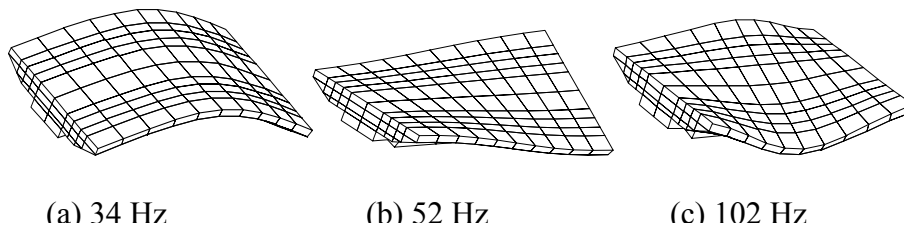
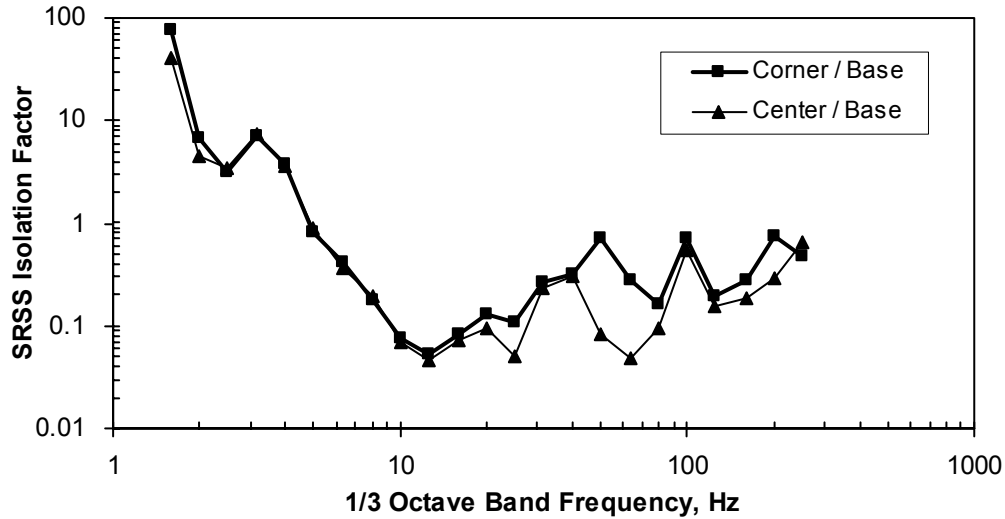


Figure 4. Computed modeshapes associated with resonances at: (a) 34 Hz, (b) 52 Hz, and (c) 102 Hz. [from Amick, *et al.* (1998)]

Figure 5 is a representation of the vibration isolation capability of this slab at a particular bandwidth associated with NIST’s vibration requirements.<sup>2</sup> The isolation becomes quite good above 8 Hz, but degrades at frequencies above 30 Hz due to the presence of amplification associated with the internal resonances of the concrete mass. At some frequencies, the effect of the isolation is completely cancelled.

