Mechanical Equipment for Consolidation of Concrete

By Ken Weden

INTRODUCTION

The lower the water content of concrete, the stronger, more durable, and less susceptible to shrinkage will be the finished product. Concrete with a low water content generally means concrete with a thick consistency or low slump. When low slump concrete is placed, it is in a honeycomb condition, consisting of mortar coated coarse aggregate and entrapped air. The amount of entrapped air will vary with different mixes, size, and shape of forms, amount of congestion (reinforcing steel), and the method by which the concrete is placed. Generally, the amount of entrapped air is in the range of 5% to 25%. This does not include the entrained air - minute air bubbles purposely induced into the mix usually by use of an admixture. If the concrete were allowed to cure in this condition, the result would be concrete that is weak, porous, and poorly bonded to any reinforcing steel. Appearance of the honeycombed concrete would be unacceptable, especially in the case of architectural concrete. To get the most out of the concrete, in terms of strength, durability, and appearance, the entrapped air must be removed.

Before mechanical vibrators were available, tamping and spading were the methods used to densify fresh concrete. Those methods involved extensive labor and were only marginally effective. Mechanical vibrators became available in the 1930's when it was discovered that freshly placed concrete, even low slump, dry concrete would flow almost like water. The entrapped air would rise to the surface and escape, if it was subjected to vibration.

Keywords: compacting; concretes; consolidation; fresh concretes; vibration; vibrators (machinery)

VIBRATOR SELECTION

Efficient consolidation of concrete requires the equipment to be geared for the job at hand. Equipment should be selected on the basis of available power and the amount of concrete to be consolidated. If there is electrical power at the job site, flexible shaft electric vibrators might be a good choice. If, on another site, there are large air compressors, pneumatic vibrators would make sense. In the case of road or airport runway paving, the use of hydraulic vibrators might be the best choice since the hydraulic system used to propel the paving machine can also be used to power the vibrators. When there is inadequate power available on the job site, a gas or diesel engine powered vibrator would be a good choice.

The amount of concrete to be consolidated should also be considered. A vibrator that is too small will be very inefficient, requiring more man hours. Inadequately consolidated concrete is also a possibility when using an undersized vibrator. If a vibrator is too large for the job, segregation of coarse aggregate may occur. When working with forms, the use of an oversized vibrator may result in damage to the forms.

VIBRATOR CLASSIFICATIONS

Concrete vibrators fall into one of two classifications; internal or external.

Internal Vibrators--usually referred to as poker or spud vibrators which consists of a vibrating head, a universal motor, and a flexible shaft. Some manufactures harden the head for longer life. Within the head, is a rotor consisting of a shaft with an eccentric or off-balance weight. As this eccentric weight is turning within the vibrator head, the eccentric weight causes the head to wobble in an orbital fashion. The heavier the head, and the more offset the eccentric weight, the more force the unit will develop and transmit to the wet concrete. The head of an internal vibrator is immersed directly in the freshly placed concrete.

The force that causes the eccentric weight to rotate can come from many sources.

Flexible shaft vibrators have the vibrator head some distance away from the motor providing the power. Generally, the length of the flexible shaft is between 2 and 20 feet (0.6 to 6m). The flexible shaft is comprised of a rubber outer casing, with a steel reinforcing liner. Within this liner, rotates the core, which consists of a shaft made of several layers of steel wire, wrapped in the direction to avoid unraveling during operation. The motor that turns the flexible shaft can be electric, or it can be a gasoline engine.

The electric motors are usually able to operate on V-Ac or V-Dc current, 120 volts, single phase, 60 Hertz. When operated without a load, these motors will rotate as fast as 20,000 revolutions per minute (r.p.m.). When the motor is connected to a vibrator head by means of a flexible shaft, and the head is immersed in freshly placed concrete, the speed of the motor will be about 10,000 / 11,000 r.p.m., which gives us 10,000 / 11,000 vibrations per minute. The electric flexible shaft vibrator is the most popular type, if electrical power is available. When electricity is not available, a gasoline or diesel engine can be connected to a flexible shaft vibrator. The gasoline or diesel engine operates at only 3,400 r.p.m., therefore, a step-up transmission is necessary to achieve an output speed of 10,000 r.p.m. Where electric power is not abundant, or where portability is an advantage, there is a 2-cycle gasoline engine, mounted on a backpack, that operates in the 10,000 r.p.m. range, thus eliminating the need for a step-up transmission. With these units, as with other 2-cycle engines, oil must be mixed with the gasoline in the proportions recommended by the manufacture. There is no worry of tripping over an extension cord with these units, but they are very noisy, so ear protection is recommended.

