

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

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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 v

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.

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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 ensue. 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.

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. (765,000m³).

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 super-plasticizing 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 $1\frac{1}{2}$ " (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 $1\frac{1}{2}$ " (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 $\frac{3}{4}$ " (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 $\frac{3}{4}$ " (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 $\frac{1}{2}$ " (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

BPL 1201 with 118ft. (36m) boom. 4" (100mm) pipelines are used with mixtures containing maximum $\frac{3}{4}$ " (20mm) aggregate and 5" (125mm) line for mixtures containing $1\frac{1}{2}$ " (40mm) aggregate. Some placements have required up to 600 ft. (183m) of pipeline. Before each placement is started, grout is pumped through to "slick" the line. Four placing booms are moved back and forth on six strategically placed masts. The placing booms are lifted by tower cranes which overlap on their swing radii which allow placing booms to be moved in less than 3 hours.

In many extremely congested forms, even the hose is too large to penetrate the available openings. In these situations, an extremely pliable hose material called "lie flat" hose has been used. The material is purchased in rolls and cut to length as required. The material is threaded down through the rebar to conform to the size of the available openings. (Figures 5 & 6). As the concrete rises in the form, the lie flat hose is cut off with a knife since it is not possible to raise it out of the steel once it has concrete in it. The cutoff piece is then removed through a side port in the form. Close radio communication is required with the pump operator to stop the pump if the hose becomes plugged.

CONSOLIDATION TECHNIQUES

The problems encountered with consolidation of concrete in heavily congested forms are common to the form cleaning operation prior to the placing of the concrete. It is a common practice to install cleanout ports in the bottom of wall forms to provide access for the purpose of cleaning and wet vacuuming. Just prior to concrete placing, the cleanout holes are sealed. In narrow wall forms, it is often impossible to thread the vibrators down to the bottom of the form. The practice at Darlington is to install placing ports (approximately 2 foot (.5m) square) on a 6 foot (2m) grid on one side form. The vibrators are inserted in the placing ports to consolidate the concrete. As the concrete reaches the level of the placing ports, the ports are bolted shut and the vibrators moved up to the next level of ports.

In many situations, it is necessary to hydraulically jack rebar apart for entry of personnel for both cleaning of the forms and consolidation of concrete. (Figure 7). As the concrete rises in the form, the rebar is replaced to its original location before being covered. At previous projects, it was possible

the vibrators across the breadth of the form under the upper mat. At Darlington G.S., the density of rebar precludes this method of operation. About twice the number of vibrators previously used are set up on top of the upper mat. All movement of vibrators must be accomplished by removing them vertically and re-inserting in a new location. The snagging of vibrators in the rebar is an ongoing concern. The most common vibrator used is 3" (75mm) in diameter and rated at 9 - 11000 v.p.m. in air. The 2" (50mm) vibrators are also used but are far less efficient. The vibrator operator must maintain a high level of concentration to ensure the vibrator head does not become snagged by the rebar. An average of 20 concrete placements are made per day. With the need to set up vibrators in advance to the start of pours and to accommodate maintenance requirements, it is necessary to have an inventory of 120 internal vibrators.

