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Modification of concrete damping properties for vibration control in technology facilities

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ABSTRACT

Several settings arise in the design of vibration control for sophisticated spaces in which it would be desirable to significantly increase the material damping of concrete, primarily to reduce resonant response. The paper presents an overview of a recent study addressing the various means by which concrete damping can be increased. A variety of methodologies are discussed, and the most efficacious approaches are examined in some detail. The easiest approach involves the introduction of polymer admixtures into the concrete when it is mixed. However, the resulting dynamic properties become dependent upon both temperature and frequency, and these must be considered when selecting the appropriate polymers to use. Experimental results are summarized, and some of the appropriate applications (as well as the limitations) of polymer usage are presented.

Keywords: Damping, concrete damping, damping modification, nanotechnology, on-grade slabs, vibration isolation

1. INTRODUCTION

Concrete is the structural material of choice for most advanced technology facilities. Plain concrete, with or without reinforcement, has relatively low damping. A number of settings arise in the design of vibration control for sophisticated spaces—especially those for nanotechnology—in which it would be desirable to significantly increase that damping.

One such setting involves the large inertial keel-slab masses associated with large-scale pneumatic isolation systems, called keel-slab systems or NIST-A1 systems. It has been shown that their performance may be degraded by amplification due to internal resonances of the inertial mass.[1] One means to reduce this problem would be to increase the damping in the keel -slab material, which is usually concrete.[2]

An overview will be presented of a recent study[3] addressing the various means by which concrete damping can be increased. A variety of methodologies are discussed, but the most efficacious approaches are examined in some detail. The easiest approach involves the introduction of polymer admixtures into the concrete when it is mixed. However, the resulting dynamic properties become dependent upon both temperature and frequency, and these must be considered when selecting the appropriate polymers to use for a given application.

2. WHAT IS DAMPING?

Damping is a process by which vibratory energy is dissipated, generally into heat.[*] It is the reason a ringing bell eventually stops ringing. Present in all real materials and structures, it can be quantified as a material property using one of several damping coefficients, which may be constants or functions of other variables, such as temperature, volume fraction of component materials, presence of cracks, and frequency. Damping can be manifested in several forms, such as:

- Decay of free vibrations, such as those of the ringing bell;[†]

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[*] The word "damping" is often misused to characterize the attenuation provided by springs or other vibration isolation hardware.
[†] Damping controls the rate at which the loudness of a bell diminishes over time after being struck. Increasing the damping leads to a higher rate of decay.

- The retardive force provided by a system being driven at resonance, thus imposing a finite bound to the response amplitude;
- Limiting the amplification a structure experiences at its resonance frequencies;
- Attenuation of propagating vibrations; and
- Energy absorption in structural systems subjected to shock or random excitation such as explosions or earthquakes.

In a structure, damping may be thought of as being due to several factors. First, the structural material itself, whether it is steel, concrete or timber, possesses some degree of damping inherent to the material. These three materials are listed approximately in order of increasing material damping. Second, damping will arise at connections, usually due to rubbing of the interfaces within the connection. Third, there is attenuation due to distance as waves propagate through a structure. Fourth, there is radiation damping, in which energy is radiated into the soil or air. All four of these factors enter into any structural dynamics setting, but this paper will concentrate upon the first aspect, material damping, and the discussion will be limited to the material damping of concrete and how it might be modified.

3. REASONS FOR MODIFYING CONCRETE DAMPING

There is a growing need for low-vibration environments for advanced technology facilities, particularly those for nanotechnology and beyond. Concrete is the structural material of choice for many critical structural components in advanced technology facilities. Most vibration-critical areas are placed in slab-on-grade locations, often with slabs much thicker than is usually found (e.g., 200 mm to 600 mm). Cleanroom spaces requiring a basement are often placed on deep waffle slab systems, on the order of 700 mm to 1200 mm deep, depending upon the column spacing. General laboratories in the upper levels of these buildings—often intended to meet the needs of microscopes—are designed in either joisted slab or composite steel/concrete framing, though the depths are greater and spans much shorter than found in conventional structures.

When designing buildings for technology, vibration control is being viewed as one more variable under the control of the design team. Vibration performance is not being left to chance, and as building performance becomes more important, aggressive measures become more justifiable. Engineers have been aware of the damping properties unique to concrete since the 1930s, but quantification did not become critical until the nuclear era and the need to predict the dynamic performance of in blast-resistant structures and nuclear power plants. However, concrete damping was assumed constant, except for the effect of the progressive damage which would occur as a structure vibrated in response to a blast or earthquake.[3] The ability to modify the damping of concrete became available in the 1970s, and the technology eventually came to be used in laboratory floors.[4] There was some resistance within the structural community because of the limited amount of documentation available regarding either damping performance or the alteration of other engineering properties (such as strength or elastic modulus).

