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ABOUT CONCRETE CONSOLIDATION AND VIBRATION

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ABSTRACT

Proper vibration of fresh concrete is an important process in order to ensure optimum strength, durability, and appearance of quality precast products. Accepted practices in the precast industry are unique in some respects due to the industry's production environment. The following is a summary of some fundamental consolidation principles and recommended practices.

1. INTRODUCTION

Fresh concrete must be properly vibrated so that once hardened its strength and durability potential are fully realized. Studies have revealed a marked influence of reduced consolidation of fresh concrete on its ultimate compressive, tensile, and flexural strength. For example, a 5% reduction in consolidation can result in a 30% reduction in compressive strength. Reduced density, due to under-consolidation, can result in increased permeability and consequently less resistance to deterioration. Other important characteristics such as rebar bond capacity, as well as appearance are likewise affected. Over-consolidation is a lesser concern.

Newly placed concrete must be worked to eliminate voids, honeycombs, entrapped air, and to fully encase all rebars and other embedments. Vibration of fresh concrete reduces its internal shear strength and enables the concrete to temporarily liquefy, facilitating the consolidation process. Once the vibration stops, its liquid flow subsides.

Adequate consolidation in congested areas due to blockouts and embedments warrants additional vibration efforts, etc, to ensure a quality product.

The selection of the type of consolidation method is largely a matter of experience. Factors to consider include the product's configuration, mix design, size and rate of concrete placement, aggregate size, rebar configuration and desired finish.

2.THE WHAT AND WHY OF CONSOLIDATION

Because finishing of quality precast concrete products depends upon consolidation and compaction, it is important to understand these two terms. Consolidation is the even distribution of all ingredients throughout the mix, while compaction refers to the packing of concrete and removal of entrapped air.

Vibration or compaction is the principle method of consolidation of concrete. Several methods of vibration are employed in the precast industry, including; external and internal vibration, tamping, centrifugation, vacuums, and pressure. Internal vibration is vibrating the concrete from within the formwork, while external vibration is vibrating the formwork from the outside. Who hasn't seen a precast patio block and wished for that kind of finish on the next concrete job? If you were to investigate, you would find that the block was externally vibrated, and you might conclude that the best method of vibration is external. But the method of vibration is not the only consideration.

3. TECHNIQUES

Vibration or compaction is the principle method of consolidation of concrete. Several methods of vibration are employed in the precast industry, including; external and internal vibration, tamping, centrifugation, vacuums, and pressure. An American Concrete Institute Committee on Consolidation of t Concrete has defined several of these methods in a manual of practice, a portion of which included as **Attachment A** of this bulletin.

3.1. INTERNAL VIBRATION

Internally vibrated, vertically cast concrete requires craftsmanship and must be done with care. Many European countries require a vibrator operator to be licensed, which can mean a 10-year apprenticeship. In the United States, no license is required and there are few consolidation courses available.

A vibrator operator for vertically cast, internally vibrated concrete should ask two questions:

- Ø How far apart should I insert the vibrator?
- Ø How deep should I penetrate the subsequent lift?

To answer these two questions a contractor needs to know the rheology of the mix (discussed later) and the radius of influence of the vibrators that are to be used.

Knowing the radius of influence, multiply by 1.5 to attain the center-to-center insertion spacing. Internal vibrators never influence downward when used vertically. The vibration rays curve upward at about a 30-degree angle * when immersed in low-slump concrete, and to a lesser upward angle in high slump concrete. The shape of the area of influence is an inverted cone, with the cone's vertex being the nose of the vibrator.

When you place concrete into vertical forms with a bucket and use internal vibration, each bucket load will be "melted down" prior to vibrating the lift (a 2-foot lift is recommended for internal vibration). But note that the melting down process is simply to get an even lift, and you have to avoid moving the concrete horizontally, which could lead to segregation.

Internal vibration is very effective for wet-cast concrete. Surface finishes, however, can often be enhanced by utilizing both stingers and form-mounted vibrators. The following recommendations will help ensure effective stinger vibration.

- Vibration time depends on frequency - the higher the frequency, the less vibration time needed.
- Frequency will be reduced by about 20-25 percent, when the stinger is immersed in the concrete.
- The diameter of the stick should be the wall thickness of the product being poured, divided by four.
- Overlap the "field of action" (vibrating radius) throughout the pour. Doing this will bond the batches and lifts of concrete together into a monolithic pour.
- Completely immerse the stinger into the concrete.
- Immerse vertically and quickly (about one foot per second), but withdraw slowly (about three seconds per foot).
- Put the stinger into each area of concrete, only once.
- When concrete is poured in layers, place the stinger about six inches into the previous layer.
- Start vibration when the stinger is completely submerged into the concrete.
- Stop vibration when the surface becomes shiny and there are no more breaking air bubbles. . These vibrators use eccentric (unbalanced) weights to generate the vibratory forces. Generally, they can be adjusted for both amplitude and frequency. Form vibration is faster than stinger vibration, but the forms usually need to be stronger.