<sup>2</sup>  $SRSS\ Isolation(f) = SRSS_{top}(f) / SRSS_{bottom}(f)$



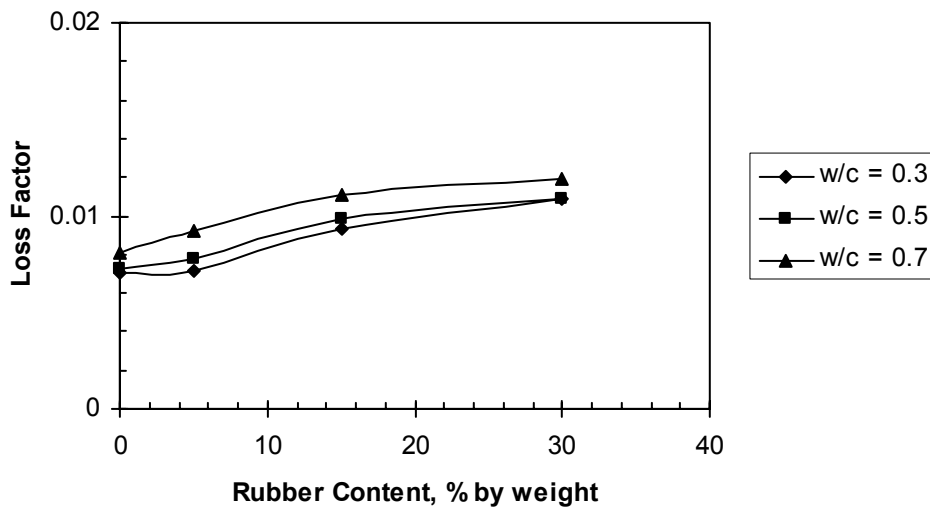
**Figure 5. SRSS representation of isolation system performance at the center and corner of the slab. [from Amick, et al. (1998)]**

In the design of NIST’s new laboratory, the degradation problem was avoided by limiting the geometry of the isolation mass. None of the dozen or so slabs had dimensions exceeding 4m, which forced the fundamental bending resonance to lie well above 100 Hz—above the researchers’ frequency range of concern. Circumstances may arise, however, in which a larger system—similar to the prototype—might be required. Significant benefit would be derived from a means by which damping could be increased, perhaps by modifying the damping of the concrete itself.

### 3. CONCRETE DAMPING – EXISTING TECHNOLOGY

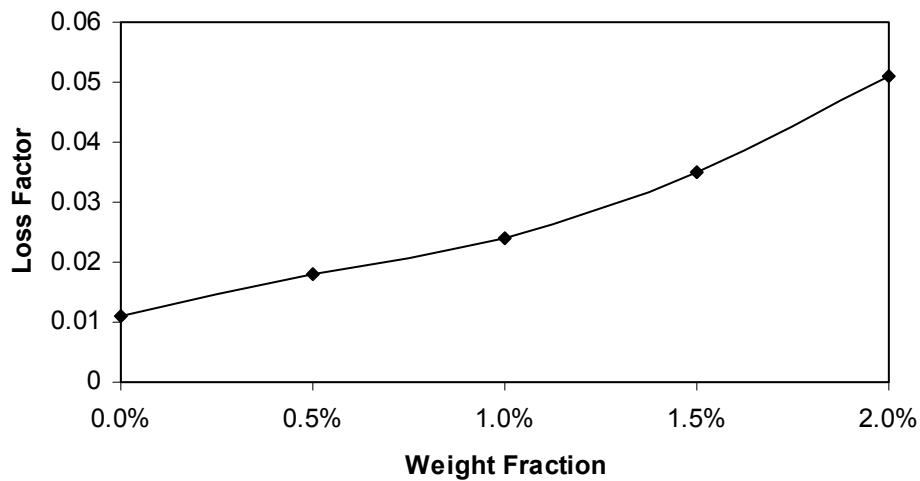
The literature provides several approaches to increasing the damping of concrete, though few of them have seen practical application. One of the most effective of these to date have involved inclusion of damping material as a replacement for some portion of the aggregate.

Rubber chips introduce soft inclusions into the concrete. Kerševičius and Skripkiūnas (2002) examined the effects of rubberized aggregate on damping, using sand-sized particles. They showed that damping increased slightly with water/cement ratio, and further increased linearly with the weight fraction of rubber chips, up to a maximum loss factor of  $\eta = 0.012$  at a weight fraction of 0.3. This behavior is illustrated in Figure 6. The increase is observable, but not dramatic.



**Figure 6. Effect of the weight fraction of rubber chips on loss factor [after Kerševičius and Skripkiūnas (2002)]**

Mayama (1987) examined a mortar in which a portion of the aggregate was replaced with asphalt-coated iron particles. He reported that the modified mortar had a higher damping constant (as illustrated in Figure 7) and high rigidity. The damping increased as the asphalt coating was increased, but the resonance frequency (and thus the dynamic elastic modulus) decreased. The damping increase was dramatic, achieving a five-fold increase though use of only a 2% weight fraction of the treated aggregate. The drawback lies with the cost and quality control associated with fabrication of the modified aggregate.



