Can vibration be controlled with damped concrete?

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ABSTRACT

Vibration has long been recognized as a contaminant in a fab. The vibrations can come from many sources both within and exterior to the facility. The most significant interior sources are the plant's mechanical systems, personnel activities, and sometimes the tools themselves. Exterior sources include nearby traffic, rail lines, construction, and mechanical equipment in neighboring buildings. To the extent possible, vibration control features, such as spring isolators, are built into the mechanical systems themselves at the time the facility is designed. The exterior vibrations are considered during site selection. Typically, it is possible to achieve a very quiet vibration environment in the as-built state of a fab simply through careful design and construction. However, it is not unusual for the owner and the users themselves to degrade the vibration environment over time with user-installed equipment or certain process tools. Gendreau and Amick (2004) call this tendency "maturation," and have demonstrated that the vibrations in the fab can more than double due to this effect. For quite some time, designers and consultants have discussed means by which future vibrations from "unplanned" sources might be mitigated via design or construction. This article presents one possible approach for using the building itself to mitigate vibrations. Concrete is the structural material of choice for the vibration-sensitive areas in a fab, via waffle slabs or concrete two-way grillages. Some benefits arise from altering the vibration damping characteristics of the concrete itself. A recent research project examined various options for concrete damping modification, finding that the use of a particular family of admixtures was the most straightforward approach. We will look at damping itself and the role it can play in vibration control. Several methods of altering the damping of concrete have been studied, but the most efficacious is the use of a particular group of polymer admixtures. These impart some significant improvements under certain circumstances, but concrete damping modification will not resolve all problems. We will look at where this approach is useful, and where it is not justified or cost-effective.

What is damping?

The term "damping" is often misunderstood and misused. It is not a generic term for vibration control. A spring isolator does not "damp" or "dampen" vibration; it may have some damping properties of its own, but primary the reason it works is unrelated to damping.

Damping is a process by which vibratory energy is dissipated, generally into small amounts of heat. It is the reason a ringing bell eventually stops ringing. It is present in all real materials and structures, and can be quantified as a material property using one of several *damping coefficients*. Structural engineers commonly quantify damping with the "damping ratio", expressed as a percentage, such as 2 per cent. Acousticians commonly use the term "loss factor", which defines the amount of the elastic modulus (such as Young's modulus) that is used for dissipation, or energy loss. Damping can be manifested in several forms, including:

- Decay of free vibrations, such as those of the ringing bell or the shock absorber on a vehicle; [1]
- Attenuation of propagating vibrations;
- 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; and
- Energy absorption in structural systems subjected to shock or random excitation such as explosions or earthquakes.

The first two forms are of significance to the present discussion involving fabs and other vibration-sensitive facilities. They can be affected by concrete-damping modification. The third form is important in some settings arising with regard to facilities for nanotechnology, and was the application which prompted my research program [Amick and Monteiro (2004)]. The last bullet item is very important to all buildings in seismic areas (which includes many fabs), but it will be shown that seismic applications of damping-modified concrete are rather limited.

Polymers in concrete

There is very little that can be done to increase the damping properties of concrete by means of "tweaking" the basic ingredients and mix proportions. Damping has a slight dependence on these factors, but not to the extent that would be useful for vibration control. On the other hand, several studies have shown that the introduction of viscoelastic polymers to the concrete can increase the concrete's damping, and in a manner suggesting that is proportional to polymer concentration. Unfortunately, none of these studies examined the resulting material in enough depth to make it useful for practical applications. It was seen as a novelty with no apparent application.

The candidate methods fall into three categories: (1) viscoelastic particles mixed with the concrete in place of some aggregate; (2) viscoelastic-coated particles; and (3) viscoelastic materials delivered in the form of latex.