3.1 Concrete inertia bases

Concrete is finding a relatively new application in spaces with the most demanding vibration requirements. These needs may be met by a combination of a quiet site and pneumatic isolation using airsprings. In the past, this isolation was achieved by commercially available optical benches supported on legs containing airsprings; however, this is not an all-purpose solution. Some applications require a very long optical path, for which multiple optical tables might lead to beam misalignment. Other applications may require the working surface to be at floor level, necessitating a pit. Some require extraordinarily large isolated mass to improve performance of additional stages of isolation or to lower the center of gravity.

Several R&D lab designs have employed large inertia masses supported on huge airsprings, such as the system shown conceptually in Figure 1. This 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”.) 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.[1]

The vibration isolation characteristics of these systems depend upon two sets of dynamic properties: (1) the large mass acting essentially 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, in its bending and torsional vibratory modes (generally greater than 35 Hz). These will be referred to as "rigid body" and "internal" resonances, respectively.

If a system causes input vibrations to increase in amplitude, it is said to *amplify*; if they decrease, the change may be represented by an amplification of less than unity, the ratio of output to input. A simple dynamic system supporting a payload tends to amplify vibrations at frequencies near its resonance frequency and attenuate them at higher frequencies.[5] Because real systems generally have multiple resonances, the mathematics become more complex, but generally there will be amplification at each resonance frequency. When the internal resonances fall within the frequency range of concern for the payload (say, 5 to 100 Hz), the designer must consider both rigid body and internal resonances. Generally, amplification is observed at the rigid body frequencies, with increasing attenuation at frequencies lying between the rigid body resonances and the lowest internal resonance, and then a series of frequencies occur at which the isolation performance is degraded.

Figure 2 shows a set of idealized amplification curves for a hypothetical keel-slab isolation system. This system exhibits a rigid body resonance of 2.5 Hz in the direction of interest. Attenuation occurs when the curve is below 1.0, i.e., frequencies above about 3.5 Hz. The lowest point on the curve—where the isolation system is most effective—before it turns upward has a value of about 0.03 at a frequency of 22.5 Hz. This hypothetical system exhibits three resonance frequencies: 34, 52 and 75 Hz, similar to those of the NIST prototype. The damping associated with the rigid body modes (controlled within the airsprings, and beyond the scope of the present study) was held constant, but three different values of viscous damping were assumed for the concrete.

Although changing the internal damping of the slab would have no effect on the rigid body resonances associated with the airspring, the internal resonances would be significantly affected. If the concrete damping were to be increased from a nominal 0.5% to 2.5%, the amplification factor of the 34 Hz mode is reduced from about 1.0 (no attenuation) to about 0.2. A further increase to 10% damping decreases the amplification factor to 0.05. The capability to augment damping in keel-slabs would allow the use of room-sized isolation systems without the significant degradation within the critical frequency range observed in the NIST prototype.

3.2 Concrete on-grade slabs

In addition to keel-slab isolation systems, the capability to increase concrete's damping as a part of the design process might lead to better attenuation of structureborne vibrations in advanced technology buildings.

Designers of buildings housing vibration-sensitive processes or equipment, such as those used for semiconductor manufacturing, wish to attenuate vibrations generated by mechanical and electrical equipment at frequencies generally between 10 Hz and 120 Hz. Vibration isolation can be provided for fans, pumps, transformers and other energetic equipment installed at the time of initial construction. However, in many facilities problems arise after occupancy, when owner-installed equipment is put in place without vibration isolation.[6] Measures are taken during design to address this issue, but it is desirable to maximize the extent to which the building itself can attenuate propagating vibrations.[7]

Some situations in advanced technology facilities can lead to concerns regarding vibrations propagating though a slab-on-grade. An example is the effect of dropping a hard, heavy object—such as a hammer or gas bottle—on the floor. An impulse can be generated with energy content over a wide frequency range. At lower frequencies (*i.e.*, lower than a few hundred hertz), much of the vibratory energy is transported in the soil beneath the slab.[8] However, at higher frequencies, the majority of the energy may be transported in the concrete slab. Research instrumentation sensitive to these frequencies might benefit from increased concrete damping.

Woods[9] determined that roughly two-thirds of the vibration energy generated by a dynamic point load on a surface is propagated via Rayleigh waves. A quarter is carried via shear waves, and the remainder by compression waves. The path of a particle undergoing Rayleigh wave motion is an ellipse involving both vertical and horizontal components. Woods also showed that the amplitude varies with depth. Most of the energy is contained within one wavelength.