**Figure 7. The effect of weight fraction of asphalt-coated aggregate on loss factor [after Mayama (1987)]**

Two research teams have examined the effect of polymers on a wide range of engineering properties, including damping, but their work has apparently led to no implementation [Fu, Li, and Chung (1998), Wong, Fang and Pan (2003)]. One polymer product has seen some use as a

damping admixture, though it is not particularly well documented in the literature [Moiseev (1991), Soon, *et al.* (1997)].

#### 4. CONCRETE DAMPING – NEW TECHNOLOGY

A study carried out at the University of California, Berkeley, has been aimed at finding means by which the material damping of plain concrete might be increased. Various studies over the last sixty years have examined the extent to which damping is controlled by standard mix parameters such as water/cement ratio, aggregate type, etc. However, the modifications provided by variation of these parameters is too limited to be of benefit for the application of interest.

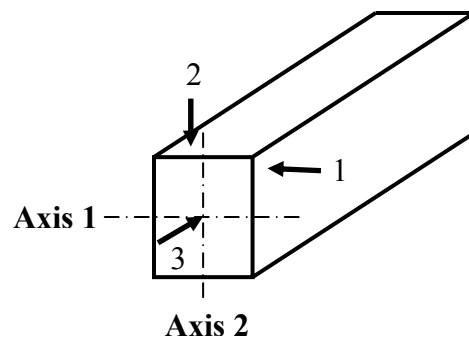
In the present study, polymer admixtures have been found to be quite effective. Their other engineering properties are well documented in the literature, but there had been very little information regarding their efficacy for damping. Three polymer formulations were examined: styrene-butadiene rubber (SBR), ethyl-vinyl acetate (EVA), and a hybrid of SBR and a vegetable gum (SBR/g).

There are several formulations of SBR in which the ratio of styrene to butadiene (S/B) is varied. The particular formulation to be discussed here has a 60/40 formulation, and will be denoted SBR-A. It is a liquid suspension, approximately half of which is water. EVA is a dry powder, and popular as an additive to commercially prepackaged tile grout. SBR/g is also a liquid suspension. All three have glass transition temperatures slightly below room temperature.

The experiment involved a quantity of concrete prisms 89mm x 114mm x 406mm (3.5 x 4.5 x 16 in.), cast in steel molds. Three specimens were cast of each mix design to allow for the statistical variation typical of concrete.

Accelerometers as sensors were attached using threaded studs to connect to conventional machine-screw nuts that had been affixed using cyanoacrylate gel adhesive. The approximate sensor locations are shown in Figure 8. The hammerblows were applied as close as practical to the sensors. (Locations 1 and 2 were deliberately placed away from the neutral axis, so as to excite and measure the torsional mode.) The specimens were supported on two taut wires, which provided vertical and axial resonance frequencies well below the specimens' fundamental resonance frequencies.

The fundamental bending resonance frequencies of this beam, with unmodified concrete, were about 1840 Hz and 2200 Hz. The longitudinal fundamental frequency was about 4700 Hz. The torsional resonance frequency was about 2500 Hz.



**Figure 8. Schematic diagram of excitation and measurement locations for prismatic specimens.**

Figure 9 shows a typical set of data (for SBR/g). It illustrates the effect of polymer concentration (represented by the polymer/cement weight ratio, P/C) on loss factor. The heavy line represents the overall average of all deformation types; the dashed lines show the range associated with one standard deviation (SD). Figure 10 shows the effect of varying P/C for the three polymers: SBR-A, SBR/g, and EVA.