Rubber chips introduce soft inclusions into the concrete. The net effect on strength is to reduce both strength and brittleness, while improving the resistance to freeze-thaw action. Kerševičius and Skripkiūnas (2002) examined the effects of this treatment on damping, using sand-sized particles (ground-up rubber tires), showed damping was proportional to the weight fraction of rubber chips.

Mayama (1987) proposed a novel use of asphalt-coated aggregate, which apparently has received no further attention. Sayir et al. (1991) examined the effects of unidentified proprietary polymer microfibers in cement paste, obtaining interesting results. Chung and her colleagues at SUNY Buffalo (several papers since 1996) have studied a variety of modifications of cement paste, including latex, methylcellulose, carbon fibers, and silica fume,[2] but their measurements were limited to frequencies below 2 Hz. Wu (1995) examined the effects of steel fibers.

1. 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.
2. Silica fume (or more precisely, "condensed silica fume") is a by-product of induction furnaces used in the silicon metal industries.

Durasol Drug and Chemical Co., a manufacturer of erasers and other polymer products, introduced the product ConcreDamp in 1975. Moiseev (1991) published a study of its effects on floor vibrations, but not in a controlled setting. Soon et al. (1997) carried out a laboratory study, but may have committed some experimental errors.

The published studies suggest that the most straightforward (and most reliable) way to deliver polymers into the concrete matrix is by means of the various liquid latex polymers already on the market. A thorough examination of the concrete literature led to several conclusions:

- There is nothing new about using polymers in concrete (indeed, the use of polymer additives for concrete is a mature technology associated with pavements in cold climates);
- In general, practising structural engineers tended to be unaware of the body of knowledge in the pavement literature, and thus have tended to be reluctant to use polymer modifiers in structural dynamics applications;
- There are several materials that have been demonstrated to modify damping, but with somewhat limited use; and
- The damping and elastic properties of viscoelastic polymers themselves are known to be sensitive to frequency and temperature, but *none* of the published studies of polymer-modified concrete have addressed either of these issues.

My study was intended to address the last item, and with it build on the third item, to address the second item. The basic materials were already in the marketplace. They simply needed to be better understood in the areas important to dynamicists and structural engineers.

In general, the popularity of polymer-modifiers for concrete has evolved because the polymer-modified concrete (PMC) has been found to have much greater durability, bond, water resistance, and chemical resistance [see Ohama (1995)]. These, in turn, together improve its ability to resist repetitive freezing and thawing in the wet and chemical-laden environment of a northern highway during the winter.

One of the most popular polymer additives is a liquid latex made from styrene-butadiene rubber (SBR). A common form of that material is the Dow-Reichhold product called "Modifier A". Another common form, popular for the mortar used for ceramic tiles, is the dry latex made from ethyl-vinyl-acetate (EVA). Both are well documented with regard to engineering properties, but were more-or-less undocumented with regard to damping, or dependency on temperature or frequency. A third material, the product tradenamed ConcreDamp, has been on the market for several decades with documented performance with respect to damping, but much less information on engineering properties or temperature/frequency effects. It consists of a vegetable gum made from partially solidified vegetable oil, suspended in Dow-Reichhold Modifier A.

