PART V. CONCRETING SITE PRACTICES

COMPACTION

CEMENT CONCRETE & AGGREGATES AUSTRALIA

In this section, the techniques used to compact or consolidate plastic concrete with the aim of achieving its optimum density are described. Generally, compaction and finishing (see Section 14 *'Finishing Concrete Flatwork'*) are two separate operations. However, on flat horizontal surfaces (i.e. flatwork), they are often parts of the same operation and can be considered together.

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1. INTRODUCTION

Compaction is one of several important site operations that, in combination, enable the concrete to reach its potential design strength, density and durability. Properly carried out, it ensures that concrete fully surrounds, engages with and protects the reinforcement, tendons and cast-in inserts. It also has a direct impact on achieving the specified surface finish.

While the compacting and finishing of concrete are generally two separate operations, sometimes, particularly with flat horizontal surfaces, they become parts of the one operation. In such circumstances, it should be noted that a smooth surface finish is not necessarily evidence of good compaction underneath it. Care should always be taken to ensure that concrete is adequately compacted.

In-depth discussions of the critical issues are contained in the following documents:

- ACI Committee 309, *'Guide for Consolidation of Concrete Report 309R – 96',* ACI Manual of Concrete Practice, Part 2, Chicago (2000);
- ACI Committee 309, *'Behaviour of Fresh Concrete During Consolidation Report 309.1R – 99',* ACI Manual of Concrete Practice, Part 2, Chicago (2000);
- ACI Committee 309, *'Consolidation-Related Surface Defects Report 309.2R – 98',* ACI Manual of Concrete Practice, Part 2, Chicago (2000);
- ACI Committee 309, *'Guide to Consolidation of Concrete in Congested Areas Report 309.3R – 92',* ACI Manual of Concrete Practice, Part 2, Chicago (2000).

2. PURPOSE

Compaction is the process that expels entrapped air from freshly placed concrete and consolidates the aggregate and paste components with a resultant increase in the density of the concrete. It significantly increases the ultimate strength of concrete and enhances the bond with reinforcement. It also results in (a) increases in the abrasion resistance and general durability of the concrete, (b) a decrease in its permeability and (c) helps to minimise shrinkage and creep characteristics.

Proper compaction also ensures that (a) the reinforcement, tendons, inserts and fixings are completely encased in dense concrete; (b) the formwork is completely filled (i.e. there are no pockets of honey-combed concrete); and (c) that the required surface finish is obtained on vertical surfaces.

AS 3600 specifies that concrete shall be compacted during placing so that:

- A monolithic mass is created between the ends of the member, planned joints or both;
- The formwork is completely filled to the intended level;
- The entrapped air is expelled;
- All reinforcement, tendons, ducts, anchorages and embedments are completely surrounded;
- The specified finish to the formed surfaces of the member is provided;
- The required properties of the concrete can be achieved.

3. THE PROCESS

When first placed in the form, normal concretes (i.e. excluding those with very low or very high workability) will contain between 5% and 20% by volume of entrapped air which has been included during the mixing process. The aggregate particles, although coated with mortar, will also tend to arch against one another and are prevented from slumping or consolidating by internal friction.

Compaction of concrete is, therefore, a two-stage process (**Figure 13.1**). First, the aggregate particles are set in motion and the concrete consolidated to fill the form and give a level top surface (by inducing 'liquefaction'). In the second stage, entrapped air is expelled. This description of the process is true whether compaction is carried out by rodding, tamping (and similar manual methods), or when vibration is applied to the concrete. Vibration, by temporarily 'liquefying' a much larger volume of the concrete, is generally much more efficient than tamping or rodding by hand, and hence is almost universally used on construction sites.

It is important to understand that compaction is a two-stage process and to recognise each stage. With vibration, initial consolidation of the concrete (liquefaction) can often be achieved relatively quickly. The concrete liquefies and the surface levels out, giving the impression that the concrete is compacted. Entrapped air takes a longer time to rise to the surface. Compaction should therefore be continued until this is accomplished, i.e. until air bubbles no longer appear on the surface.