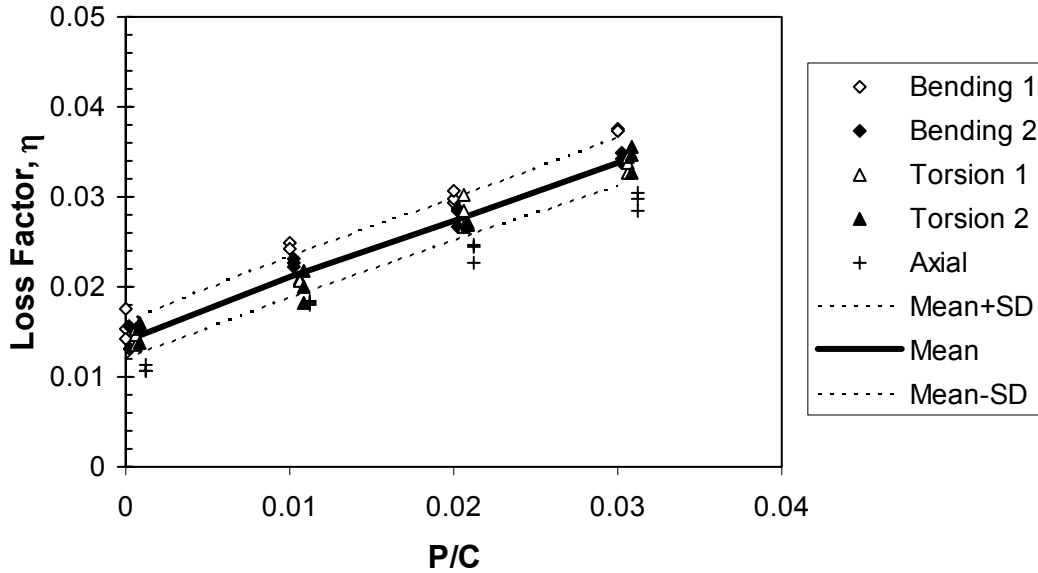


Figure 9. Damping with SBR/g as a function of P/C, in terms of raw data and statistical summary,  $1450 \leq f \leq 4200$  Hz, room temperature, 28 days.

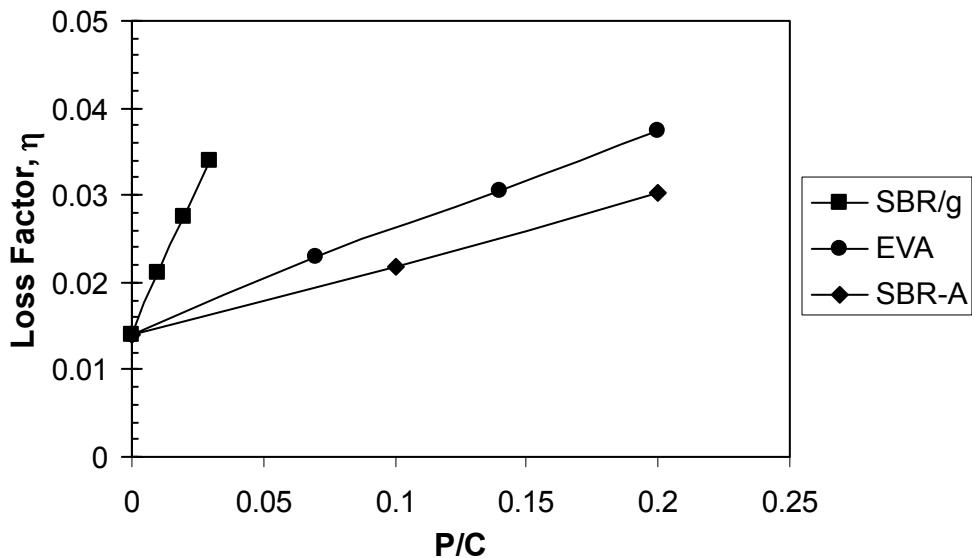


Figure 10. Effect of polymer concentration, P/C, on loss factor at room temperature and  $1450 \leq f \leq 4200$  Hz, room temperature, age between 4 and 5 weeks.