The generally accepted Rayleigh wave propagation model is given as

$$v_b = v_a \left(\frac{r_a}{r_b} \right)^{\gamma} e^{\alpha (r_a - r_b)} \qquad (1)$$

which defines the vibration amplitude v_b at point "*b*" on the surface at a distance r_b from the source if we know the amplitude v_a at point "*a*" on the surface at a distance r_a from the source. The term γ is associated with geometric spreading, and for Rayleigh wave propagation is assumed to have a value of 0.5. The term α is associated with material damping or loss, and is essentially a material property.

Traditionally, α is often assumed constant for a particular material. However, Barkan[10] and Dowding[11] have observed that a soil's material damping provides a specific amount of attenuation per wavelength. This implies a constant loss factor, and is consistent with observations for many other propagation media.

Using relationships defined by Richart, Hall and Woods[8], the coefficient α may be defined as

$$\alpha = \frac{\eta \pi f}{c} \qquad (2)$$

where η is loss factor, c is the wave velocity, λ is the wavelength, and f is the frequency.

As noted above, Woods[9] demonstrated that the amplitude of Rayleigh waves varies with depth, and is greatest near the surface. Most of the energy is contained within one wavelength of depth, which will vary with frequency. When a Rayleigh wave propagates through a slab-on-grade, the setting is more complex than with a homogeneous halfspace. The energy will be proportioned between the soil and the slab according to the fraction of the wavelength that is occupied by each. The slab will carry a significant portion of the energy only at relatively small wavelengths.

Wavelength λ is given by

$$\lambda = \frac{c}{f} \qquad (3)$$

and is shown in Figure 3 for an assumed wave velocity of c = 150 m/s. Note that at frequencies less than 100 Hz, the wavelength is greater than 1500 mm (4.8 ft), and that at 15 Hz it is 10 m (32.3 ft). In conventional construction, the slabs-on-grade are generally between 100 mm and 150 mm. Thus, for the given medium, the slab-on-grade will carry a large fraction of the energy only at frequencies above 1000 to 1500 Hz. In sensitive areas of advanced technology facilities, they may be between 200 mm and 300 mm, corresponding to frequencies between 500 and 750 Hz. This may not be useful in all cases, but may be of value where attenuation of vibrations at high frequencies is important.

There are three probable components to the damping of Rayleigh waves propagating through soil supporting a slab-on-grade. Damping is contributed by: (1) the soil itself; (2) the slab; and (3) the interface between the two. Very little is known about the third, but the other two are comparatively well understood when considered individually.

Damping in soil is highly dependent upon the cyclic strain amplitude. At low strain values, such as those associated with ambient vibrations (or low amplitude, induced vibrations), it is on the order of ζ = 1% (or η = 0.02) for granular soils (sands and gravels) and cohesive soils of a wide range of plasticity. As strain amplitude increases, so does damping, particularly with granular soils and cohesive soils with low plasticity. Under seismic loading, the damping can be on the order of ζ = 20% (or η = 0.4).[11] In general, however, we are concerned only with low strain when considering ambient vibrations, thus only the minimum values of soil damping.

Damping in concrete is also strain dependent, but the variation is much smaller and the variation is generally associated with varying degrees of maximum strain. Under normal circumstances (ambient amplitudes), concrete damping is on the order of ζ = 0.5% to 1% (or η = 0.01 to 0.02).[3]

Thus, without any special measures, the damping of the slab and soil are so similar that they might as well be a single medium (with respect to damping). However, if we can make a substantial change in the concrete damping, the damping of the *system* might be changed. This effect will be frequency dependent.

In order for concrete damping to play a significant role in system damping, a significant portion of the vibratory energy must be contained within the depth of the slab. This is an approximate concept, but it might be stated that if the slab depth is about the same as a wavelength, then most of the energy will be contained in the slab, and thus the slab's damping will play a dominant role.

Figure 3 shows how wavelength varies with frequency. The wavelength fraction t / λ is defined in Equation (4), where t is slab thickness. With appropriate conversion of units, it is plotted in Figure 4. With a 150mm (6 in.) slab, the slab thickness is equivalent to one or more wavelengths only at frequencies above 1000 Hz. The wavelength fraction is 1.0 or greater for a 300mm (12 in.) or 450mm (18 in.) slab only at frequencies above 500 Hz and 250 Hz, respectively. This shows that modification of slab damping will be more effective at lower frequencies with a thick slab than with a thin one.

$$\frac{t}{\lambda} = \frac{f}{c} \tag{4}$$

An illustration may be of assistance. Consider an assessment of the merits of altered damping versus a slab joint at a distance of 6.2m (20 ft) from the dropped hammer or other impulsive source. The initial assumption may be of a halfspace consisting of one material, namely concrete. The propagation mechanism implied by Equation (1) may be combined with the frequency dependent definition of α given in Equation (2).

