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A "Toolbox" of Damping Treatments for Concrete Structures

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Abstract

The paper presents measures by which *significant* changes in the damping of concrete may be achieved. A variety of alterations in mix design were examined experimentally, and the most effective treatments involved the use of polymer admixtures. Significant changes in damping were associated with the use of several types of styrene-butadiene rubber (SBR) latex, ethyl-vinyl-acetate (EVA) latex, and styrene-acrylic ester (SAE), as well as a blend of SBR and partially-solidified vegetable gum. The polymer treatments resulted in frequency- and temperature-dependent damping properties.

Introduction

Damping is a process by which vibratory energy is dissipated, generally into heat. 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, or frequency.

Concrete damping has been the subject of study since the 1930's, but most of the fundamental research was carried out prior to the 1970's. Virtually all of that work dealt with plain concrete with or without reinforcement. Very little research has been carried out since then with regard to means by which *significant* changes could be made to concrete's damping properties, and the extant literature is generally not geared toward the practicing structural engineer. A definition of what constitutes a "significant" change in damping is somewhat nebulous, but we are assuming this to mean an increase of two times or more. A doubling of damping will lead to a halving of resonant response or amplification.

This paper presents some of the practical issues addressed by a detailed study carried out at the University of California, Berkeley. The objective of that study was to develop a "toolbox" of methodologies with which a structural designer and concrete technologist can select damping as part of the design process, much as one selects strength, density, or other properties. Increasing the damping provided by concrete would benefit a variety of applications in structural dynamics.

The most efficacious means for modifying concrete damping appears to be through the introduction of viscoelastic polymers into the concrete matrix in one of several approaches. Some of these approaches are discussed in the literature, but the most straightforward implementation appears to be the use of polymeric admixtures. This became the focus of the Berkeley study, and important practical considerations will be outlined here, along with a brief review of alternate approaches documented by others.

Context

There is a growing need for low-vibration environments for facilities engaged in advanced technology R&D or production, especially for those facilities involved with nanotechnology. [Amick, *et al*., (1998), Amick and Monteiro (2004)].

Damping is relevant to a variety of structural several settings, each of which has its own frequency range of interest. These are summarized in Table 1.

Table 1. Summary of frequency ranges in which damping might be useful

Application	Freq. Range, Hz	Reference
Wind response	0.05 to 5	Jeary (1997)
Seismic response	0.05 to 8	Chopra (2001)
Propagation in advanced technology facilities	10 to 120	Amick, Gendreau and Bayat (1999)
Inertial masses for keel-slab vibration isolation systems	30 to 200	Amick, *et al*. (1998)
Acoustics	16 to 16,000	Cremer, Heckl and Ungar (1988)

System damping is that associated with an assemblage of members, and will include losses associated with connections, as well as those associated with the individual members. It is in this category that one expects to find the mechanisms associated with the amplitude-dependent damping proposed by Jeary (1997, 1998), particularly that portion associated with stiction.

Jeary (1997) presented a damping model for full-scale structures that involved three regimes as a function of amplitude, illustrated conceptually in Figure 1 using loss factor η. At low amplitudes of motion (on the order of microns), shown as segment (a), he proposed a "low amplitude plateau" at which damping is minimal, perhaps that associated with damping in the structural materials themselves. As amplitude increases, damping also increases, until another plateau is reached, section (c). In the region of the latter plateau, the structure's damping mechanisms—mostly associated with friction in connections and cracks—are fully mobilized.

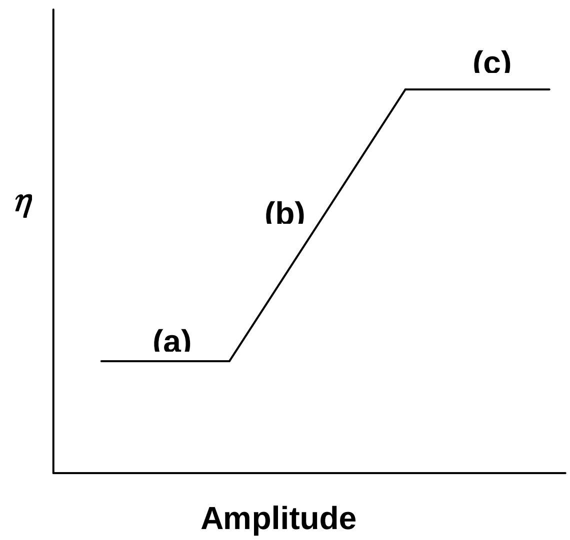

Figure 1. Amplitude-dependent damping model proposed by Jeary (1997).