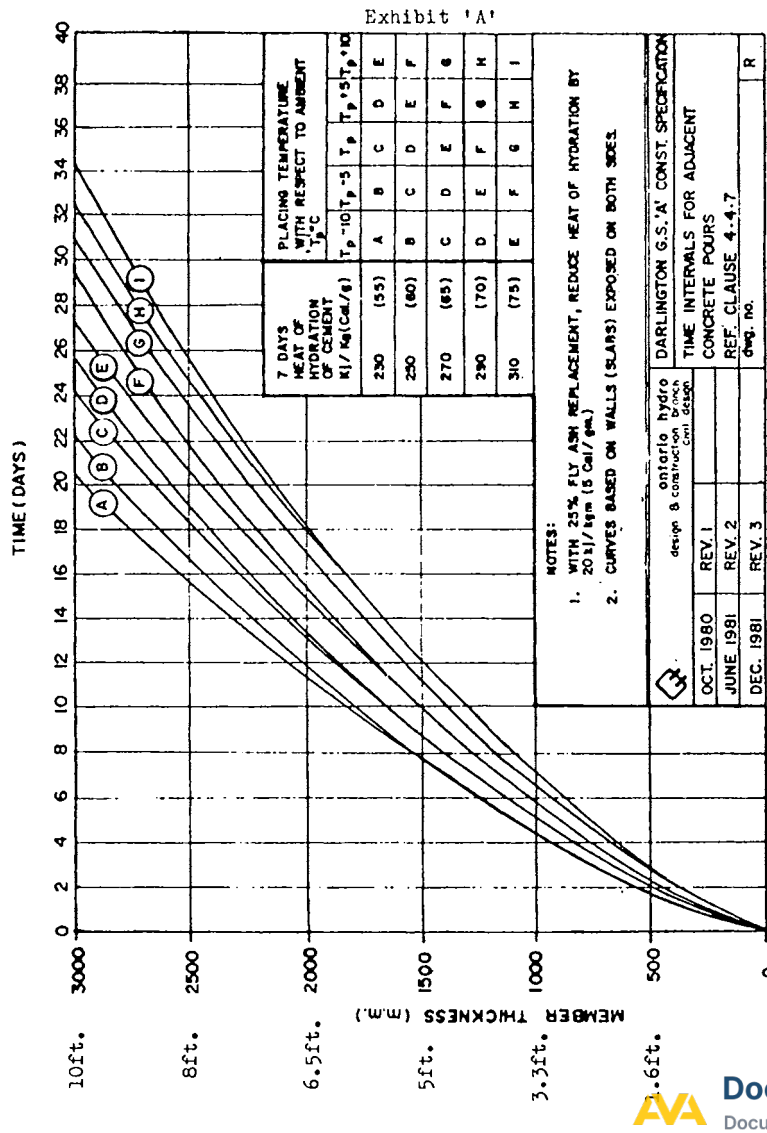
Most of the internal rooms in the reactor auxiliary bays and turbine auxiliary bays are designated as steamproof rooms. The walls must therefore be poured up tight to the underside of the structural steel beams. The top of the walls also have a 3" x 3" (75mm x 75mm) angle iron retainer for seismic considerations. With this type of form, slide valves are situated within 1 foot (.3m) of the top of the wall and the concrete is pumped in place under pressure.

Special consideration must be given to doorways or large embedded parts that span across wall forms. It is often necessary to cut holes in the bottom of the cut-out, both as an entrapped air release and to allow insertion of vibrators for proper consolidation. (Fig. 8) It is also good practice to pause for about an hour at the top of these embedments to minimize differential cracking. At recommencement of the placing operation, it is important that vibrators penetrate the previous lift. This re-vibration ensures a homogenous pour and minimizes cracks.

CONCLUSIONS

1. The requirement for dense reinforcing steel and numerous embedments in the design of nuclear plants in seismic zones, precludes the incorporation of features which could facilitate the placing and consolidation of concrete.
2. Tight engineering control during construction of forms and physical testing of the delivered concrete ensures quality concrete which meets the requirements of the Quality Assurance program.

3. The use of "cool" concrete, primarily type IV and type II cements, special admixtures, sound placing and consolidation techniques, good mix designs and control of time intervals between adjacent pours ensures quality concrete under extreme congestion conditions.