Figure 5 shows for several frequencies how increasing the damping affects the attenuation at 6.2 m (20 ft), ignoring the geometric attenuation. At frequencies of 100 Hz or less, the attenuation is rather small (5 dB or less) at 3% damping, representing a fairly large increase in concrete damping. At 800 Hz, on the other hand, an addition 20 decibels is gained with 2% damping and almost 40 decibels with 3% damping. Figure 6 swaps the variables shown, such that we see the effect of frequency for several selected values of concrete damping.

Figures 5 and 6 assumed that the halfspace was entirely concrete. This allowed an assumption that the entire depth of the Rayleigh wavefront contributed to the damping. However, this is generally not the case; usually there is a slab of fixed thickness. Refer again to Figure 4, where a value of 1.0 or greater for the wavelength fraction only occurs above certain frequencies that are functions of the thickness. It is only when the wavelength fraction is approximately equal to or greater than 1.0 that the damping of the slab will have much effect. Thus, with a 150mm (6 in.) thick slab, it is unlikely there would be any of the improvement suggested by Figures 5 or 6. With a 300mm (12 in.) slab, the full effect of the concrete damping would be present only at frequencies above 400 to 500 Hz.

4. CONCRETE DAMPING MODIFICATION

Amick[3] examined a number of concrete mix parameters involved in mix design with regard to their impact on damping. Some of these had been examined by others in the past; others were examined for the first time. The most efficacious treatments were those introducing elastomeric polymers into the concrete matrix in some form. These polymers could take the form of discrete particles replacing some fraction of the aggregate, liquid latex that eventually solidified during the curing process, or constrained-layer systems embedded in the concrete in some manner.

Viscoelastic polymers can exhibit significant damping properties. In fact, they are popular in a number of settings as a means by which damping can be introduced to a system. However, they offer a particular challenge for a designer, as their damping and elastic properties are functions of several variables, notably frequency and temperature.[‡]

Most materials familiar to the civil engineer exhibit elastic modulus and damping properties that are relatively constant with temperature and/or frequency. This is not the case with many polymers. Many polymers[§] behave as shown in Figure 7, after Lazan,[13] which is presented in terms of the components of a complex shear modulus and loss factor.

The variations in modulus and damping that occur with of increasing frequency are similar to those that occur with decreasing temperature. Over a large range of temperatures or frequencies, one may define three regions. At high frequencies or low temperature, the polymer is said to be *glassy*, and the modulus is at its greatest. At low frequencies or high temperature, the polymer is characterized as *rubbery*, and the modulus is at its least. The range between these two regions is simply called the *transition region*.

Damping may also be considered in the same three zones. It tends to be low in the glassy and rubbery zones, and greatest in the transition region. The damping peak occurs at or near the temperature known as the *glass transition temperature*, T_g. Polymer designers can control T_g by means of varying the amounts of each polymer component. A given polymer, such as styrene-butadiene-rubber (SBR) may be available with several different glass transition temperatures.[14]

The contribution of a polymer additive to concrete damping is a linear function of polymer concentration. Figure 8 shows how loss factor varies with polymer concentration for three concrete additives, all of which have T^g near room temperature. There is a significant variation in the effectiveness of each polymer, indicated by the slope of the data.

Recall from Figure 7 that the damping in a polymer is a function of temperature and frequency. It happens that the damping of polymer-modified concrete takes on the same characteristic. Figure 9 shows how loss factor varies with frequency and polymer concentration. At high and low frequencies, the effect of the additive is less than at the frequency of the maximum damping.

Figure 10 shows how varying the ambient temperature affects the frequency distribution of damping (lower set of curves) and elastic modulus (upper set of curves) when the concentration is held constant. For the three polymers indicated in Figure 8, the maximum damping at room temperature occurs in the neighborhood of 150 Hz. Note also that the frequency axis in Figures 9 and 10 is logarithmic; it covers about eight orders of magnitude. Damping may thus be assumed constant over a frequency range of 50 to 300 Hz. It is only slightly less than the maximum at the frequencies associated with the resonances of structural components such as floors. [Specific (and extensive) data are available in Ref 3.]

5. CONCLUSION

Concrete has been the structural material of choice in facilities for technology. It continues to be so in nanotechnology facilities. As demands for vibration control continue to grow, it may be possible to add some degree of conservatism by increasing the damping in the concrete. Because of the additional cost, this must be approached judiciously. The designer must take into account the limitations imposed by temperature, frequency, and geometry.

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[‡] Polymers, like many other materials, have a "large-strain" regime in which the modulus varies with strain. The present discussion is limited to the "small-strain" regime with a modulus that is constant with strain. However, for some polymers, the "small-strain" regime can extend to very large strains compared to conventional structural materials.