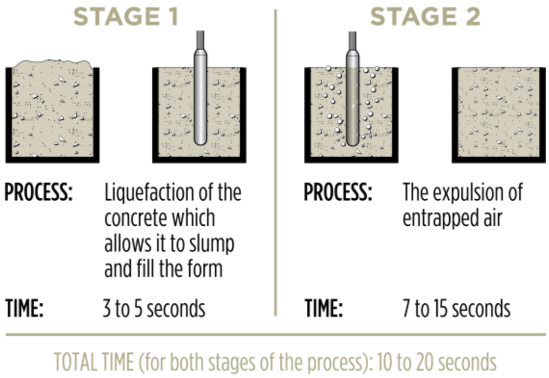

Figure 13.1 – The Process of Compaction

4. EFFECT ON PLASTIC CONCRETE

The effect of vibration on the properties of plastic concrete needs to be understood to ensure that the type and amount of vibration applied to the concrete are appropriate, otherwise defects such as excessive mortar loss and other forms of segregation can be the result.

The concrete mixture as supplied to the project needs to be properly proportioned. Concretes lacking fines can be difficult to compact and, even when fully compacted, can have high porosity. On the other hand, those with too high a fines content, particularly if they also have a high slump, may be prone to segregation and excessive bleeding. Importantly, it should be noted that properly proportioned concretes are difficult to over-vibrate and cautionary notes in specifications regarding over-vibration may result in concrete on the project actually being under-vibrated with resulting loss of potential strength and durability performance.

Concretes with lower workability (i.e. stiffer mixes) will require a greater energy input to compact them fully. This may be achieved by using a high-energy vibrator or by vibrating the concrete for a longer time. In the latter case, the vibrator must have sufficient capacity to liquefy the concrete. Conversely, more workable mixes will require less energy input.

The size and angularity of the coarse aggregate will also affect the effort required to fully compact concrete. The larger the aggregate, the greater the effort required. Angular aggregates will require greater effort than smooth or rounded aggregates.

5. EFFECT ON HARDENED CONCRETE

Since compaction of concrete is designed to expel entrapped air and optimise the density of the concrete, it benefits most of the properties of hardened concrete. As can be seen (**Figure 13.2**), its effect on compressive strength is dramatic. For example, the strength of concrete containing 10% of entrapped air may be reduced by as much as 50% compared to when the concrete is fully compacted.

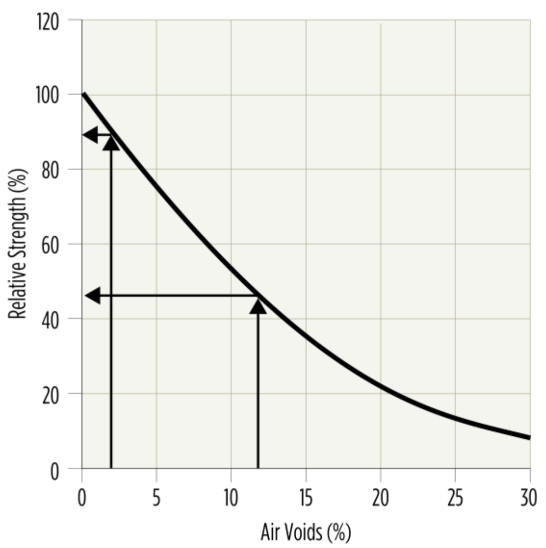

Figure 13.2 – Loss of Strength due to Air Voids from Incomplete Compaction

Permeability is similarly affected since compaction, in addition to expelling entrapped air, promotes a more even distribution of pores within the concrete, resulting in more of them becoming discontinuous. The durability of the concrete is consequently improved except, perhaps, in freeze-thaw conditions, where excessive vibration can expel amounts of intentionally entrained air which is designed to increase the freeze-thaw resistance of hardened concrete (see Section 25 *'Properties of Concrete'*).