The amount of available damping in a concrete structure increases as structural damage commences and increases. Newmark (1971) collected damping constants for concrete at various levels of operation and failure, for use in the seismic analysis of nuclear power plants. His data may also represented at a conceptual level by Figure 1.

The Newmark (1971) and Jeary (1997) studies both suggest a need to estimate damping at very low amplitude motion when analyzing buildings intended for advanced technology, where the objective is to limit amplitudes to a few microns. This "system" damping will have as a lower bound the "material" damping of the primary structural component, this often being concrete.

The rather complex details of the experimental program are reported by Amick (2004). The coarse and fine aggregates (*e.g.*, gravel and sand), as well as the ASTM Type I-II Portland cement, were commercially available bagged products and used throughout the study. The coarse aggregate had 10 mm (3/8 in.) maximum size aggregate. The water/cement ratio (W/C) of the plain concrete was 0.53.

Damping in Plain Concrete

The vast majority of the research on concrete damping has dealt with plain concrete with or without reinforcement. Only a few parameters (*i.e.*, frequency, W/C, and age) were re-examined as part of the present study, and the bulk of the following summary for plain concrete is drawn from the literature.

Damping in plain concrete is independent of frequency and temperature. Our study confirmed this independence over a wide frequency range (150 to 3000 Hz) but only for a limited temperature range. It is possible that extremely high temperatures could cause microstructural changes in the concrete which could alter damping. Repeated freezing and thawing was shown by Janssen and Snyder (1994) to increase damping, though the frequency and temperature dependence of this change, if any, is unknown.

Water/Cement ratio W/C has no significant effect on damping. Immediately after removal of a sample from moist curing at an age of 4 weeks, a slight increase in loss factor is observable as (W/C) is increased. However, as the concrete further cures under ambient conditions, the damping generally decreases, and the dependence on W/C diminishes.

Microfracturing increases damping but is hard to control. Cracking in concrete produces mating surfaces along which energy may be dissipated via frictional damping. This accounts for the observation by Newmark (1971) that damping increases with stress and damage. However, it is difficult to introduce cracking into a structure in any controlled way and still maintain structural integrity.

Aggregate affects damping, but not to a significant extent. The introduction of small amounts of aggregate into cement paste initially decreases damping, but further increasing the aggregate/cement ratio leads to an increase in damping. Under conditions in which bond is improved between cement and aggregate (such as limestone aggregate instead of granite, or pre-soaked lightweight aggregate) the damping may decrease slightly [Jones and Welch (1967), and Hop (1991)].

The presence or absence of reinforcement has little effect on damping. Passive reinforcement does not appear to have an effect on damping [Pozzo (1961)]. On the other hand, prestressing can have a significant effect on damping. The prestressing places the tensile zone of a section into compression, thus reducing microcrack formation, increasing normal stress, or forcing microcracks to close [Srinivasulu and Sharma (1979), Spencer (1968)]. Thus, prestressing *reduces* damping, and it appears that the extent to which this happens depends upon the degree of prestressing [Penzien (1962), Holand (1962), Hop (1991)]. It does not appear that prestressing plays a role in damping, other than controlling the amount and configuration of cracking [Penzien (1962)]. It does not appear that the effect of prestressing *per se* is enough to justify considering reinforcement in any form as one of the tools available to the designer for control of damping.

Damping only decreases with age. It is the nature of concrete damping to diminish over time, perhaps due to hydration of free water, and the designer should rely on long-term data, rather than base analyses on data measured at an early age, such as that measured at an age of 4 weeks.