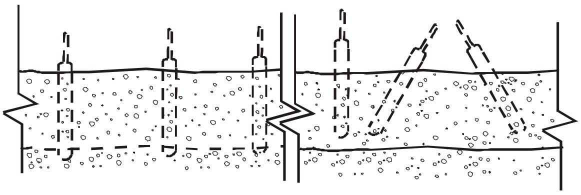
Some tips for form vibration:

- Don't fasten the vibrators directly onto the form. Mounting brackets should be welded onto a form stiffener with the vibrator attached to the mounting bracket.
- Vibrator location is critical. They must be mounted on the form at locations where their potential will be maximized (confirm with vibration supplier).
- Check with your vibrator supplier to determine the size of vibrator required for your product. The vibratory force required can vary from the total weight of the form and concrete divided by two; for walls, to as much as two or three times the total form and concrete weight to achieve zero-slump concrete.
- Start vibration when the concrete is about six inches above the vibrator.
- Stop vibration when the concrete has a level, glossy surface and there are no more breaking air bubbles.
- Fully tie rebar cages to ensure that their positions are maintained during the consolidation effort and to reduce the potential for adverse vibrations that could compromise the concrete-rebar bond.

The primary factors that influence the effectiveness of internal vibrators are the vibrator`s head diameter, frequency and amplitude. Head diameter for range from %" to

T dia. and are available in varied shapes. However, larger diameter heads are not employed in the precast industry. Internal vibrator frequencies range from 4,000 to 15,000 vpm and many have variable frequencies and amplitudes to accommodate a wide range of use.

Internal vibrators should be vertically dropped into the concrete, allowed to vibrate in place (e.g., 5-15 seconds for wet mixes or up to 2-3 minutes for stiff mixes) and then removed. The with drawl should be at a some what quicker rate than its placement. Vibrators should not be used to transport concrete laterally. An internal vibrator should slightly penetrate into the previous lift to ensure an adequate bond, note sketch below.



Correct **Incorrect**

Figure 1. Internal Vibration of Top Lift

Care should be taken to avoid touching or damaging the formwork.

3.2. EXTERNAL VIBRATION

External vibration also requires a qualified operator, but more important is the position of the vibrators or vibrator brackets on the form. External vibrators also have radii of influence, and positioning the vibrator locations should follow the 1.5-times-the-radius rule. The shape of the area of influence is a hemisphere centered on the location of the vibrator. A concrete element that is thicker than the radius of influence of the vibrator will require vibrators on both sides of the formwork. If vibrators are required on both sides, never position them directly opposite one another--typically the backside or second-side vibrator locations should be positioned at the halfway points of the front side.

If the height of the element is greater than the radius of influence, a second set of vibrators or mounting brackets is needed if the vibrators are to be moved from location to location. If a vibrator track is used, the track should be installed vertically, since entrapped air migrates vertically, not horizontally. Unlike an internal vibrator that can easily be moved vertically, external vibration is usually started when the first concrete is discharged into the form and operated until the form is filled. The lift depth should be 1.3 times the radius of influence and may be greater than the 2 feet recommended for internal vibration. The time duration should not exceed the 2-inches-per-second or 3-inches-per-second rule, or the vibrators must be activated intermittently to allow the vibrator to density the concrete and assist in the migration of entrapped air.

If the vibrators operate continually without observing timing constraints, the formwork will be overstressed, and the entrapped air will appear in pockets at the outer extremities of the radii of influence.

With both internal and external vibration, the weight of concrete helps consolidate the lower lifts, but gravity's effect in the upper parts of the lift is negligible. The top lift should be revibrated for aesthetically pleasing concrete or for any high-quality concrete, and this can be done well after placement is complete. An internal vibrator, properly equipped to allow the vibrator to remain in a horizontal position, can be pulled horizontally through the top section of concrete. This step can often be delayed by an hour or more, allowing the concrete to density by gravity, and it greatly improves both the density and appearance of the concrete in the top area of a vertical placement by reducing bug holes. The technique requires practice and will not be feasible for every application, especially in areas of reinforcing congestion. This technique is possible only for external vibration when multiple vertical vibrator locations are used.