[§] Polymers which conform to the single-peak behavior shown in Figure 7 would be characterized as "rheologically simple" materials. Many others have multiple peaks and slope changes. Many co-polymers, including the ones used as concrete additives, will have multiple peaks, but only one peak within the frequency and temperature ranges in which they are commonly used.

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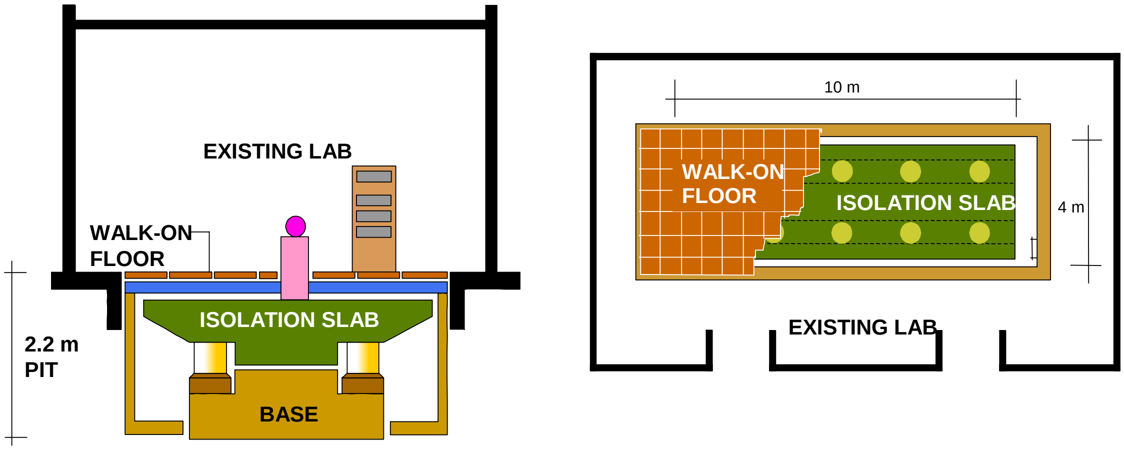

Figure 1. Conceptual section and plan views of NIST-A1 isolation system.[1]

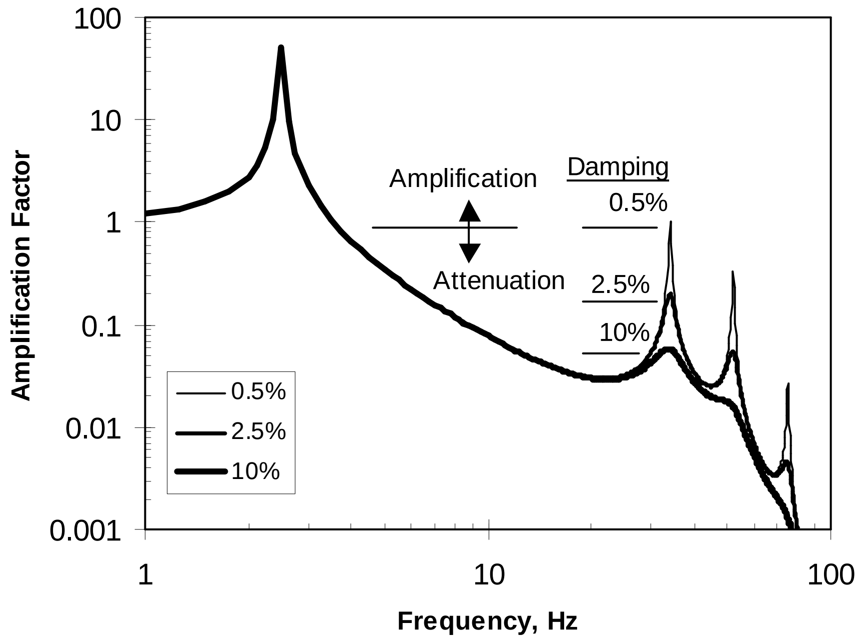

Figure 2. Amplification factor (below airsprings to top of slab) for a hypothetical keel-slab showing the effect of varying concrete damping.[3]