Damping Effects of Polymers in Concrete

Many polymers—particularly those characterized as “viscoelastic”—are known to possess desirable damping properties. Many of these are well documented, and a variety of methods exist in which viscoelastic polymers may be incorporated into plate and beam components of several types of structures [Nashif, *et al.* (1985)].

Viscoelastic polymers may be incorporated into concrete in a number of ways. Prior studies have demonstrated significant effects on damping with the introduction of asphalt-coated aggregate [Mayama (1987)], ground rubber from tires [Kerševičius and Skripkiūnas (2002)], and several forms of cement-compatible latex [*e.g.*, Wong, *et al.* (2003)]. In each case, the studies were limited to observations that damping increased (in an approximately linear fashion) with the concentration of the polymer. None of these studies examined the role of temperature and frequency.

In all of these options, the temperature and frequency dependence typical to polymer damping is introduced into the resulting concrete member or structure. This must be considered during mix design, and some treatments may be better than others at a given temperature and frequency. Although previous studies have generally not reported it, the polymer's glass transition temperature T_g is a critical consideration, as will be shown.

A number of polymer admixtures were examined in the present study. The dynamic properties of concrete with these admixtures had not been examined previously. Three were liquid latex suspensions of styrene-butadiene rubber (SBR) in water. Some of the properties are given in Table 2, including the glass transition temperatures, T_g. SBR-A is popular for use in concrete pavements, in part because of its improvement of durability. The other two are not used as extensively. The specific gravity of these admixtures is approximately 1.02.

A fourth polymer additive included in the study was ethyl-vinyl-acetate (EVA) powder, popular as an additive to commercially prepackaged tile grout. It has a T_g of 11.2°C [Silva, (2003)]. In this study, it was blended with the dry cement prior to mixing.

Table 2. Styrene-butadiene rubber (SBR) latex suspensions used in the study; S/B, T_g, and Percent Solids from Barclay (2004)

Designator	S/B	T_g (°C)	Percent Solids	pH
SBR-A	60/40	10	48%	9.0
SBR-447	55/45	-17	47.5%	10.3
SBR-813	40/60	-41	47%	10.1

The fifth polymer additive is an emulsion of vegetable gum suspended in SBR-A liquid latex suspension and denoted here as SBR/g. The gum results from soybean oil reacted with sulfur monochloride. The resulting latex has a specific gravity of 1.036 and a pH of 0.9, and it consists of 48% polymer solids.

The important concrete mix parameters, including concrete compressive strength, are summarized in Table 3. The term W/C represents the mass ratio of water to cement solids, the primary determinant of concrete strength. The term P/C represents the mass ratio of polymer solids to dry cement, the most common form for expressing polymer concentration in concrete. Shown are the upper-bound P/C values used for all experiments (except for those in which concentration was varied.)

Table 3. Summary of compressive strengths at ~28 days

Polymer	W/C	P/C	f_c', MPa (psi)
none	0.53		33.0 (4790)
SBR-A	0.2	0.2	39.0 (5650)
SBR-447	0.2	0.2	32.5 (4710)
SBR-813	0.2	0.2	26.7 (3870)
EVA	0.42	0.2	18.7 (2710)
SBR/g	0.63	0.03	18.6 (2700)

Damping in Polymer-Modified Concrete (PMC)

A portion of the study examined the effect of polymer concentration when using SBR-A, EVA and SBR/g. The tests were performed at an age of about 4 weeks. The measured loss factors[1] for fundamental bending, torsional and extensional modes were averaged together. The results are shown in Figure 2, which shows the effect of varying P/C for three polymers with T_g near room temperature, SBR-A, SBR/g, and EVA. Each of these polymers exhibits a nearly linear relationship between P/C and loss factor.