Another form of an electric vibrator is the motor in head type. This type is restricted to a High-Cycle motor. High-Cycle vibrators operate on three phase power at 180 Hertz. High-Cycle vibrators experience far less drop-off in speed when immersed in concrete. The High-Cycle vibrator requires a High-Cycle generator to operate. In this country, vibrators and generators are available in 120 and 230 volt configurations - overseas, the 42 volt models are popular. The vibrator head is connected to the generator by approximately 20 feet (6m) of electric wire which is encased in a heavy rubber hose. The hose provides protection to the wire and aids in handling the vibrator.

If there are large air compressors on a job site, or if you are working with mass concrete, pneumatic vibrators might be the right choice. Pneumatic vibrators are available in larger head sizes, up to 6 inches (150mm) in diameter, than flexible shaft vibrators. The frequency of pneumatic vibrators can be varied by controlling the air pressure. If pneumatic vibrators are used with filters and oilers on the air lines, very little maintenance should be required.

Hydraulic vibrators which are connected to a paving machine's hydraulic drive system by high pressure hoses, use gear motors to turn the eccentric rotor. The frequency of these vibrators can be adjusted by regulating the flow rate and pressure of the hydraulic fluid.

Internal vibrator heads are available in various shapes and sizes. The round shape is the simplest to manufacture. Square heads provide more surface area than a round head of the same size. It is suggested that the square head, with more surface area, can transfer energy to the fresh concrete more efficiently. Vibrator heads are available from 3/4" (20mm) diameter to about 6" (150mm) diameter. The typical vibrator head is from 10 to 12 (250 to 300mm) inches long, a shorter head, about 4-1/2 (115mm) inches long is available for special applications such as tilt-up walls. Vibrator heads are available with rubber tips to minimize damage to forms.

External Vibrators--Large slabs such as bridge decks, floors, and pavements require vibration and leveling. This can be accomplished with a vibrating screed. A beam is mounted on rollers with a vibration mechanism attached to the beam. The beam contacts the concrete and the vibration is transmitted to the concrete over the entire length of the beam. The screed is moved forward to strike-off and consolidate the concrete in one operation.

Another type of external vibrator is the form vibrator which is attached to the outside of the form. Vibration is transmitted through the form walls to the freshly placed concrete in the form.

When molds are used rather than forms, they are usually placed on a platform or table. External vibrators are attached to the platform and the vibration is transmitted from the table thru the mold to the concrete.

VIBRATOR MAINTENANCE

All mechanical devices require maintenance to keep them operating efficiently and reliably. Concrete vibrators are no exception. The concrete vibrator is probably the most neglected, abused, and maligned tool there is. When a concrete vibrator fails, improper, or inadequate maintenance can usually be traced as the cause of the failure. Each type of vibrator, pneumatic, hydraulic, and electric have maintenance requirements unique to that type. Pneumatic vibrators require dry air to operate efficiently. When air is compressed, the moisture condenses and forms water in the air lines and in the tools. If this moisture is allowed to remain in the tool, a failure is sure to insue. Impurities in the water can scratch the inner surfaces and destroy the seal necessary for proper operation. Drier/filters should always be used. An oiler in the air line will keep the working parts of the vibrator lubricated.

Flexible shaft vibrators have several areas that require attention. The electric motor on a flexible shaft unit requires inspection after each use to insure the unit will operate the next time it is used. Attention to the filter is required to make sure it is not clogged or missing. The brushes in an electric motor are subject to wear and should be checked at regular intervals. It is far less expensive to replace brushes than to replace the armature or the whole motor just because the brushes weren't checked. The flexible shaft requires cleaning and lubricating to insure that it is not grinding itself up. If a flexible shaft has been bent at too sharp an angle, the casing will kink causing premature failure. The vibrator head should also be checked at regular intervals. The bearings are under a tremendous load. Therefore, seals that keep the oil in and the concrete out must also be checked.

High-Cycle vibrators require attention in several areas. The hose which connects the switch to the head, within this hose are the electrical wires. If this hose wears thru at any point such as where it has come in contact with rebars, moisture, or concrete will enter the hose and could cause a short circuit which would damage the head. In this country, High-Cycle vibrators are designed to operate on one of two voltages, 115 volt-3 phase or 230 volt-3 phase. The voltage of the vibrator must be matched to the voltage of the generator, or a failure will occur.