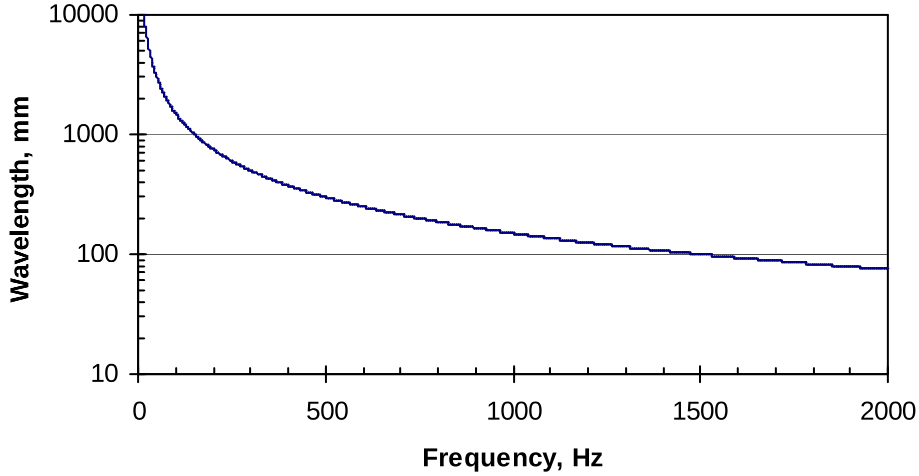

Figure 3. Rayleigh wavelength in a medium with a wave velocity of *c* = 150 m/s.

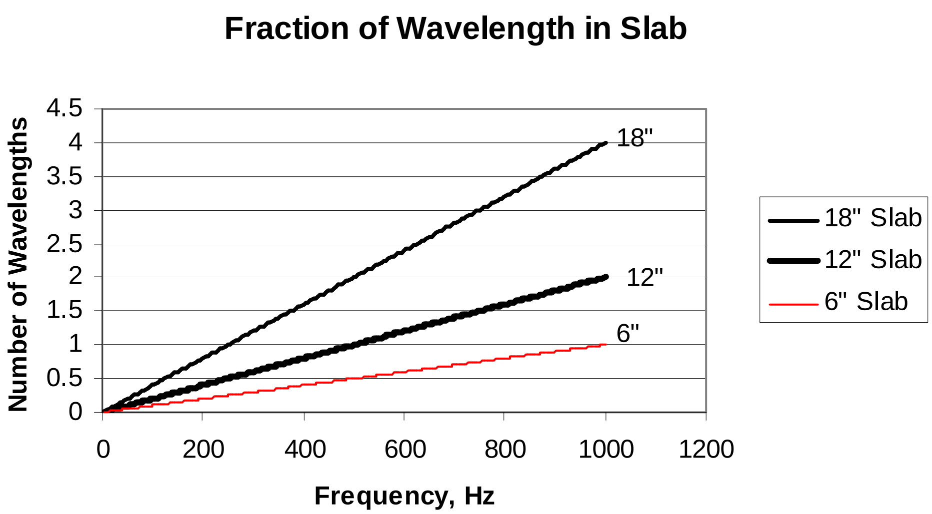

Figure 4. Fraction of wavelength contained in slab, for several slab thicknesses.

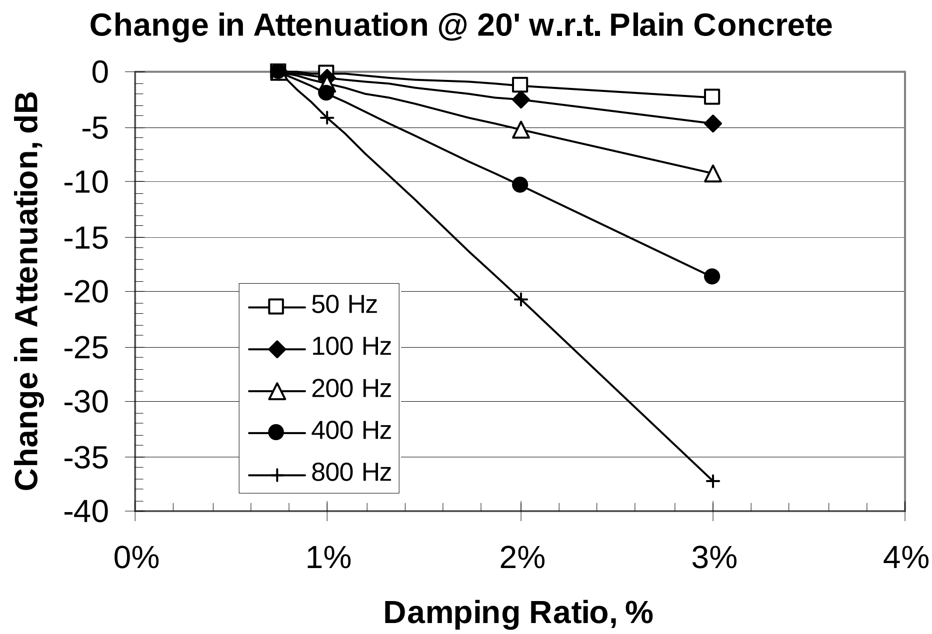

Figure 5. Attenuation as a function of damping ratio at a distance of 6.2m from source, of concrete with increased damping with respect to to unmodified concrete.