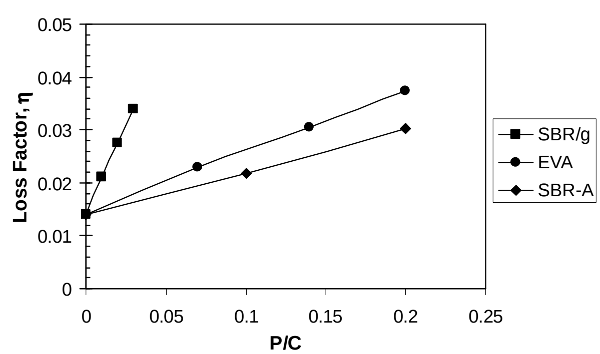

Figure 2. Effect of polymer concentration, P/C, on average loss factor at room temperature and 1450 ≤ f ≤ 4200 Hz, room temperature, age between 4 and 5 weeks

[1] There is little uniformity in the literature with regard to notation for damping. Here we will use loss factor, denoted η, as it is the most directly applicable to a material, and is recommended by Lazan (1968). Loss factor may be related to other common representations of damping by $\eta = 2\zeta = \tan\lambda$, where ζ is the damping ratio, and $\tan\lambda$ is the so-called "loss tangent."

Polymers by themselves are known to exhibit different frequency-dependent loss factor curves depending upon temperature. The polymer-modified concrete (PMC) specimens were subjected to several ambient temperatures, ranging from -3°C to 27°C. All of these specimens were of the P/C shown in Table 3.)

The left graph in Figure 3 shows the loss factor measured for bending in the weak direction (denoted B1) in concrete modified with SBR-447 (T_g = -17°C). The right graph shows the corresponding data for SBR-A (T_g = 10°C). The maximum loss factor measured for both SBR-A and SBR-447 was 0.038 at 27°C and -3°C, respectively, between 500 and 1000 Hz. Note that the loss factor for SBR-A generally *increases* with temperature, while that of SBR-447 *decreases* with increasing temperature.

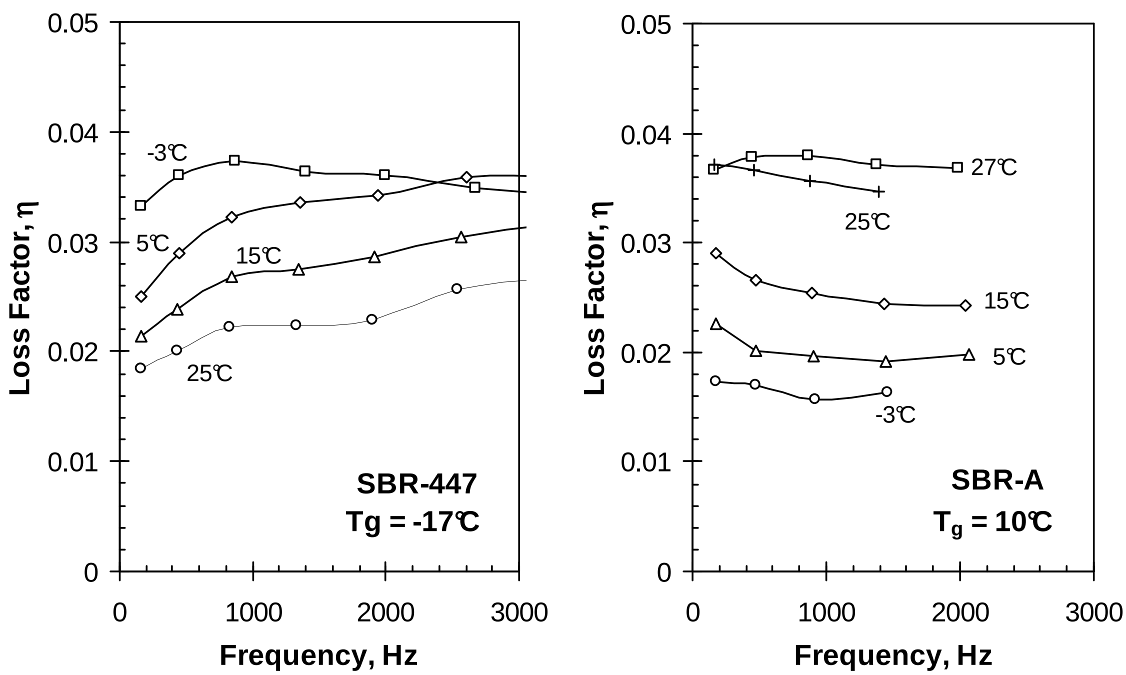

Figure 3. Left: loss factor for weak axis bending (B1) at four temperatures in concrete modified with SBR-447 (T_g = -17°C); Right: loss factor for B1 at five temperatures in concrete modified with SBR-A (T_g = 10°C).