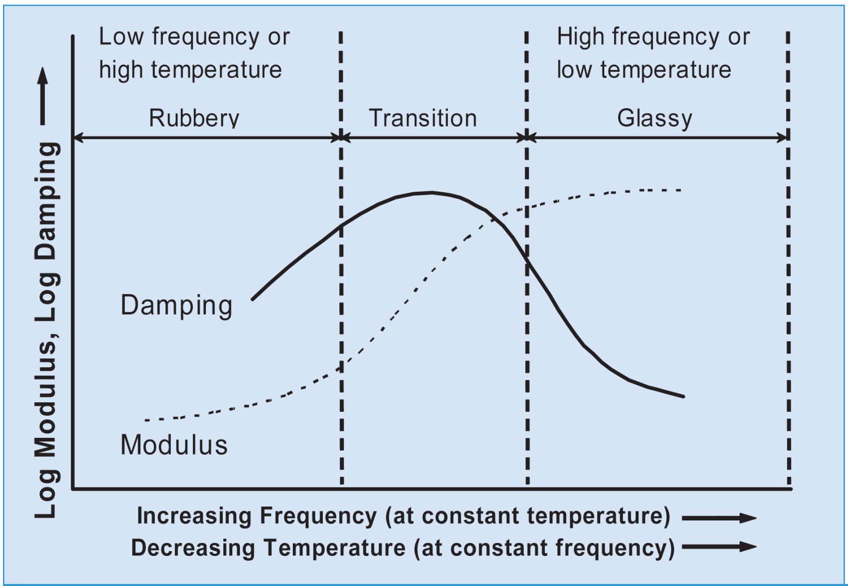

Figure 1. Effect of frequency and temperature on modulus and damping for typical "simple" polymer such as SBR or EVA alone.

Concredamp – how it works

The makeup of the vegetable gum in ConcreDamp is almost identical to that in the common artgum eraser and drafting drycleaning pads (two of Durasol's consumer products), except it is semisolid instead of solid. On its own, artgum has very high damping, but it is not compatible with cement. A bond does not form between the hydrated cement paste and the rubber. However, when suspended in SBR, which *is* cement compatible, a bond does develop because the SBR will bond to both the cement and the gum.

Any form of cement-compatible latex (including ConcreDamp) has a somewhat symbiotic relationship with the traditional concrete components of cement and aggregate. In order for a latex to form a solid, it must be suspended in water, and then give up that water. As the proportion of water in the latex drops below a critical fraction, the polymer particles suspended in the water begin to coalesce into a solid. (This same process is involved with the drying of latex paint.) On the other hand, cement requires water in order to carry out the process of solidification (called hydration). When a liquid latex suspension and cement are placed together, the water in the latex is taken up by the cement in hydration, and the two materials each tend to form solids in an interlacing skeleton.

Viscoelasticity is a characteristic of certain materials that exhibit both viscosity (typically a property of "thick" liquids like honey) and elasticity (typically a property of solids). Viscoelastic polymers are generally made up of long-chain molecules that tend to intertwine and tangle. At low temperatures, the chains are close together and interlocked, causing the material to behave as an elastic solid. (Envision the famous experiment of a soft rubber placed in liquid nitrogen, such that it becomes rigid.)

At high temperatures, the chains move apart, so that they can stretch a long way and become very flexible, as is the case with rubber. In the transition from low to high temperature, the chains rub against each other when the material deforms, and that rubbing dissipates energy as friction. (This is viscous behavior.) That dissipation leads to high damping. (Try stretching a rubber band many times fairly quickly, then touch it. You will find that it has become warm as it dissipated energy through friction between chains.)

The polymer behavior is illustrated in Figure 1. Note that the horizontal axis can be either frequency or temperature, but that frequency and temperature increase in

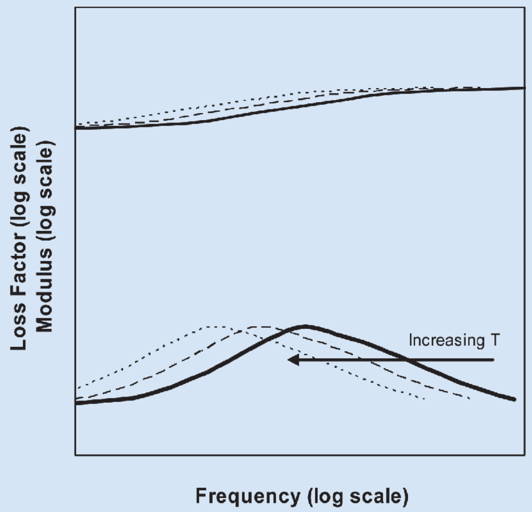

Figure 2. Typical curves showing effect of frequency on loss factor and modulus at several ambient temperatures [from Amick (2004)].