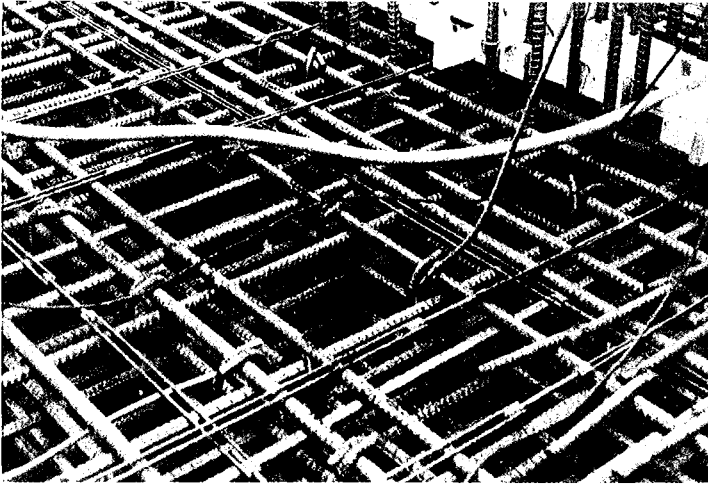


Fig. 1--Heavily reinforced reactor vault roof slab

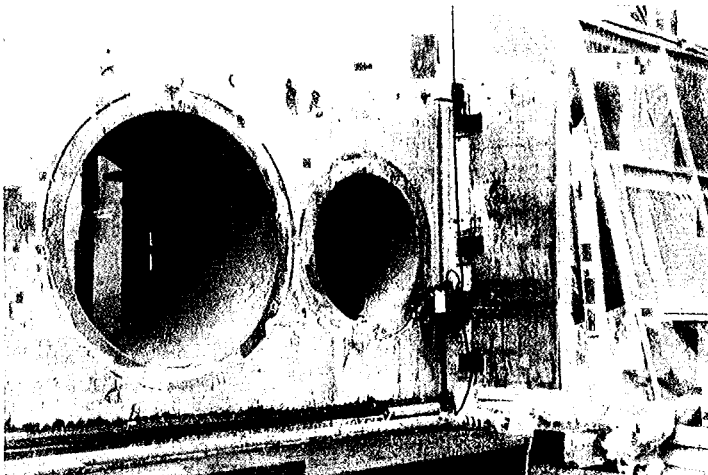


Fig. 2--Closely spaced embedded parts in wall

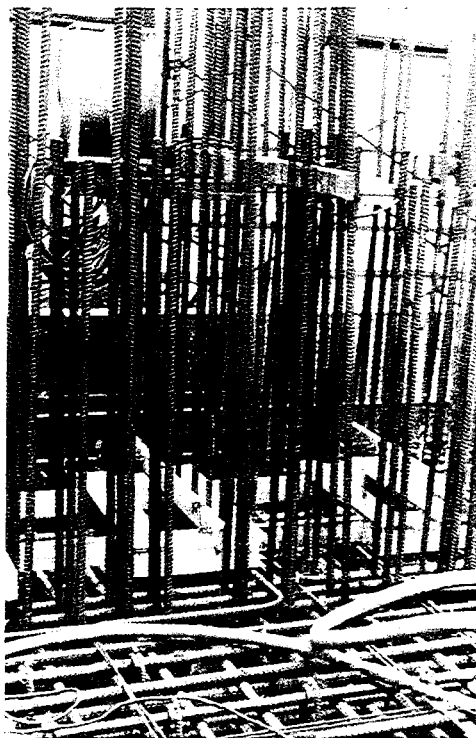


Fig. 3--Continuous bar above pour

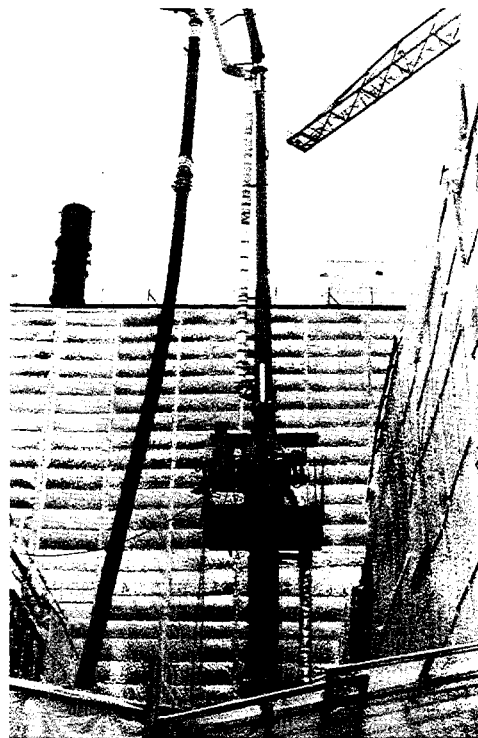


Fig. 4--Long wire reinforced hose attached to placing boom

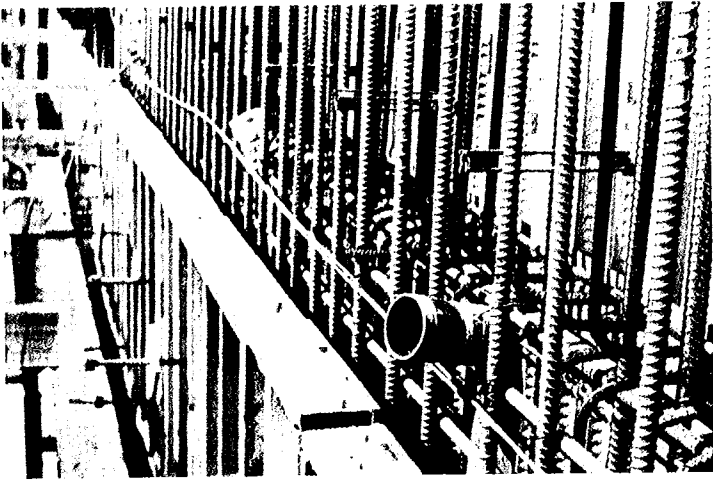


Fig. 5--Lie flat hose coupling installed in form

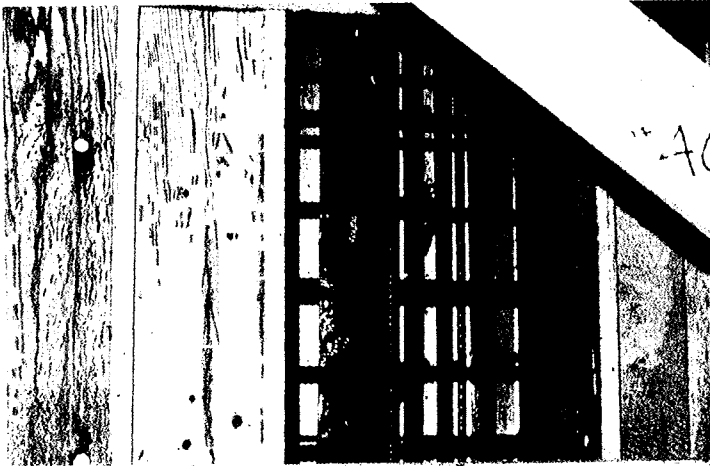


Fig. 6--Lie flat hose seen through side port