Shifting by Frequency

The loss factors of PMC with SBR-447 (for weak-axis bending, denoted B1) shown in Figure 3 may be combined with those of the strong axis (denoted B2) modes and then manually shifted as a function of frequency times a temperature-dependent shift factor a_T, in the classical WLF method [11] of reduced variables as presented by Ferry [12]. The shifted data for SBR-447 are shown in the left graph of Figure 4. A similar process for SBR-A will lead to the results shown on the right side. [The details of this analysis, including the temperature-dependent shift factors, were shown in more detail in Amick (2004).]

It may be seen that over this range of temperatures and frequencies, the concrete with SBR-A (Figure 4, right side) exhibits the peak loss factor and a portion of the *right* side of a curve similar in shape to the loss factor curves associated with SBR alone [Nashif, *et al.* (1985)]. The concrete with SBR-447 (the left side of Figure 4) shows the peak loss factor and the *left* side of and SBR-like curve. These observations suggest that over a much larger temperature range, there would be full curves with a peak in the middle, similar to those for SBR alone. [Elastic moduli are also affected by temperature and frequency, and must be considered in the WLF protocol. The role of the moduli was documented by Amick (2004)]

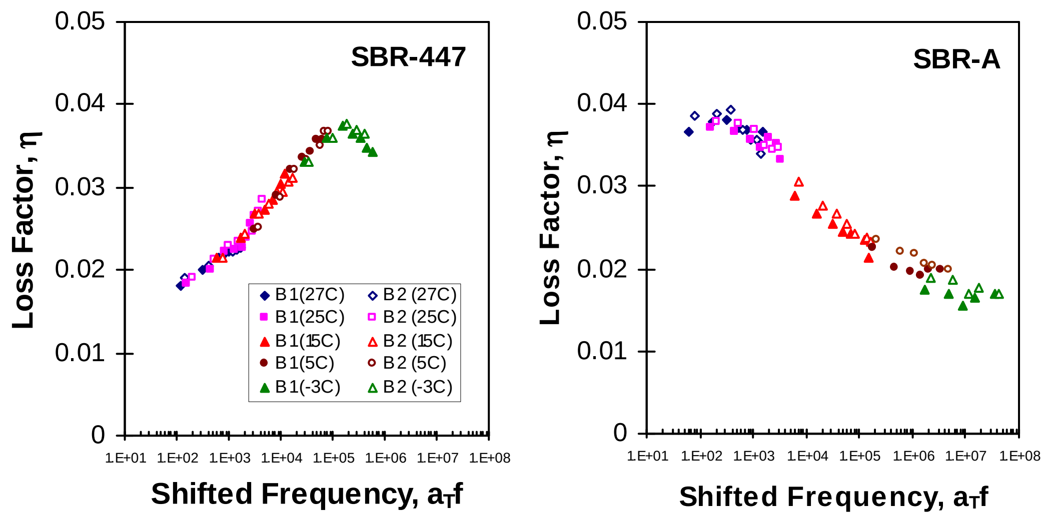

Figure 4. Loss factor for (left) B1 and B2 bending of concrete beams modified with SBR-447 (T_g = -17°C) and (right) SBR-A (T_g = 10°C), shifted by frequency using the protocol of reduced variables, using a reference temperature of 25°C.

The individual loss factor data points from the reduced variables plots may be smoothed such that they may be represented by curves. These smoothed curves are compared in Figure 5.