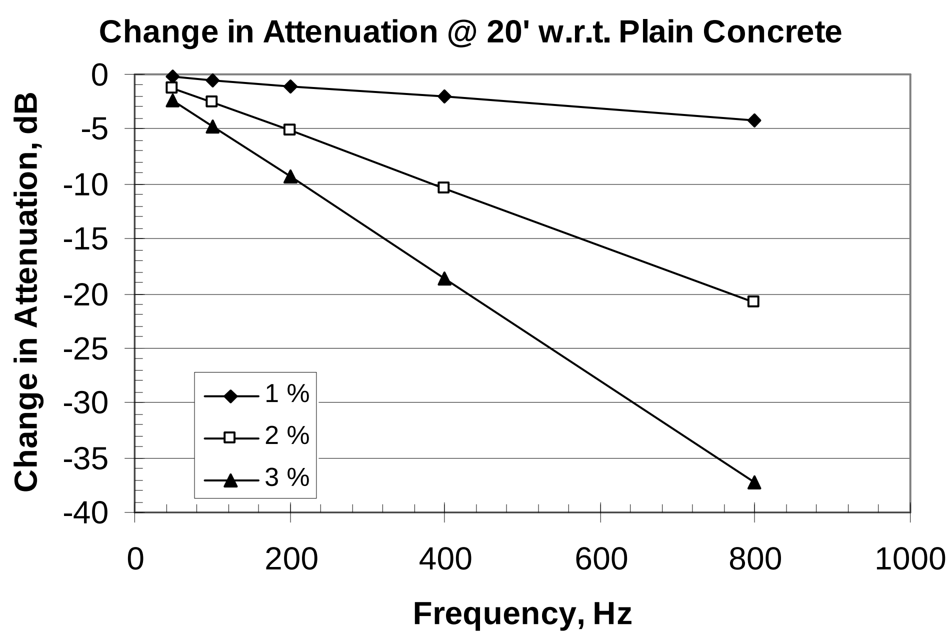

Figure 6. Attenuation as a function of frequency at a distance of 20 ft from source, of concrete with increased damping with respect to to unmodified concrete.

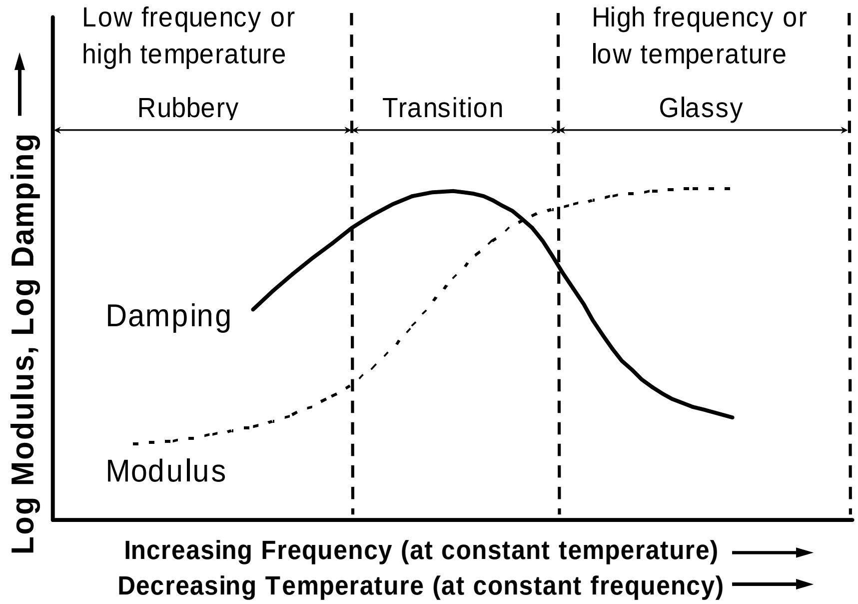

Figure 7. Effect of temperature and frequency on elastic modulus and damping in a "typical" polymer [after Ref. 13].