Fig. 8--Large stacked blockouts

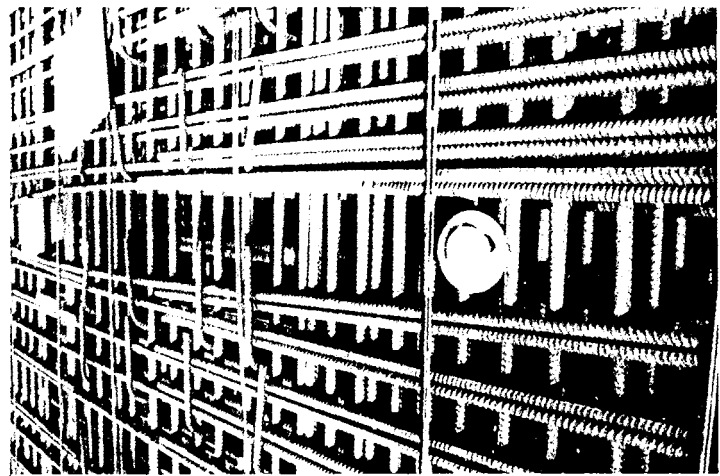


Fig. 7--Rebar jacked open and blocked for access

Need for Consolidation of Superplasticized Concrete Mixes

By Lars Forssblad

Synopsis: The subject of consolidation of superplasticized concrete with flowing consistency has been studied by, among others, the Swedish Cement and Concrete Research Institute and the Dynapac Research Department. A basic question is the need for consolidation with regard to different consistencies of the mix, different applications, etc.