Upon examination of only the curves for SBR-A and SBR-447, we see two halves of a possible characteristic shape for SBR in general. However, without actually testing the SBR-A specimens at lower frequency (or higher temperature) and the SBR-447 specimens at higher frequency (or lower temperature) it is impossible to confirm if there exists a “master curve” which can simply be shifted by some function of T_g, or if the shapes are unique for each T_g. Although the curves appear to be reaching constant values at their minima, this aspect is also impossible to confirm without extending the frequency or temperature range.

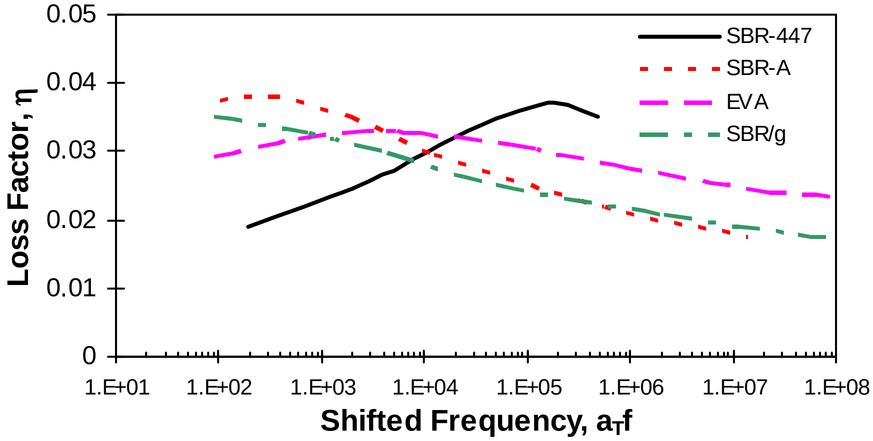

Figure 5. Shifted loss factors beams modified with SBR-A, SBR-447, SBR/g, and EVA, using a reference temperature of 25°C.

Note in Figure 5 that at an ambient temperature of 25°C and a fixed frequency (*e.g.*, 200 Hz) there will be a large variation in loss factor from one polymer to another, even though the maxima are similar.

Generalizations

The data suggest that the maximum damping available at a given temperature in PMC is related to both polymer concentration and the relationship between ambient temperature and the glass transition temperature T_g of the particular polymer. It appears that in the frequency range of interest to structural dynamicists and acousticians dealing with structureborne noise in conventional structures, the maximum damping occurs when T_g is at or slightly below the ambient temperature. Increasing T_g also increases the temperature at which peak damping occurs.

Within the range examined in this study, damping varies linearly with polymer concentration. This means that the shapes of the curves in Figure 5 must also vary with concentration. The effect of concentration on the frequency distribution of loss factor over many decades of frequency is suggested in Figure 6. (Approximately two decades are indicated.) As concentration approaches zero, the curve flattens and approaches that of plain concrete.

If ambient temperature is changed, the loss factor curve shifts horizontally, as shown in the left graph of Figure 7. Increasing the ambient temperature shifts the peak to the left, such that the peak occurs at lower frequencies.

Furthermore, the inverse relationship between temperature and frequency for polymers suggests that the shift to the right on a $\eta - T$ graph as T_g increases would correspond to a shift to the left on a $\eta - f$ graph [Ferry (1961)]. This is illustrated in the right graph of Figure 7. Thus, if maximum damping is desired at extremely low frequencies (as associated, perhaps, with lateral building motion), a polymer with a T_g

of 10°C or lower should be used. On the other hand, if maximum performance is desired at higher audible frequencies (say, a few thousand hertz), then a polymer with a higher T_g should be used.