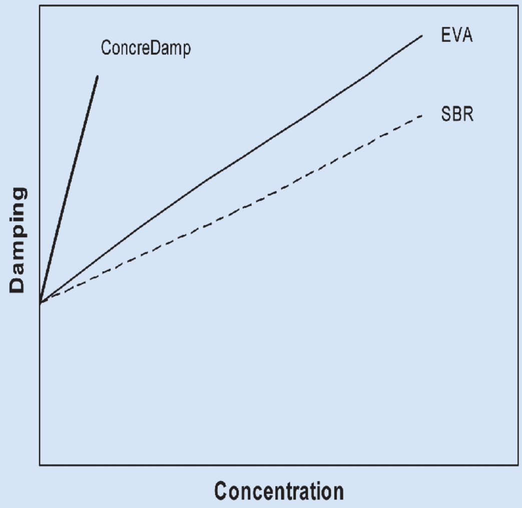

Figure 3. Effect of polymer concentration on damping performance of PMC with three different polymer additives (both axes linear) [after Amick (2004)].

opposite directions. (In other words, high temperature corresponds to low frequency, and vice versa.) One of these curves shows elastic modulus (such as Young's modulus), and the other shows damping. At low temperatures (or high frequencies) the material has a high modulus, or is stiff (the materials world calls this state "glassy"). At high temperatures (or low frequencies) the material has a low modulus, and is rubbery. However, the damping behavior is quite different. At both extremes of temperature or frequency, damping is low. It peaks in the mid-ranges of either temperature or frequency, where modulus is about halfway between its minimum and maximum.

The combination of temperature and frequency at which the maximum damping occurs is determined largely by the quantity that materials scientists call the "glass transition temperature," which is determined by the proportions of the different components of the particular polymer. (SBR is made up of styrene and butadiene, and the glass transition temperature is determined by the ratio of one to the other.) The three polymer additives we are discussing here (SBR, EVA and ConcreDamp) have glass transition temperatures about 10°C, slightly below room temperature. This leads to damping that is tailored to low to mid frequencies at room temperature.

When a viscoelastic polymer is combined with concrete, the resulting PMC is a hybrid of the two materials. The modulus is very slightly affected by variations in temperature or frequency, but the variation in damping is more dramatic (though not as dramatic as the polymer alone)[Amick (2004)]. Figure 2 shows data for PMC with a typical polymer additive. The frequency axis covers about eight orders of magnitude, and for ConcreDamp, SBR and EVA the peak is at around 100 Hz at room temperature.

Comparing the performance of different polymers

The three polymer additives considered in the study exhibited markedly different performance, though all three clearly modified damping. Figure 3 illustrates the variation with concentration. ConcreDamp is clearly more effective in terms of amount of damping per unit of polymer. However, it was designed expressly for that purpose, and the other two were designed for other desirable benefits and not for damping. (In fact, prior to this study, the manufacturers had not even considered the damping effects.)

Polymers are used in concrete for a variety of reasons. Many of them, including SBR and EVA, dramatically improve bond. SBR is used for this reason as an additive for concrete pavement repairs – it bonds very well with old concrete surfaces, such as those in potholes.

EVA improves the bond between a ceramic tile and whatever substrate is being used. (A side effect is that both adhere to formwork and tools.) Several polymers improve the chemical resistance of the concrete surface. ConcreDamp exhibits all these properties.

All three polymers act as water reducers to some extent. (A water reducer increases the workability of the concrete, in some cases allowing reduction of the ratio of water to cement, which increases strength.) SBR is the most powerful water reducer of the three, and leads to dramatic increase in strength. ConcreDamp exhibits the least water reduction of the three.

Both it and EVA lead to a reduction in strength. (It is possible that the reason ConcreDamp is so different from SBR in this regard is the difference in pH. This is still being examined.)