All types of vibrators should be cleaned after use. They should be inspected for wear and any worn or damaged part replaced, before that tool is used again. It is much less expensive to replace one or two parts, at that time, than to replace the entire tool later. If tools are maintained properly, it is far less likely that they will malfunction while they are in use. Even with proper maintenance, tools do fail, for any number of reasons. That is why it is important to have spare vibrators available at all times.

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Consolidation of Concrete in Congested Areas at Darlington N.G.S.

By Dan Bonikowsky

Synopsis: Placing concrete for a CANDU Nuclear Power Plant has become a concrete superintendent's nightmare. He has to devise placing methods that will allow quality concrete to be placed through highly congested reinforcing steel and around a multitude of embedded parts so that all the requirements of the specification are met.

Some of the problems experienced while placing concrete at the Ontario Hydro Darlington Nuclear Generating Station, located on the north shore of Lake Ontario, are described. Also presented are the novel placing methods and procedures used to overcome the placing problems to obtain the resultant quality concrete. With the ever-growing demands in the design of concrete structures that are needed to withstand higher seismic loadings, there has been a steady increase in the amount and diameter of reinforcing steel. Three or four curtains of rebar on all faces along with extensive use of tie bars, shear bars and continuous lengths of rebar leave little access space for the placement of concrete which must be dense and have low shrinkage and creep characteristics.

Most of the concrete can be considered mass concrete because of its large dimensions. Placements in narrow walls have particular congestion problems and also require a slow placing rate due to formwork design limitations. Methods of achieving good consolidation and controlling time of set are described.

The Design Engineer's requirements can only be met if the construction forces can resolve the placing problems by using unusual methods and procedures and taking full advantage of various concrete mixtures and admixtures that are available.

Keywords: concretes; consolidation; cooling; fresh concretes; mass concrete; nuclear power plants; placing; quality control; setting (hardening)

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INTRODUCTION

The Darlington Nuclear Generating Station is located on the north shore of Lake Ontario about 30 miles (50km) east of Toronto, Ontario, Canada. The station will be comprised of four 881 megawatt Candu Nuclear units. The concrete placing program started in the fall of 1981 and will be substantially complete by 1989. The total volume of concrete will be about 1,000,000 C.Y. (765,000m^3).

Due to seismic considerations, all concrete on the project is heavily reinforced. (Fig. 1). The overall average weight of reinforcing steel per cubic yard of concrete is 273 lbs. (162kg/cubic metre). In containment and safety related areas, where extra protection is required, the average is 438 lbs./C.Y. (260 kg/ cubic metre).

Embedded parts are also a major impediment to the consolidation of concrete. (fig. 2). Using Reactor Building #2 as an example, the weight of embedded parts installed for 61,500 C.Y. (47020 cubic metres) of concrete was 1,742,065 lbs. (791 848kg).

This paper describes the innovative techniques and methods used to overcome the problems encountered in properly consolidating the concrete to ensure quality concrete in these highly congested placements at the Darlington Nuclear Generating Station. The problems of consolidation and maintenance of quality are attacked from five basic directions. The five major considerations are:

- Quality Control & Quality Assurance
- Mix Design
- Admixture Usage
- Placing Techniques
- Consolidation techniques

When the fourth unit at Darlington is completed in 1992, Ontario Hydro will have built 20 nuclear units over 500 megawatts each. Most of the concrete placed in these units is of the 3000 to 5000 P.S.I. (21 to 35MPa) strength range. The main thrust of the specifications is for top quality with minimal shrinkage and creep characteristics, ensuring complete containment and shielding, rather than high strength only.

QUALITY CONTROL & QUALITY ASSURANCE

Prior to the placement of concrete in any given pour, the work required to complete the formwork is closely controlled by use of a "work progress card". Each appropriate trade foreman must sign the work progress card as work is completed. After the engineering verification has been made, the Engineer countersigns each trade signature. The Engineer then issues an "Approval to Pour" card. Prior to release, the concrete control staff check for cleanliness, form tightness and adequacy of the placing method.

A Concrete Control Inspector is assigned to each pour. All loads of concrete not discharged within one hour, after the addition of the mixing water, are rejected. The inspector checks each load for air content, slump, unit weight and temperature. The inspector also measures and supervises the addition of the superplasticizing admixture, when required, into the concrete at the point of unloading. Test cylinders are taken in accordance with requirements of the specification. Daily concrete placing reports are prepared by the inspector detailing all aspects of each pour and the mixtures used.