Formwork for externally vibrated concrete construction must be watertight to prevent water or grout leakage and to achieve the best possible finishes. Water tightness in either conventional or custom-built forms adds to the cost, and conventional formwork is rarely watertight. To produce a watertight form, compressible gasketing between each form joint and tie hole is necessary, and the compressed gasket must be able to expand in the joint when the face sheet deflects due to differential pressure. Externally vibrated formwork is also very susceptible to uplift due to the formwork developing a slight batter during vibration, or due to increased lateral stresses on the base anchorage if the vibrators are operated sequentially, although sequentially operated external vibration is a necessity for most jobs.

Vibration tables, external form vibrators, drop tables and other specialized equipments are common in precast plants. Specialized equipment can offer product specific benefits, ofering more uniform control and greater overall economy.

Vibration tables are unique to the precast industry. Vibration tables are rigid decks mounted on flexible supports which operate at 3,000 to 6,000 vibrations per minute (vpm).

External form vibrators should be mounted just below poured concrete surfaces and have frequencies ranging from 2,000 to 6,000 vpm. Precautions should be exercised to ensure that a pumping action is not created that could introduce air into the fresh concrete.

Drop tables are also unique to the precast industry. This equipment employs a low-frequency, high amplitude method of shock compaction.

All consolidation equipment should be adequately secured and the formwork should be sufficiently study to resist the repeated vibration and/or shock loads. Locking mechanisms are recommended on connectors as needed.

4. MIX CONSIDERATIONS

Many people in our industry have the misconception that external vibration can produce aesthetically pleasing concrete with any mix. With the heavy use of admixtures today, very low-slump mixes are not as common as they once were. But whether slump has been increased by water or by admixture, the potential for segregation is great with poorly proportioned mixes. For aesthetically pleasing concrete, the rheology of the mix is much more important than slump. Rheology is defined in ACI 309 as "the science that deals with the flow of materials," and this includes the deformation of hardened concrete, the handling and placing of freshly mixed concrete, and the behavior of slurries and pastes. The rheology of concrete is characterized by three properties: stability, compactability, and mobility.

Stability is fresh concrete's ability to resist segregation as it flows into forms.

Compactability is a measure of how easily the concrete is compacted and is the most-abused characteristic of vertical concrete's rheology. Highly sanded mixes are the norm, and the results they produce are not aesthetically pleasing, durable, or generally acceptable. Compactability can be checked in the field by placing some of the mix in a pile in a wheelbarrow and then vibrating the concrete with the internal vibrator that is to be used on the job, or vibrating the wheelbarrow for external vibration. In either case, observe the reaction of the concrete. If consolidation occurs almost instantaneously, the mix is compactible. This is not a highly scientific method, but it tells us a lot about how the concrete will behave in the formwork.

6. EXCESSIVE VIBRATION

Over-vibrated concrete has a very wet surface and a layer of mortar without coarse aggregate. When over-vibration is evident, the slump should be reduced. Over-consolidation, however, is normally not a significant concern and rarely occurs in the precast industry. In fact, in cases in which the appearance of the concrete surface is important, it is common to double the normal vibration time to ensure a smooth, defect-free finished surface. This depends upon the type of vibration system, so check with the vibrator supplier.

5.HOW DO VIBRATORS WORK?

Vibrators impart a vibratory force into the concrete through a combination of frequency and amplitude. Frequency is the number of vibration cycles per minute, and is expressed as "rpm" or "vpm." It is noisier than amplitude and more effective with lighter mass. It moves the sand and slurry around the rock, and governs liquefaction.

Vibration of fresh concrete reduces its internal shear strength and enables the concrete to temporarily liquefy, facilitating the consolidation process. Once the vibration stops, its liquid flow subsides.

Amplitude is more effective with a heavier mass of concrete. It moves the rocks and determines the radius of action. It may be simpler to think of frequency as the number of times that the vibratory forces occur, while amplitude is the distance that the force is "thrown." A light, thin section, for example, would be vibrated at a high frequency and low amplitude, because high amplitude would throw the concrete out of the form. Heavier, thicker sections, on the other hand, are more effectively vibrated with higher amplitude and lower frequency.

Vibrators, either internal or external, are characterized by their frequency and amplitude of vibration. Optimum frequencies and amplitude will vary with mix design, form configurations, and other factors. For example lower water-cement ratios, greater cement contents, greater angularity of coarse aggregate all require greater compactive efforts. Also, superplasticized concretes typically require 20-50% of the compactive effort of conventional concretes and can effectively employ smaller diameter internal vibrators.

The ideal vibrator is one in which the frequency and amplitude can be varied ranging from low-frequency, high-amplitude during initial consolidation to high-frequency, low-amplitude at final consolidation,

Fresh concrete should be vibrated until all voids and entrapped air pockets are released. The consolidation of the concrete will be evident when escaping air bubbles cease.