The abrasion resistance of concrete surfaces is normally improved by adequate compaction. However excessive vibration, and particularly excessive working of the surface, can cause a thick layer of mortar (and moisture) to collect (and eventually harden) on the surface, thereby reducing its potential abrasion resistance. In flatwork, a careful balance is therefore required to expel entrapped air without bringing excessive amounts of mortar (fines) to the surface of the concrete.

6. METHODS AND EQUIPMENT

6.1 GENERAL

Two types of vibrators are common on building sites – immersion vibrators and surface vibrators. Each has its appropriate sphere of application, although on floors and other flatwork it is not uncommon for them to be used in combination. A third type – form vibrators – is commonly used in factories for precast work, and sometimes on building sites.

6.2 IMMERSION VIBRATORS

Frequently referred to as 'poker' or 'spud' vibrators, immersion vibrators consist essentially of a tubular housing which contains a rotating eccentric weight. The out-of-balance, rotating weight causes the casing to vibrate and, when the vibrator is immersed in concrete, the vibration force is transferred into concrete itself. Depending on the diameter of the casing, and on the frequency and the amplitude of the vibration, an immersion vibrator may have a radius of action of between 100 mm and 500 mm (**Table 13.1**).

Immersion vibrators may be driven by:

- A flexible shaft connected to a petrol, diesel, or electric motor;
- An electric motor situated within the tubular casing;
- Compressed air.

Flexible-shaft vibrators may have either (a) a conical pendulum, which runs around the inside of the casing like an epicyclic gear, or (b) a straight rotating weight. Type (a) have the advantage that they generally have thinner heads (which is useful in reinforced members). They also have higher amplitudes at the tip than that obtained further up the casing. This helps compact the concrete at the surface as the vibrator is withdrawn from the concrete.

Electrically powered vibrators, with the motor in the head driving an eccentric weight, are relatively light in weight and, with a switch located on the vibrator, are easy to handle.

Vibrators powered by compressed air normally have the motor driving an eccentric weight located within the casing. They are most common in the larger diameter tools used for compacting mass concrete (e.g. in dams).

The effectiveness of an immersion vibrator is dependent on its frequency and amplitude, the latter being dependent on the size of the head, the eccentric moment and the head weight – the larger the head, the larger the amplitude.

Table 13.1 – Characteristics and Applications of Internal Vibrators

Head Diameter (mm)	Recommended frequency (Hz)[1]	Average amplitude (mm)[2]	Radius of action (mm)[3,5]	Rate of concrete placement (m^3/h per vibrator)[4,5]	Application
20-40	150-250	0.4-0.8	80-150	0.8-4	High slump concrete in very thin members and confined places. May be used to supplement larger vibrators where reinforcement or ducts cause congestion in forms.
30-60	140-210	0.5-1.0	130-250	2.3-8	Concrete 100-150 mm slump in thin walls, columns, beams, precast piles, thin slabs, and along construction joints. May be used to supplement larger vibrators in confined areas.
50-90	130-200	0.6-1.3	180-360	4.6-15	Concrete (less than 80 mm slump) in normal construction, e.g. walls, floors, beams and columns in residential, commercial and industrial buildings.
80-150	120-180	0.8-1.5	300-500	1-31	Mass and structural concrete of 0-50 mm slump placed in quantities up to 3 m^3 in relatively open forms of heavy construction.

NOTE*: Adapted from Table 5.15, ACI Committee Report 'Consolidation of Concrete', ACI Manual of Concrete Practice, Part 2 (1993).*

[1] While vibrator is operating in concrete.
[2] Computed or measured. This is peak amplitude (half the peak to peak value), operating in air. Reduced by 15-20% when operating in concrete.
[3] Distance over which concrete is fully consolidated.
[4] Assumes insertion spacing 1.5 times the radius of action, and that vibrator operates two-thirds of time concrete is being placed.
[5] Reflects not only the capability of the vibrator but also differences in workability of the mix, degree of de-aeration desired, and other conditions experienced in construction.