To minimize the risk of cracking due to excessive rise in temperature during early heat of hydration, a time interval between adjacent placements was established. This was accomplished by laboratory analysis along with field temperature measurements of placed concrete. A graph, shown in exhibit 'A', was developed to establish the time interval between adjacent pours. This graph correlates the specific cement being used and the thickness of the adjacent placement.

Extensive use of type II and IV cements is made at Darlington. Of the 137,000 C.Y. (105 000 cubic metres) of concrete placed at Darlington G.S. in 1985, 72% contained type IV cement, 20% contained type II and only 8% contained type I.

MIX DESIGN

Wherever possible, the mix designs at Darlington G.S. call for a maximum size aggregate of 1½" (40mm). However, due to extreme congestion of reinforcing steel and embedded parts, provision is made in the specification to replace a portion of the mix with a smaller size aggregate.

Where the concrete design mix is 3500 p.s.i. (25 MPa) with a maximum size aggregate of 1½" (40mm), the specification allows for substitution of a portion of the concrete (in practice about 20-30%) with 4000 p.s.i. (28 MPa) design strength and ¾" (20mm) maximum size aggregate.

In narrow, heavily congested wall sections, where the design mix is 3500 p.s.i. (25 MPa) and an allowable maximum size aggregate is ¾" (20mm), the specification permits a substitution of a portion of the concrete with a 4000 p.s.i. (28 MPa) mix containing maximum size aggregate of ½" (14mm). The combination of increased cement and smaller aggregate greatly enhances the consolidation operation. There is also a general provision in the specification to use up to 5% flyash for pumpability and workability, but not as a cement replacement.

The maximum allowable placing temperature is closely controlled. All concrete that is designated as 'cool' concrete must not exceed a placing temperature of 65 F (18 C). The specifications for the ring girder and dome of the Vacuum Structure (a unique part of the CANDU system) specify a maximum placing temperature of 60 F (15 C). This low temperature was accomplished by using 125 lbs. of shaved ice per C.Y. (74kg/cubic metre) of concrete.

ADMIXTURES

The Darlington Nuclear plant is the first plant in Ontario to make extensive use of superplasticizing admixtures in containment structures. Depending on the situations, the superplasticizer is used both with or without air entrainment. It is also used in conjunction with a water reducing agent. The water reducing agent dosage is cut in half when used in conjunction with the superplasticizer. The combining of a normal water reducer with the superplasticizer has proven to be very effective.

In all cases, the superplasticizer is added to the mixture at the form just prior to discharge from the truck and supervised by the Concrete Inspector. With formwork rate of rise restrictions as low as 3.6 feet (1.1 metres) fluid head, some problems have been encountered in the concrete reverting to its design slump of 3" (75mm) prior to placement in the form. In recent months, a superplasticizer with a built in retarder has successfully been used. The product increases the time prior to reversion from 30-40 minutes to 70-80 minutes. Test mixes have also shown that double dosing the normal water reducing agent will double the time of set.

PLACING TECHNIQUES

The design of the rebar and embedments at Darlington G.S. has made it necessary to dispense with many of the more traditional methods of placing such as hoppers and trunks and crane and bucket.

On average, there is 98 lbs./C.Y (58kg/cubic metre) more reinforcing steel at the Darlington project compared to the previous project built by Ontario Hydro at Bruce G.S. At previous projects, it was common to have dowels projecting only about 3 feet (1 metre) above placements to tie to the next lift. The design at Darlington makes extensive use of continuous bars projecting up to 33 feet (10 metres) above the pour elevations. (Figure 3). This design requirement seriously limits access at the top of the form for placing concrete.

About 90% of the concrete is placed with concrete pumps, very often in conjunction with placing booms. The standard procedure is to attach a wire reinforced hose to the end of the boom. The hoses vary in length from 8 to 40 feet (2.5 to 12 metres). (Figure 4) Depending on the density of the rebar, the hose diameters used are 4 or 5 inch (100 to 125mm). The hose is lowered down through the rebar as close to the final placement as possible. The hose is retracted by the boom and reinserted as the placing lift moves across the form. The concrete placing foreman is in constant radio communication with the placing boom and pump operators. Each placing crew is on a separate radio frequency. These portable radios have 6 channels. There is a separate channel for each of four placing crews, one for communications with the redi-mix supplier and one for the concrete quality control group.

The project presently has 5 truck mounted concrete pumps. Three model BPL 801's with 92ft. (28m) booms. One model BPL 801 with 105ft. (32m) boom and one model