All three polymers cause a reduction in elastic modulus. This is to be expected, since a certain fraction of the hybrid material is made up of a relatively soft material. Despite the common perception that SBR increases strength, all polymers reduce strength, as well, from that expected from the water/cement ratio alone. SBR's apparent strength increase is due simply to its water-reduction capability. The strength reduction associated with ConcreDamp for a given water/cement ratio is really no greater than that of SBR with the same ratio.

Settings appropriate for polymer modification for vibration control

The title of this article asks a question: Can vibration be controlled with damped concrete? The simple answer is: "It depends." There are some applications in which it is effective, and others in which it is not. Let's review some of them, but be forewarned, this will involve explanations of why the various applications do or do not work, and they are necessarily somewhat technical. Some of the discussion will assume some knowledge of mechanics.

First, let's look at a basic requirement. In order for the *damping properties to* *contribute to the overall behavior, that material must play a significant role in the deformation*. The damping improvement only occurs when the material (modified concrete in this case) provides a significant amount of the resistance to deformation. This makes use of one form of the *rule of mixtures*.

Let's illustrate that with an example. Imagine a beam of rectangular cross section, divided into four parts, as shown in Figure 4, the top part is of modified concrete, and the other three parts are of plain concrete, but the section is fabricated so the whole cross section is interconnected. This would be the case if the beam were formed, the bottom three-quarters filled with plain concrete and allowed to cure a few days, and then a topping of damping-modified concrete (the shaded area) poured to complete the beam. There are standard ways to prepare the top of the plain concrete to ensure a bond between it and the topping.

If the beam is deforming axially (into and out of the paper), then the resistance is provided by the entire area uniformly. One quarter of that resistance is provided by the shaded area. Likewise, the total damping for axial deformation is made up of one-quarter part contributed by the modified concrete and three-quarters by the plain concrete. The damping contribution of the modified concrete in axial deformation is proportional to the percentage of the total cross section that is of the modified concrete. If the bottom quarter of the beam was also of modified concrete, then the damping contribution would double. The only way to fully exploit the modified-damping material is to make the entire cross section from it.

Other than columns, it is unusual to have structural members with axial loading. We are more accustomed to having concrete bending members, as in beams or floors. Here the mechanics becomes a bit more complicated. When a beam bends, the top surface and bottom surface deform more than the middle. At the "neutral axis" shown in Figure 4, there is no deformation. Thus, modified concrete contributes more when used in layers near the surface than near the neutral axis. (If the entire beam is of modified concrete, the whole cross section contributes to damping.)

This discussion has several ramifications. The most common floor type in a fab is a waffle. If the entire depth of the waffle is modified concrete, the damping will be at a maximum, but it will be a costly pour and the strength of the floor as a whole will be reduced. If only the topping slab is of modified concrete, most of the strength will be contributed by the plain concrete, but since the modified concrete is near the surface, it will play a major role. Most importantly, the cost may be dramatically reduced.

A second ramification deals with a concrete slab on a steel frame. This is less common for a cleanroom, but very common in laboratories. [This was the setting discussed by Moiseev (1991).] In this instance, the concrete contributes much less to structural integrity, and one relies very much on the steel. However, since the concrete forms the top surface of the system, the damping in the modified concrete is quite effective.

The previous mechanisms dealt with vibration that may be visualized in a single place, such as within one structural bay, bounded by four columns. Damping also plays a role in the attenuation of vibration with distance. A material with high damping will tend to attenuate propagating vibrations to a greater extent than one with low damping. The next two mechanisms deal with propagating vibrations.

The third mechanism deals with a slab-on-grade, in which the concrete is poured directly on the soil. The mechanics are quite different, as vibration on the surface of the ground (and in the slab sitting on it) exists and propagates as Rayleigh or "surface" waves. While it is beyond our scope here to fully define Rayleigh waves, the important thing to recognize for the present discussion is that propagating energy (and deformation) is concentrated near the surface.