Table 13.1 summarises the characteristics and applications of internal vibrators. As a general rule, the radius of action of a given vibrator not only increases with the workability of the concrete, but also with the diameter of the head. A good general rule is to use as large a diameter head as practicable, bearing in mind that vibrators with diameters in excess of 100 mm will probably require two workers to handle them. For smaller diameter vibrators the appropriate head size will be dependent on the width of the formwork, the spacing of the reinforcement and the thickness of concrete cover.

The *frequency* of a vibrator is the number of vibrations per second [the unit is Hertz (Hz)]. In general, high-frequency vibrators are most suited to high-slump concrete and small maximum-sized aggregates; while low frequency vibrators are more suited to low slump concrete and large maximum-sized aggregates.

The *amplitude* is the maximum displacement of the head from its point of rest (measured in mm). It will be larger in air than in plastic concrete which has a damping effect. Generally, high-amplitude vibrators are most suited to low-slump/large maximum-sized aggregate concrete; while low amplitude vibrators are most suited to high slump concrete and small maximum-sized aggregates.

Immersion vibrators should be inserted vertically into concrete, as quickly as possible, and then held stationary until air bubbles cease to rise to the surface – usually about 15-20 seconds (**Figure 13.3**). The vibrator should then be slowly withdrawn and reinserted in a fresh position adjacent to the first. These movements should be repeated in a regular pattern until all the concrete has been compacted (**Figure 13.4**). Random insertions are likely to leave some areas of the concrete uncompacted. The vibrator should not be used to 'help' concrete to flow horizontally in the forms, as this can lead to segregation.

Figure 13.3 – Using an Immersion Vibrator

In deep sections such as walls, foundations and larger columns, the concrete should be placed in layers (lifts) about 300 mm thick. The vibrator should penetrate about 150 mm into the previous layer of compacted concrete to meld the two layers together to avoid 'cold-pour' lines on the finished surface. In small columns where concreting is continuous, the vibrator may be slowly raised as the concrete is placed. However, care should be taken to ensure that the rate of placement is slow enough to allow the concrete to be fully compacted and the entrapped air to be able to reach the surface. Care should also be taken to avoid trapping air on the form face and a means of lighting the interior of the form while the concrete is being placed and vibrated should be provided.

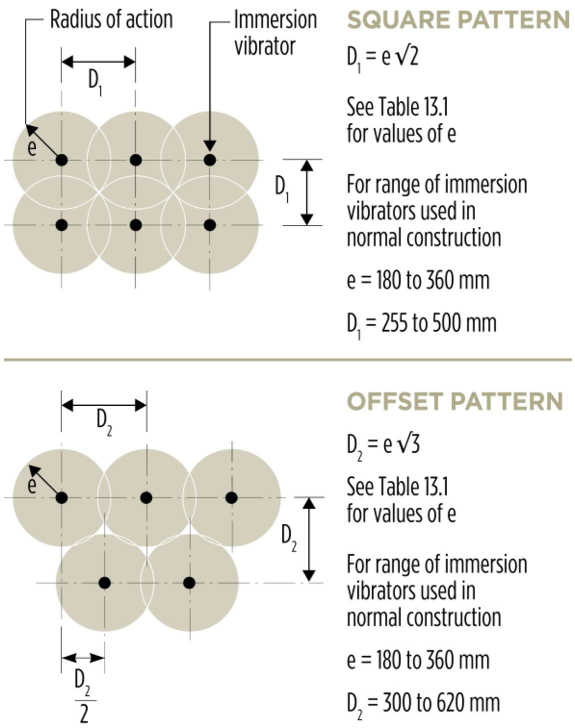

Figure 13.4 – Alternative Patterns for Use of Immersion Vibrators

The vibrator should not be allowed to touch the forms as this can cause 'burn' marks that will be reflected on the finished surface. Generally, the vibrator should be kept about 50 mm clear of the form face. Similarly, the vibrator should not be held against reinforcement as this may cause its displacement.