The effect of internal vibration of superplasticized concrete mixes has been investigated in laboratory tests. The performance of internal vibration in practice is discussed. Surface and form vibration of superplasticized concrete have been studied in laboratory and field tests.

Keywords: admixtures; air entrainment; concretes; consolidation; fresh concretes; plasticizers; vibration; vibrators (machinery)

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INTRODUCTION

The use of superplasticizing admixtures is probably the most radical change within the concrete technology to have taken place in recent years.

Effective plasticizing agents have long been used to achieve fluid and stable concrete mixes. Superplasticizing admixtures enabling the use of concrete mixes with flowing consistency (slump > 8 in (200 mm)) were introduced in West Germany around 1970.

Despite their fluid consistency, correctly composed superplasticized concrete mixes have acceptable coherence and stability. Since the admixture provides a fluid consistency without the addition of water (followed by a reduction of the water-cement ratio) the strength of the hardened concrete is not affected.

Flowing concrete makes it easier to cast heavily reinforced structures and to deal with difficult concreting jobs. Flowing concrete offers opportunities for improved production capacity and economy both on construction sites and in precast concrete plants. The pumpability is good. A further advantage of flowing concrete is that it offers a better working environment in the form of reduced work loads.

A problem in connection with the use of superplasticized mixes has been the difficulty of obtaining a stable air-entrained pore system with sufficient volume. This has limited the use of flowing consistency in structures exposed to frost action. Combinations of certain types of superplasticizing and air-entraining admixtures can be especially unsuitable. A careful pre-testing is therefore necessary in design of frost resistant superplasticized concrete mixes.

A superplasticized concrete mix with flowing consistency is about 10 % more expensive than an ordinary plastic concrete mix with the same strength.

CONSISTENCY

Superplasticized concrete is not an exactly defined concept. In Sweden three consistency classes have been defined, see Table 1/1/.



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TABLE 1 - Consistency classes for superplasticized concrete

Definition	Slump		Spread (in drop-table test)	
	in	mm	in	mm
Semi-superplasticized	6-8	150-200	18-21	450-530
Full superplasticized	8-10	200-240	21-24	530-620
Extra superplasticized	>10	>240	>24	>620

So-called full superplasticized concrete is defined as having a slump test in the range 8 to 10 in (200-240 mm). Flowing concrete with a slump > 10 in has been defined as "extra superplasticized".

Semi-superplasticized concrete has been found to be a suitable and economical alternative for many types of concrete constructions. In practice, superplasticizing agents have in Scandinavia been used to about 75 % for concrete mixes with a slump between 6 and 8 in (150 and 200 mm).

When casting concrete floor slabs and precast products, superplasticized concrete with even lower slump, often of plastic consistency, is successfully used in order to obtain a workable mix with a high strength.

Including all the applications mentioned above, superplasticizing agents are today used for about 15 % of the total production of concrete in Sweden. The use is increasing. Observe, however, that fully superplasticized mixes with a slump > 8 in (200 mm) represent only a limited share of the total use.

The slump test is not a very precise method of consistency measurement, especially for flowing concrete, Fig. 1. It is therefore preferable to determine consistency using a flow (drop) table (DIN 1048). In this case the spread of the mix on the table is measured, Fig. 2.

CONSOLIDATION

When superplasticized concrete was first introduced it was sometimes claimed that no compaction was needed and that it was sufficient only to fill the form with the flowing mix.

It has been found, however, that to obtain acceptable results with regard to density, strength, reinforcement embedment, form filling and surface appearance, superplasticized concrete normally needs consolidation. The compaction should, however, be less intensive than for ordinary concrete. According to earlier studies and test results reported below, superplasticized concrete with flowing consistency needs only 20 to 50 % of the compaction work necessary for ordinary concrete.



Fig. 1--Slump test with flowing mix



Fig. 2--Consistency determined on flow (drop) table. The spread of the concrete is measured. The concrete sample is placed on the plate 28 x 28 in. (700 x 700 mm) with the help of a lower cone than that used in the slump test. The plate is hinged at one side. The opposite side is lifted and dropped 15 times from a height of 1.6 in. (40 mm).