The vast majority of deformation in Rayleigh waves occurs within one wavelength of the surface. Wavelength is a function of frequency, decreasing as frequency increases. Thus, the wavelength in a given soil might be 100 feet at 10 Hz, but 10 feet at 100 Hz. The maximum deformation is at a maximum near the surface, and diminishes to near zero at one wavelength depth. Returning to the discussion regarding Figure 4 in bending vibration, this means that the effect of having modified concrete in a slab on that soil will be a function of frequency. If the wavelength is 100 feet, and the slab is one foot thick, then the damping of the slab contributes very little to the overall damping of the system. However, at some higher frequency, say several hundred hertz, the slab makes up a significant portion of the total depth of one wavelength. In this situation the majority of the energy is traveling through the slab, and the damping modification is quite effective.

The fourth mechanism we will discuss is that of propagation within a floor. For example, we might have an area of the fab that has a vibration-sensitive tool, and several bays away there is a pump of some sort, also sitting on the waffle slab. That pump will generate a vibration at a single frequency, perhaps around 30 Hz. The vibrations will remain constant at a given location, but as we move away from the pump, the vibration amplitude will decrease. Part of this is simply due to the distance and changing geometry (geometric spreading), but part of it is a function of the material damping in the waffle.

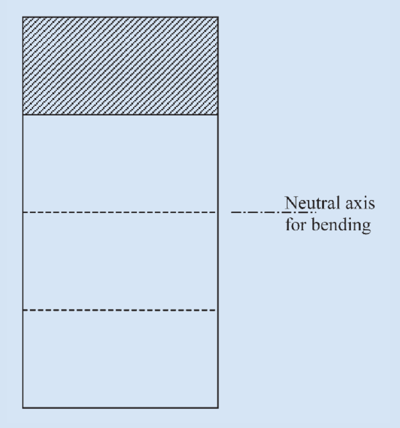

Figure 4. Beam cross section in which the top (shaded) quarter is of damping-modified concrete and the other three quarters are of plain concrete.

Figure 5 shows results from a finite element model that is 9 bays by 9 bays. The waffle floor is supported on columns, which appear as blue dots. The geometry of the waffle and the column spacing are such that the resonance frequency of this floor is 12 Hz, appropriate for a non-lithography support area. A single-frequency load is being applied at the center of the model, which is also the center of a bay. This would correspond to a mechanical system at 720 rpm (12 Hz) or the vibration resulting from a person walking at that location.

From the color contour map in Figure 5, we can use the colors to indicate how the vibrations attenuate with distance. The maximum amplitude is in the middle bay where the excitation occurs, and is shown in red. The next highest amplitudes are found in the *diagonally* adjacent bays. The laterally adjacent bays have relatively low amplitudes, except along the column line in common. Thus, we see vibrations at resonance in a waffle floor propagate diagonally with respect to column lines, not along the column lines.

Figure 6 shows the same floor being excited at a frequency somewhat removed from a resonance, at 30 Hz.

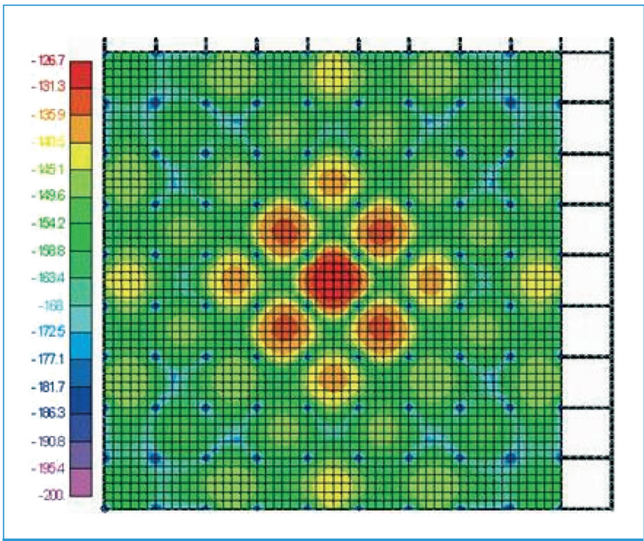

Figure 5. Contour map of vibration amplitude due to excitation at resonance (12 Hz) in a 9-bay by 9-bay finite element model of a waffle floor.