Stop-ends, joints and inclined forms are prone to trapping air. To minimise this tendency, the best technique is to place the concrete close to, but away from, the form and insert the immersion vibrator close to the leading edge of the concrete forcing it to properly fill the corner (**Figure 13.5**).

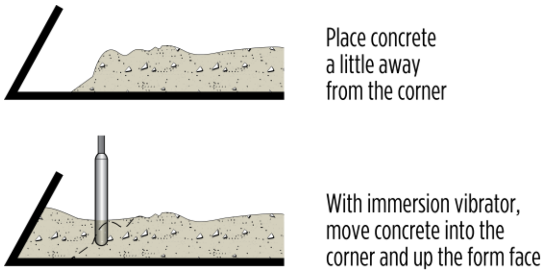

Figure 13.5 – Compaction at Stop Ends and Inclined Forms

Void-formers are prone to trapping air on their undersides if concrete is placed from both sides and then compacted. Concrete should be placed at one side and, while maintaining a head, vibrated until it appears at the other side. (Note that the void-former needs to be fixed so it can resist the pressure of the concrete – from both sideways and vertical directions) Once the top surface of the concrete is fully visible from above, then placing can continue normally (**Figure 13.6**). This technique should be used in other similar situations, such as encasing steel beams.

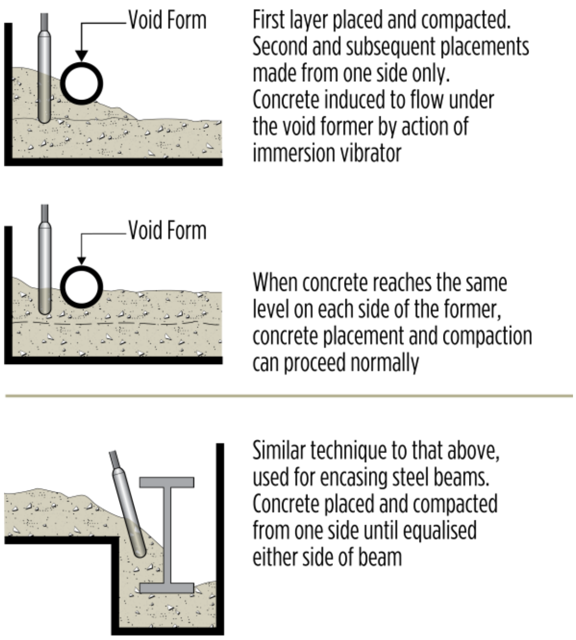

Figure 13.6 – Compacting around Void Formers and Encased Beams

6.3 SURFACE VIBRATORS

Surface vibrators are applied to the top surface of concrete and act downwards. They are very useful for compacting slabs, industrial floors, road pavements, and similar flat surfaces. They also aid in levelling and finishing the surface.

Several types of surface vibrators are available. Some of these (e.g. vibrating-roller screeds and pan-type vibrators) are used mainly on specialised equipment such as road paving plant – but the most common type is the single or double vibrating-beam screed.

A vibrating-beam screed consists of either one or two beams, made from aluminium, steel or timber, to which is attached some form of vibrating unit. This may be a single unit, mounted centrally, or may consist of a series of eccentric weights on a shaft supported by a trussed frame and driven by a motor at one end. In general, the centrally mounted units have a maximum span of about 6 m, but the trussed units may span up to 20 m. The small units are normally pulled forward manually (**Figure 13.7**), whereas the larger units may be winched, towed or be self- propelled.