Figure 10 demonstrates that the loss factor of polymer-modified concrete depends linearly upon P/C. Thus, the damping in these three polymers may be represented by a simple relationship shown in Equation (1). Each polymer can be represented by a single quantity,  $\alpha$ , the slope in the equation, which represents the polymer's effectiveness at damping enhancement. Table 1 summarizes the effectiveness coefficients  $\alpha$  of the three polymer admixtures, and gives the standard deviation with respect to the linear fit.

$$\eta = \eta_0 + \alpha \frac{P}{C} \quad (1)$$

**Table 1. Summary of damping performance of three polymer admixtures.**

Polymer	Damping Effectiveness, $\alpha$	Standard Deviation, $\sigma_\eta$
SBR/g	0.658	0.0023
EVA	0.116	0.0030
SBR-A	0.081	0.0030

The data in Figure 10 suggest that a tripling of loss factor is a reasonable expectation. However, it must be borne in mind that the concrete's workability and strength are also affected by the polymer concentration. The effects vary from one polymer to the next. For example, SBR/g and EVA lead to a loss of strength that is a function of P/C, and which might limit P/C in some applications. The use of SBR-A actually leads to an increase in concrete strength, owing to the water-reducing nature of unmodified SBR latex. However, P/C = 0.2 is the commonly accepted upper bound for SBR-A concentration, though it appears one may consider higher concentrations. The selection of a particular polymer and P/C is a matter for engineering judgment

## 5. CONCLUSIONS

Several options for increasing concrete's material damping are available to the designers of a concrete keel-slab isolation system. Most options involve some degree of strength reduction, and perhaps reduction in wear resistance. Resilient aggregate—in the form of rubber particles—offers some promise, but does not appear as effective as polymer admixtures. Resiliently coated aggregate appears quite effective, though fabrication cost and quality control would likely pose a problem. Polymer admixtures appear to be the most straightforward option, though the limits on polymer concentration are a matter of engineering judgment.

### Acknowledgements

The authors acknowledge the contribution of test materials by Dow Chemical Corporation and Dow Reichhold Specialty Latex LLC, and the financial support of Durasol Drug and Chemical Corporation, as well as the long-term commitment to the concept of large-scale isolation systems provided by NIST and HDR Architecture. Brian Scace of NIST provided valuable observations regarding critical details of the original NIST prototype study.

### References

- Amick, H., B. Sennwald, N. C. Pardue, C. Teague, and B. Scace, "Analytical/Experimental Study of Vibration of a Room-Sized Airspring-Supported Slab," *Noise Control Engrng. J.*, March/April 1998, Vol. 46, no. 2, pp. 39-47 (March/April, 1998).

- Fu, X., Li, X. & Chung, D.D.L. (1998), "Improving the vibration damping capacity of cement," *Journal of Materials Science*, Vol. 33, No. 14, pp. 3601-3605, 1998.
- Kerševičius, V., and Skripkiūnas, G. (2002). "Physical Properties and Durability of Concrete with Elastic Additive from Rubber Waste," *Materials Science (Medžiagotyra; ISSN 1392-1320)*. Vol. 8, No. 3. 2002, pp. 293-298
- Mayama, M. (1987), "Vibrating properties of coated ferrite concrete," *Proceedings, Japan Society of Civil Engineers (Tokyo)*, No. 384, July 1987, pp. 93-101 [in Japanese].
- Moiseev, N. (1991), "Effect of a viscoelastic admixture on transient vibration in a concrete and steel floor," *SPIE Proceedings 1619, Vibration Control in Microelectronics, Optics and Metrology*, San Jose, CA, 4-6 November 1991, pp. 192-202.
- Soon, S., Koh, S., Paramasivam, P., Koh, C. G., and Loo, Y. H. (1997). "Comparative Studies on Concrete Test Specimens Containing ConcreDamp Admixtures," SHAMA Technologies (S) Pte Ltd, Singapore, 28.