Superplasticised concrete, as the name implies, flows out by itself. When filling formwork, however, a continuous and uninterrupted flow of concrete is important for the homogeneity of the mass.

In larger forms the filled-in superplasticized concrete is free from large voids but it still contains a number of medium-size and small air bubbles, normally say 3 to 5%. With light vibration this air void content can be reduced with 2 to 3% /2/. This will improve the strength of the concrete, as every percentage of remaining air voids caused by insufficient compaction decreases the strength by about 5% /3/.

The bond strength of the reinforcement bars in superplasticized concrete has been studied by the Swedish Cement and Concrete Research Institute (CBI) /1/. Without consolidation a certain reduction of the bond strength was obtained. About 20 % of the vibration required for ordinary concrete was sufficient to achieve satisfactory bond between the reinforcement and flowing concrete, Fig 3. Corresponding results were obtained at a study at the University of Kansas/4/.

Settlement cracks around the reinforcement were also observed in the Swedish investigations. Channels along the undersides of the reinforcement bars have been found, revealed by core drilling in uncompacted superplasticized concrete structures. As with conventional concrete, proper consolidation is important because of the risk for corrosion of the reinforcement.

In a Swedish guide/5/ it is recommended that placement of superplasticized concrete without compaction should be allowed only after careful testing of trial mixes in consultation with the designer and the authorities. Possible applications may be those in a non-corrosive environment where the reinforcement is not fully utilised structurally, as well as in completely unreinforced structures. One example is unreinforced concrete slabs.

One risk with the reduction or elimination of consolidation is that, in practice, there are always variations in consistency. Single batches with lower slump are more or less inevitable.

ACI Committee 309 recommends that the amount of consolidation effort required when using admixtures should be determined by trial mixtures under field conditions. (Draft to revised "Guide for Consolidation of Concrete.")

TESTS ON INTERNAL VIBRATION

Studies on the compaction of superplasticized concrete using internal vibrators have been done at the Dynapac Research Laboratory/6/. Test methods earlier developed for ordinary concrete have been applied, see Fig 4. A reference can be made to /7/.

Typical relationships between radius of action and time of vibration are shown in Fig 5. Normally the radius of action in superplasticized concrete is 20-30 % greater than in ordinary concrete with plastic consistency. The necessary vibration time

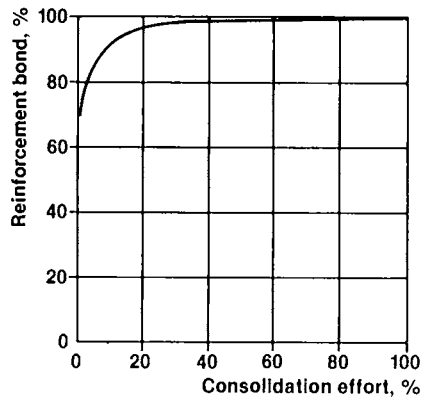


Fig. 3--Relationship between reinforcement bond and consolidation effort. 100 percent corresponds to normal vibration of ordinary concrete with a plastic consistency /1/.



Fig. 4--Standardized laboratory test for the determination of radius of action of an internal vibrator, using photos taken every second of the surface of the concrete.

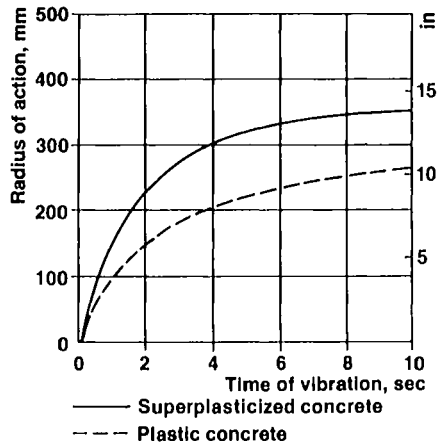


Fig. 5--Radius of action of an internal vibrator in superplasticized concrete and in ordinary concrete of plastic consistency. Tube diameter $1\frac{1}{2}$ in. (37 mm). Frequency 200 Hz (12,000 vibr/min). Amplitude 0.4 in. (1.0 mm).