Figure 13.7 – Typical Vibrating Screed Surface Vibrator

The intensity of vibration and, hence, the amount of compaction achieved, decreases with concrete depth because surface vibrators act from the top down. They are most effective on slabs less than about 200 mm thick. With slabs greater than 200 mm in thickness, immersion vibrators should be used to supplement the surface vibration. A thick slab compacted by both immersion and surface vibrators will have a denser, more abrasion-resistant surface than one compacted by immersion vibrators alone.

With centrally mounted vibration units, the degree of compaction achieved may vary across the width of the beam. When they rest on edge forms, the latter may tend to damp the vibration at the extremities of the beam (**Figure 13.8**). It is generally desirable, therefore, to supplement vibrating-beam compaction by using immersion vibrators alongside edge forms and at construction joints – particularly for paving >150 mm thickness (**Figure 13.9**).

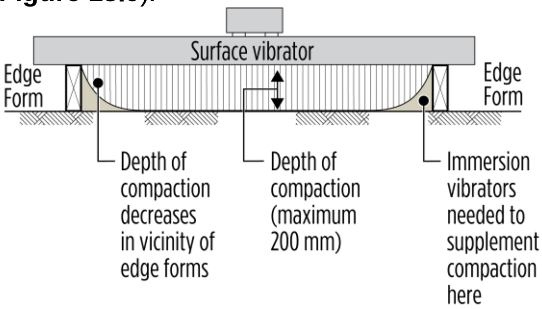

Figure 13.8 – Degree of Compaction varies across Width when Surface Vibrators are supported Off Edge Forms

Figure 13.9 – Use of an Immersion Vibrator at a Slab Edge

The effectiveness of vibration (and hence the degree of compaction) increases with an increase in the beam weight and the amplitude and the frequency and decreases with an increase in forward speed. Forward speed is critical when using a vibrating-beam screed and should be limited to between 0.5 m/minute and 1.0 m/minute.

Generally, vibrating-beam screeds are not suitable for concretes with slumps greater than about 75 mm as an excessive amount of mortar may be brought to the surface. Ideally, they should be used on concrete with slumps between 25 mm and 50 mm.

For the reasons noted above, slabs 200 mm in thickness or above should be compacted initially with immersion vibrators. Slabs of less than 200 mm thickness may also benefit from the use of immersion vibrators along their edges (**Figure 13.9**). In using vibrating-beam screeds to compact concrete, the uncompacted concrete should first be roughly levelled above the required final level (i.e. a surcharge should be created) to compensate for the reduction in slab thickness caused by the compaction of the concrete. The amount of surcharge should be such that, when the beam is moved forward, a consistent 'roll' of concrete is maintained ahead of the beam. An even surcharge may be provided on slabs of up to about 4 m in width by using a 'surcharge-beam' – simply a straightedge (usually made of timber) with small packing pieces on the ends, which 'ride' on the edge forms (**Figure 13.10**).

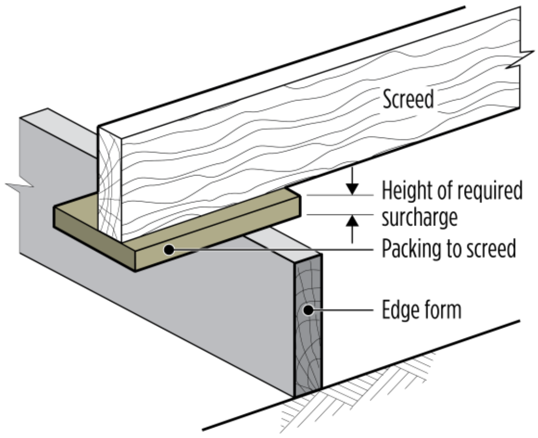

Figure 13.10 – Method of providing an Even-Surcharge of the Uncompacted Concrete

The surcharge-beam is pulled over the uncompacted concrete without any attempt being made to compact or finish it. The sole purpose is to provide an even and adequate surcharge. The correct thickness for the packing pieces (and hence the surcharge) is found by observing the thickness of the 'roll' of concrete. Providing an even surcharge has the advantage that only one pass of the vibrating-beam screed is generally sufficient to compact, level and provide the initial finish. This is preferable to multiple passes, as a slower single pass is more efficient and effective than two faster passes.