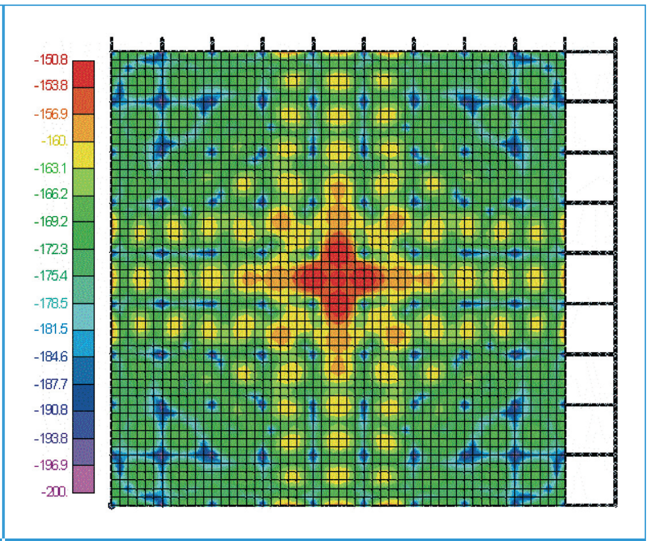

Figure 6. Contour map of vibration amplitude due to excitation at a frequency well above resonance (i.e. 30 Hz) in a 9-bay by 9-bay finite element model of a waffle floor.

This models the effect of an un-isolated 1,800 rpm dry pump in the middle bay. Here, the propagation pattern is quite different. In this case the vibration *does* propagate along column lines, and less so along the diagonal. (You were warned it would get complicated.)

The thing to observe in both Figure 5 and Figure 6 is that the vibration *does* attenuate with distance, simply due to geometry. However, if we were to increase the damping in the propagating medium (the waffle) the vibration would attenuate more rapidly with distance. The maximum amplitude would still be about the same at the drive point, but the vibration two or three bays away would be less.

The impact loading from people walking tends to excite the resonance frequency of the floor, so the propagation pattern of Figure 5 is applicable. The maximum vibrations will attenuate more rapidly with *distance* if damping is increased. However, the vibrations generated by these repeated impacts are analogous to the ringing bell. They will also die out more quickly over time if the damping is increased. Thus, the RMS amplitude (the energy average *over time*) decreases, but the maximum amplitude occurring at footfall does not. In the diagonally adjacent bay, there is a reduction in both the maximum and the RMS amplitudes, and both of these reductions are enhanced by increased damping.

It should be noted that long span floors (with lower resonance frequencies) benefit about the same as shorter-span floors (with higher resonance frequencies) with regard to the improvement of walker-generated vibrations if one considers the amount of decay *per vibratory cycle*. However, vibrations in a higher-frequency floor will decay more rapidly *per unit time* than those of a lower-frequency floor.

Generally, there will be little variation in ConcreDamp's damping effectiveness over the range of frequencies associated with floor vibrations (e.g., 4 Hz for a long-span floor with slab on steel framing to perhaps 40 Hz for a short-span waffle floor). This frequency range lies within the range of its best performance at room temperature.

Where PMC may not be beneficial

It was with some reluctance that I had to conclude that the hoped-for benefits in seismic engineering might not materialize. When buildings are designed for earthquakes, it is assumed that the concrete undergoes some cracking. When concrete cracks, the friction in the cracks generates much higher damping than can be economically provided by polymers. Thus, whatever contribution is made by the polymers becomes insignificant compared to that from the cracking.