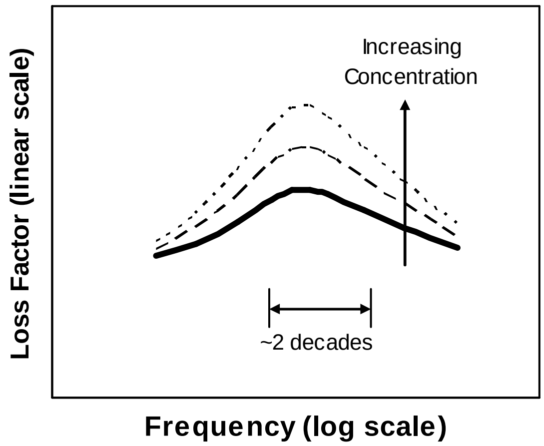

Figure 6. Typical curves showing effect of frequency on loss factor of polymer modified concrete as polymer concentration is varied.

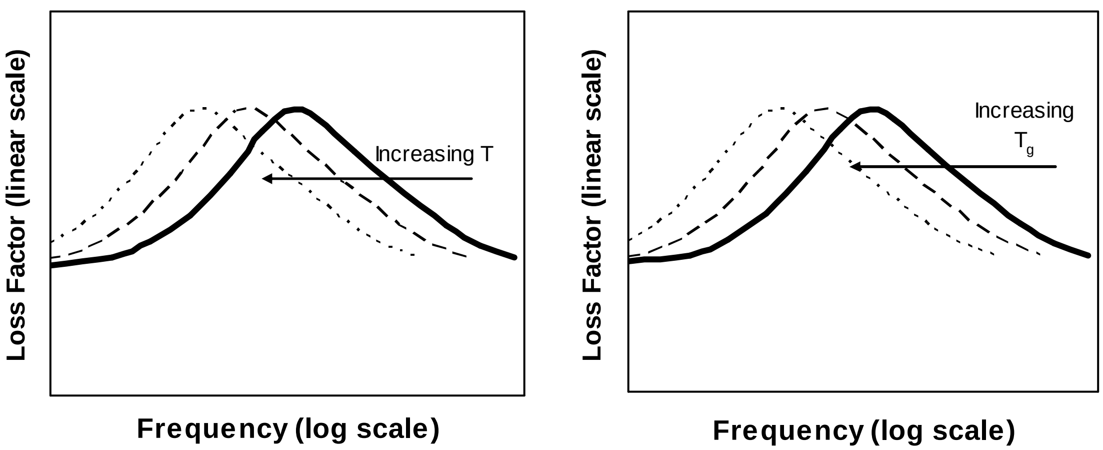

Figure 7. Typical curves showing effect of frequency on loss factor and modulus at several ambient temperatures (left) and with several glass transition temperatures (right).

It is important to note that the simple shifts shown in Figure 7 are, in practice, most likely bounded. At temperatures well below 0°C, the entrained free water tends to freeze and ice crystals begin to form in the pore spaces. This may affect damping properties of the concrete (though this is unproven). However, the change in dynamic properties of the polymers probably conforms to the behavior of the polymer alone. At temperatures well above 100°C, the entrained water can vaporize, which may also change the concrete's properties. Neither of these extrema was examined in the present study.

Unfortunately, a method was not found in the present study with which the dynamic properties of the individual concrete and polymer components could be used to predict the damping and dynamic elastic modulus in the resulting polymer modified concrete.

Conclusions

The study found that *significant* increases in damping at low amplitudes cannot be achieved through adjustment of the conventional parameters of concrete mix design, namely W/C, aggregate type, or proportions of aggregate to cement.

However, significant increases can be obtained through the introduction of polymers to the mix. This may be done in several ways, but the easiest method appears to be the use of latex polymer admixtures. The damping of the resulting PMC is dependent upon frequency and temperature. Damping remains fairly constant over two orders of magnitude of frequency. However, a shift of 20°C can cause a very large change in damping, and the nature of the change—increase or decrease—depends upon the difference between ambient temperature and glass transition temperature. Generally, for a midrange frequency (*e.g.*, 200 Hz), we find that if the ambient temperature shifts *toward* T_g, then damping will increase. A shift *away* from T_g will decrease the damping.

The introduction of polymers will affect other properties not discussed here. The changes in strength and elastic moduli vary with the polymer, and the moduli have a very slight temperature dependency. In general, durability is improved by the use of polymers. These factors, of course, will need to be considered by the designer as well.

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