The forward speed is very important and, as noted previously, should be between 0.5 m/minute and 1.0 m/minute. The lower speed should be used for thicker slabs and where reinforcement is close to the top face. A second, faster pass may be made as an aid to finishing.

6.4 FORM VIBRATORS

Form vibrators are normally called 'external' vibrators and are useful with complicated members or where the reinforcement is highly congested. They are clamped to the outside of the formwork and vibrate it, thus compacting the concrete contained inside the form (**Figure 13.11**).

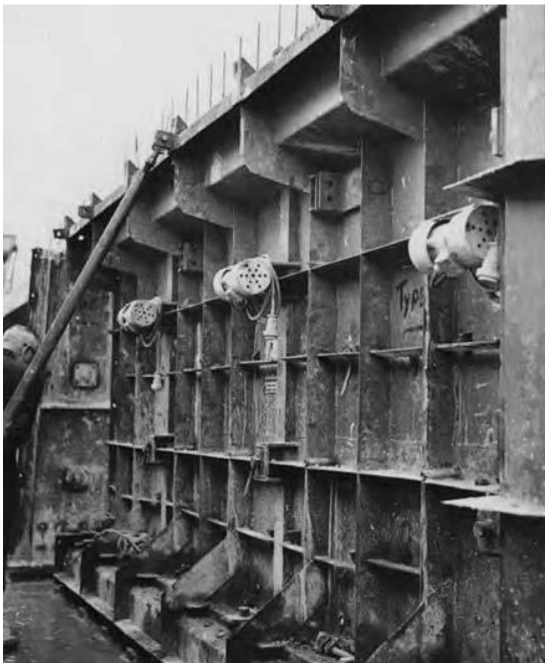

Figure 13.11- Electric Form Vibrators attached to the Steel Formwork of a Bridge Girder

Since form vibrators impose large forces on the formwork it requires special design and construction methods. Determining the positioning of the vibration units requires skill and experience. For all these reasons, the use of form vibrators is most common in the manufacture of precast members and products in a factory environment.

When consideration is being given to using form vibrators, the fact that air bubbles tend to migrate towards the source of vibration should be understood. Hence, if a high standard of off-form surface finish is important, careful consideration must be given to the location of form vibrators.

For some products, formwork may be clamped to a vibrating table – i.e. a rigid unit isolated from its supports by springs, neoprene pads or similar means – which is set in motion by vibrators attached to it. The whole unit, including the formwork, then vibrates to compact the concrete. These units are most commonly used in the manufacture of concrete products, where, with very stiff mixes, pressure may also be applied to the surface of the unit to compact it (e.g. the manufacture of concrete blocks).

7. UNDER-VIBRATION AND OVER-VIBRATION

Normal-weight concretes, which are well proportioned, are not readily susceptible to defects caused by over-vibration. If they occur, such defects result from segregation and are characterised by an excessive thickness of mortar on the surface of the concrete. The surface may also have a frothy appearance. Over-vibration may cause problems when grossly oversized vibration equipment is operated for an excessive length of time but is more likely to be problematic with poorly proportioned mixes or those to which excessive amounts of water have been added.

When signs of over-vibration are detected, the initial reaction may be to reduce the amount of vibration. The proper solution is to adjust the mix design.

Under-vibration is far more common than over-vibration and, when it occurs, can cause serious defects. Invariably, under-vibrated concrete is incompletely compacted which reduces its strength, its durability and possibly adversely affects its surface finish.

Despite this, many specifications contain a caution against over-vibration (and even define a length of time for vibration that must not be exceeded) while neglecting totally the question of under-vibration.