On the other hand, small earthquakes generally do not cause cracking, so the damping from PMC may reduce the response to the smaller events. This may or may not be of importance, depending upon the nature of the structure and the local seismicity. It is possible to design a structure such that the horizontal resonance frequency of the structure may be excited by a small earthquake. In this case, the vibrations from a Magnitude 5 earthquake may be severe enough to damage tools. (This has actually occurred, but it requires a particular combination of circumstances.) The use of a polymer modifier would reduce the response to the smaller earthquakes somewhat, though it might be more practical to design the structure so this didn't happen.

A second application is still being examined with regard to effectiveness of PMC. The vibrations of a stiff waffle floor in a fab (such as a floor designed for photolithography), for the most part, are excited by the fab's mechanical systems and the behavior defined by Gordon's Model [Amick and Bayat (1998)], which relates floor vibration velocity to floor stiffness. Gordon's Model is empirically based, but there are qualitative factors that we now know are under the designer's control. It remains to be seen (from further research) whether polymer modification of the concrete in a waffle will affect this steady-state performance that is attributed to the mechanical systems.

The newest issue of concern in vibration control, dynamic stiffness[3] or accelerance [see Amick and Bayat (2001)], will only be affected in a limited way by the use of PMC. In most cases, floors with accelerance requirements are designed with high resonance frequencies, and the benefit increased damping will become quite application specific.

3. It is important to make the distinction between waffle floors designed for photolithography and those designed for support areas. Photolithography floors, with more stringent vibration criteria, are usually designed using deeper waffles and/or more closely spaced columns, and their resonance frequencies are usually in excess of 20 Hz. The typical non-photo floor is designed to be much less stiff, either by shallower waffle slabs and/or columns spaced farther apart, leading to resonance frequencies on the order of 8 to 15 Hz. In general, vibrations due to walkers on a photolithography floor are significantly less than those due to mechanical systems, to which Gordon's Model applies. In non-photo areas, walker-generated vibrations tend to exceed those from the mechanical systems, though Gordon's Model is still applicable.

Conclusion

Polymer additives for concrete, such as ConcreDamp and SBR Modifier A, will increase the damping available in concrete. They work by forming a solid polymer matrix intertwined with the cured concrete, such that both concrete and polymer undergo the same deformation.

It appears that this characteristic applies to many of the polymers compatible with concrete, though not all of them provide the same amount of damping at a given concentration.

The resulting hybrid product, commonly denoted PMC, has damping and elastic properties that are dependent upon both frequency and temperature. Each polymer will have particular ranges of frequency and temperature at which they are most effective, and those ranges are dependent upon the polymer's glass transition temperature. For room-temperature applications in which the frequencies of concern are between 1 and 500 Hz, the ideal transition temperature appears to be around 10°C. Optimal performance at higher frequencies would require a higher transition temperature.

There are a number of applications in which PMC provides additional damping that might be beneficial in a fab.

PMC will offer improved performance of floors excited by people walking, though the improvement will be an increase in the decay rate, not a decrease in the maximum amplitude. This means that the RMS amplitude will be reduced, as well. The value of this is primarily in non-photolithography waffle floors as well as conventionally framed lab floors.

PMC will also increase the rate at which vibrations reduce with distance when propagating in a suspended floor. This effect becomes more pronounced at increased frequency. It might be a way to reduce the impact of user-installed equipment (such as dry pumps) that are not adequately isolated.

The value of PMC in a slab on grade is limited to frequencies of several hundred hertz and higher, unless the slab is very thick and PMC is used for all or most of the slab thickness. At lower frequencies, the wavelengths of the vibrations are such that propagation occurs primarily in the soil.

PMC is of limited value in seismic applications. When designing against failure in an earthquake, the damping provided by the (assumed) cracked concrete is much greater than that which can economically be provided by PMC. However, if one wishes to influence the response to low-magnitude earthquakes, it may have some value, as seismic response is limited by a structure's damping.

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