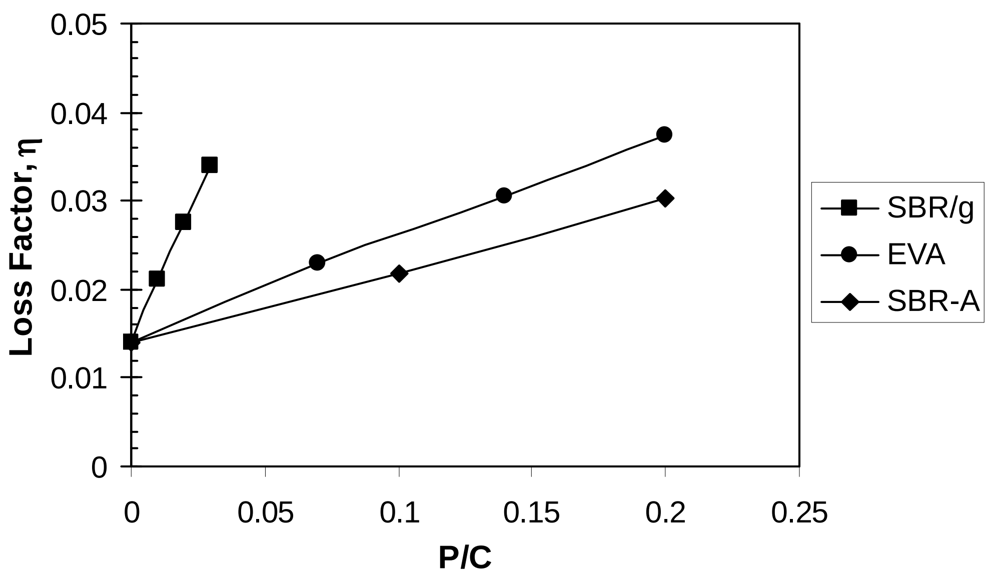

Figure 8. Effect of polymer concentration, P/C, on average concrete loss factor at room temperature and $1450 \leq f \leq 4200$ Hz[3]

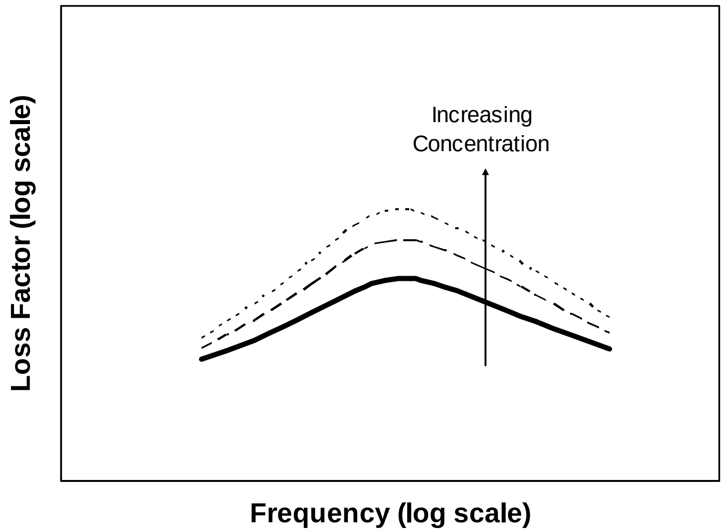

Figure 9. Typical curves showing effect of frequency on loss factor of polymer modified concrete as polymer concentration is varied.[3]

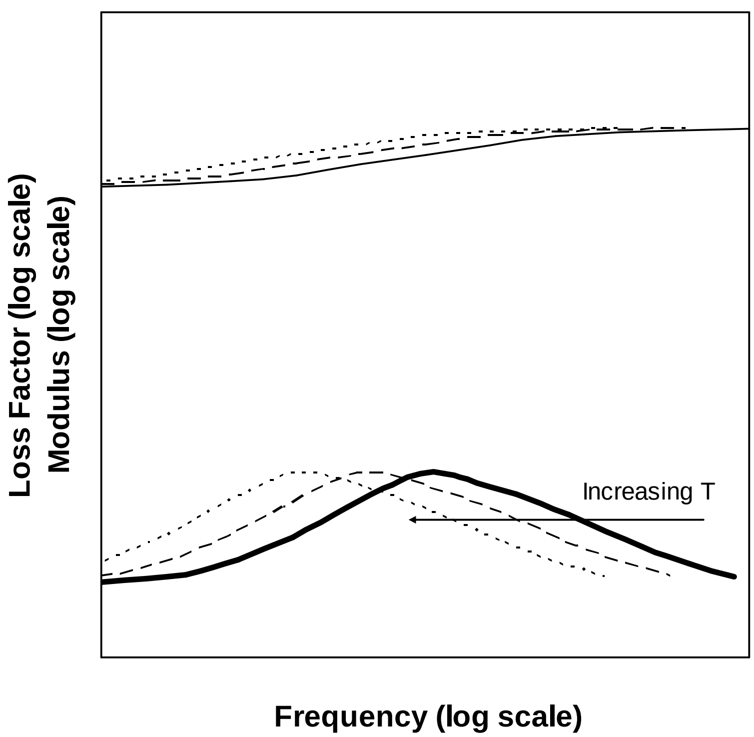

Figure 10. Typical curves showing effect of frequency on loss factor and modulus at several ambient temperatures.[3]