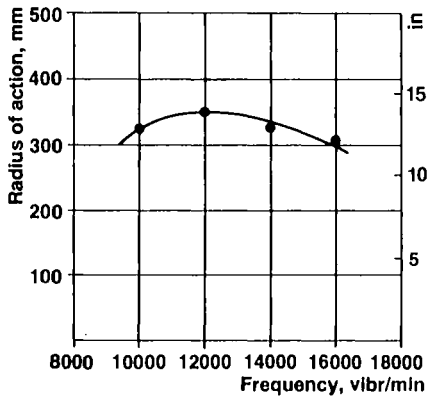


Fig. 6--Optimal frequency for internal vibration of superplasticized concrete. Tube diameter $1\frac{1}{2}$ in. (37 mm). Amplitude 0.4 in. (1.0 mm).

can be reduced by about 50 %. Compaction work will then be roughly 25 % of that required for ordinary concrete, in good agreement with the range of 20 to 50 % mentioned above.

A relevant question is whether the internal vibrators normally used also have optimal technical data - frequency, amplitude, diameter, weight, etc. - for the vibration of superplasticized concrete. Studies have therefore been conducted with different technical data of the vibrators to see whether there is a need for vibrators with frequency, amplitude, etc., especially adapted to superplasticized concrete.

For ordinary concrete and normal internal vibrators, a frequency of about 200 Hz (12,000 vibr/min) is optimal. This applies also to superplasticized concrete, as will be evident from Fig. 6.

Since superplasticized concrete requires less compaction work than ordinary concrete it may well be asked whether ordinary vibration equipment is also optimal for superplasticized concrete. Perhaps some form of puddling or pulsating type of compaction would be preferable? Some alternative forms of compaction have been studied at the Dynapac Laboratory but so far no better alternative to ordinary internal, surface or formwork vibration has been found. Tests involving vibration of the reinforcement bars have also been carried out, but this method did not appear to be practicable either.

INTERNAL VIBRATION IN PRACTICE

It has been shown that superplasticized concrete only needs say 25 % of the compaction work necessary for ordinary concrete. That does not mean, however, that the number of internal vibrators can be reduced to one fourth of the number required for ordinary concrete.

A reduction of the time for each insertion of the vibrator from, say, 10 to 5 sec. has only limited influence on the total capacity efficiency. The possibility of allowing larger distances between the insertion points has a greater influence on capacity. Thus a change from plastic to flowing consistency will allow about 50% higher capacity for an internal vibrator used in casting of ordinary wall and slab constructions, Fig. 7. In practice it has also proven suitable to use an internal vibrator that is "one size smaller" than would have been required for ordinary concrete in the same structure. Radius of action and capacity will be sufficient with a slightly smaller vibrator and the danger of segregation is reduced. With a smaller and lighter vibrator, the working load on the operator will be decreased.

One problem connected with internal vibration of superplasticized concrete, compared to ordinary concrete, is that the operator has greater difficulty in judging from the appearance of the surface of the concrete mix when the vibration is sufficient.

With regard to the compaction effort needed for internal vibration of superplasticized concrete in narrow, congested forms, the following example can be given. Slipform casting of a Norwegian offshore platform with heavy reinforcement, using superplasticized flowing concrete (slump >8 in, >200 mm) has been found to require a substantial compaction effort. The number of internal vibrators with a tube diameter of 2 in (50 mm) corresponds to a capacity of 4 cu yd (3 cu m) of concrete per hour for each vibrator. This value falls within the capacity range recommended by ACI committee 309 for ordinary concrete with plastic consistency. (Courtesy: Norwegian Contractors).

In concrete construction there has been a general development towards more fluid consistencies and higher casting capacities. In combination with underestimation of the need of consolidation, the vibration equipment has not seldom been underdimensioned with regard to the necessary number of internal vibrators. In a number of cases this has resulted in more or less severe casting defects. Observe also the need for reserve vibrator units.

SURFACE VIBRATION

Investigations made at the Dynapac laboratory have shown that the efficient depth effect of a vibratory screed in unreinforced superplasticized concrete with flowing consistency is about 10-12 in (250-300 mm). This is about 50% more than in ordinary concrete. The depth effect was determined by coredrilling.