8. REVIBRATION

Re-vibration of concrete is the intentional systematic vibration of concrete which has been compacted some time earlier. It should not be confused with the double vibration that sometimes occurs with the haphazard use of immersion vibrators or multiple passes of a vibrating-beam screed.

While it is generally agreed that re-vibration of concrete can be beneficial to its strength, its bond to reinforcement and its surface finish, the practice is not widely used, partly due to the difficulty of knowing just how late it can be applied. A good 'rule of thumb' is that re-vibration may be used as long as the vibrator is capable of liquefying the concrete (and sinking into it under its own weight).

Situations in which re-vibration may be beneficial include:

- To bond layers of concrete into those preceding them. In elements such as walls, deep beams and columns, which are being filled in successive layers, the vibrator should penetrate the previous layer;
- To close plastic shrinkage and settlement cracks. These form within the first few hours of concrete being placed and can sometimes be closed by vibration. However, a reasonable level of energy input is required since mere reworking of the surface may simply close the cracks superficially. They will then reopen as the concrete dries out;
- To improve the surface finish at the tops of columns and walls by expelling the air which tends to congregate there as the concrete settles in the formwork;
- To improve the wear resistance of floors. Re-vibration, coupled with hard-trowelling, helps to create a dense wear-resistant surface layer.

9. SUMMARY: SURFACE DEFECTS FROM CONCRETE PLACEMENT AND COMPACTION

Defects	Causes		
	Plastic Concrete Properties	**Placement**	**Compaction**
Honeycombing	Insufficient fines, low workability, early stiffening, excessive mixing, too large an aggregate for placing conditions.	Excessive free fall, too thick a layer (lift) of concrete in forms, drop chute omitted or of insufficient length, too small a tremie, segregation due to horizontal movement.	Vibrator too small, too low a frequency, too small an amplitude, too short immersion time, excessive spacing between immersions, inadequate penetration.
Air surface voids	Lean sand with a high FM, low workability with low FM sand, excessive cement content, particle degradation, excessive sand, high air content.	Too slow, caused by inadequate pumping rate, undersized bucket.	Too large an amplitude, external vibration inadequate, head of vibrator only partially immersed.
Form streaking	Excess water or high slump.	Improper timing between placing and timing.	Excessive amplitude or frequency for form design.
Aggregate transparency	Low sand content, gap-graded aggregate dry or porous, excessive coarse aggregate, excessive slump with lightweight concrete.		Excessive external vibration, over-vibration of lightweight concrete.
Subsidence cracking	Low sand, high water content, too high slump, poorly proportioned mix.	Too rapid.	Insufficient vibration and lack of re-vibration.
Colour variation	• Non-uniform colour of materials, inconsistent grading, variation in proportions, incomplete mixing; • Calcium chloride can cause darker colour; • Variable or too high a slump.	Segregation (slump too high).	Vibrator too close to form, vibration next to forms variable, over-working of the concrete.
Sand streaking	Lean over-sanded mixtures and harsh wet mixtures deficient in fines.	Too rapid for type of mix.	Excessive vibration, excessive amplitude, over-working the concrete.
Layer lines	Wet mixture with tendency to bleed.	Slow placement, lack of equipment or manpower.	Lack of vibration, failure to penetrate into previous layer.
Form offsets	Excessive retardation of time of setting of concrete.	Rate too high.	Excessive amplitude, non-uniform spacing of immersion, horizontal movement of concrete.
Cold joints	Too dry, early stiffening, slump loss.	Delayed delivery, layers (lifts) too thick.	Failure to vibrate into lower layer (lift), insufficient vibration.

***NOTE**: Adapted from ACI Committee 309 Report 'Consolidation-Related Surface Defects ACI 309.2R – 98', ACI Manual of Concrete Practice, Part 2.*

10. RELEVANT AUSTRALIAN STANDARDS

1) AS 1379 – *Specification and supply of concrete*
2) AS 3600 – *Concrete structures*

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