Full consolidation can be judged by the formation of a mortar rich appearance on the concrete surface and, in cases, a noticeable difference in the sounds emanating from the vibrator. If a concrete is over-vibrated its surface will appear very wet and have a layer of mortar without coarse aggregate. When over-vibration is evident the slump rather than the amount of vibration should be reduced. Over-consolidation is normally not significant concern. In fact, in cases in which the appearance of the concrete surface is important, it is common to double the normal vibration time to ensure a smooth defect free finished surface.

Re-vibration of concrete after initial consolidation is an accepted practice as necessary to weld successive lifts together.

Fully tied rebar cages are urged to ensure that their positions are maintained during the consolidation effort and to reduce the potential for adverse vibrations that could compromise the concrete-rebar bond.

7. CONSOLIDATION METHODS

Consolidation of precast concrete products can be accomplished using a variety of vibration methods. An optimal vibration system depends upon the concrete mix design and whether the concrete to be consolidated is wet-cast or dry-cast. External vibration can be accomplished with forms and tables, while stingers (spuds, pencils, sticks, pokers) are used for internal vibration. Dry-cast concrete can be vibrated with vibrators mounted on external and/or internal forms, while some systems utilize a vibrating table that imparts vertical vibratory forces to the concrete.

8. TYPES OF VIBRATORS

Several different types of vibrators are used in the precast concrete industry. Each has its advantages for a given application.

A variety of features are offered with each type of vibrator. These features include adjustable speed and force (frequency and amplitude), remote converters, and various types of mounting brackets. Vibrator types are:

- electric (115 volt / 220 volt)
- pneumatic
- operating pressure
- turbine models
- hydraulic
- compaction tables
- foot pedal, on-off switch

Some high-end features can result in great benefits for a precaster. For example, a producer of box culverts installed radio control of an inverter-driven vibrator, with great benefits. The casting process included a vibrating system with a variable-speed drive. The inverter was usually moved away from the product to allow for more room during casting.

However, this set-up usually required a worker to be assigned to running the inverter.

Radio control of the variable-speed drive was installed. This has saved lots of footsteps (25-30 each way) for workers and often completely freed up a worker. The crew likes it because they can run the vibrators without leaving the product during casting. An additional feature is that they can vary the frequency with the radio controller, as needed.

9. CONCLUSION

Surface imperfections can be caused by either under-vibration or over-vibration. Under-vibration generally results in honeycombing, excessive entrapped air, and sand streaks. The results of over-vibration can be segregation, form deflection, form damage, and sand streaks.

It may take a few trial runs to determine which combination of frequency and amplitude, as well as vibration time, are correct for a given product.

It is important to recognize that the vibration of dry-cast products is very different from wet-cast vibration. Suppliers of dry-cast systems design their forms to work with their specific vibration system. It is not, therefore, a good idea to "mix and match" forms that were designed for one system with a vibration system supplied by another manufacturer.

Dry-cast forms are specially designed to withstand the high vibratory forces that are required for zero-slump concrete. As a result, they are generally more expensive than wet-cast forms.

REFERINCE

[1] **Bartos, P.** *Fresh Concrete: Properties and Tests,* Elsevier. (1992);

[2] **Ford, J.** *Internal or external vibration? Done correctly, either will produce a high-quality finish - of concrete,* Concrete Construction, 2003;

[3] **Shane Tymkowicz ,S. , Steffes R. F.** *Vibration Study for Consolidation of Portland Cement Concrete,* 1996 Semisesquicentennial Transportation Conference,1996.

Attachment A
Consolidation Methods for Precast Concrete Products

Product	Mix Classification	Forming Material	Conveying and Placement method	Consolidation method
Concrete Pipe	a to d	Steel	Pumping or bucket (thin layers)	Tamping; internal or external vibration; centrifugation; vacuum; pressure
Concrete piles and poles	c,d	Steel	Pumping or conveyed by mixer trucks	Centrifugation; internal or external high frequency, low amplitude vibration; roller packed
Concrete block	b	Steel	Machine hopper	Low frequency, high amplitude vibration plus pressure
Slab and beam sections	b,c	Steel	Traveling hopper, mixer trucks, belt conveyors	External vibration with or without roller compactions; internal vibration with surface vibration screed
Wall panels	a to c	Reinforced concrete steel or wood	Buckets and belt conveyors (continuous ribbon feed)	Tampers; internal and external vibration

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Notes:

a. Very stiff mixes, with water-cement ratios of 0.30 by weight or less
b. Stiff mixes having a water-cement ratio exceeding 0.30 but with less than 1 in. slump
c. Uniformly gap graded mixes with slump in the 1-4 in. range
d. Mixes with over 4 in. slump, which flow readily and segregate if mechanical vibration is apllied.