FORM VIBRATION

Since superplasticized concrete requires less compaction work, it is also possible to use less powerful form vibration than usual. Superplasticized concrete can therefore drastically affect form vibration techniques. Normally, evenly distributed vibration over the form surface with an acceleration of 1-2 g is desired. In the case of superplasticized concrete an acceleration of about 0.5 g will suffice.

When placing ordinary concrete in large forms, high frequency vibration in the 100-200 Hz range (6,000-12,000 vibr/min) is required to achieve evenly distributed vibration over the entire form surface, as well as to obtain surfaces that are sufficiently free from air voids. High-frequency form vibration is not normally required for superplasticized concrete.

Since superplasticized concrete requires less intensive vibration, the noise level is also distinctly lower. Form vibration of ordinary concrete with vibrators operating at standard frequencies (50 or 60 Hz, 3,000 or 3,600 vibr/min) often gives rise to noise levels in the region of 100 dB(A). This can be reduced to 85-90 dB(A) when using superplasticized concrete. The human ear perceives the noise as being 2-4 times less intensive. A comparison with high-frequency form vibration is even more favourable.

An extensive study into form vibration of superplasticized concrete used for building single-family houses with tunnel forms has been initiated

by the Swedish company ABS-Gell and implemented jointly by this company, CBI and Dynapac, /8/.

Standard-frequency external vibrators were used. The walls could be filled to full height before vibration. The floor slab form was also fully filled before all vibrators were started. The homogeneity of the concrete, formwork filling and concreting round the reinforcement were satisfactory. No visible settlement cracks arose in the joints between walls and floor slab.

When casting is done in tunnel forms with form vibration and superplasticized mixes, trowelling of the surface without prior internal and surface vibration represents a labour-saving alternative, Fig 8. When internal vibration of walls and floors and surface vibration on the floor were replaced by form vibration, placement work was reduced by about 80 %. The cost for superplasticizing admixture and external form vibrators result in additional expense and therefore the total cost in this case was largely the same for both alternatives.

Working conditions are naturally improved when an hour of internal vibration is replaced by 15 minutes of form vibration at a noise level of only 85 dB(A).

A problem associated with the form vibration of superplasticized concrete was an increase in surface porosity compared to internal vibration. On the other hand, the pores were shallower.

Our experience is that superplasticised admixture generally speaking is not particularly effective

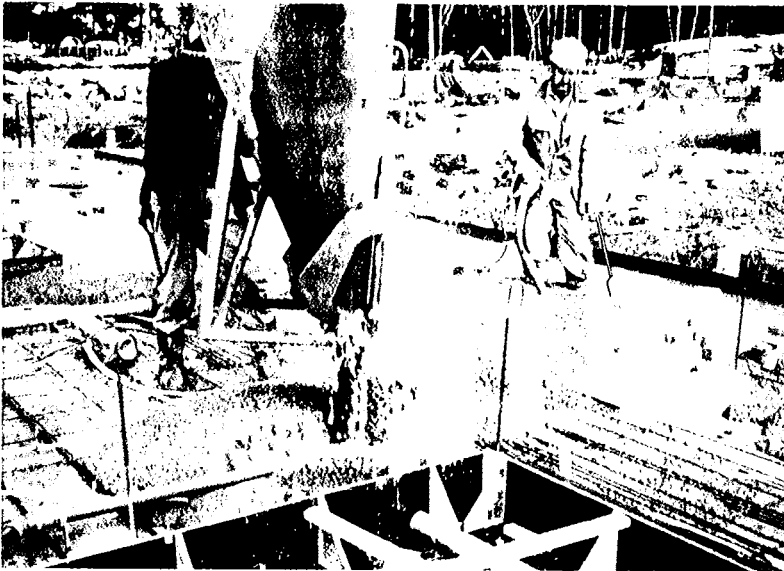


Fig. 7--Slab construction with superplasticized concrete mix. The operator of the internal vibrator also measures the thickness of the slab. Alternatively, laser levelling can be applied.

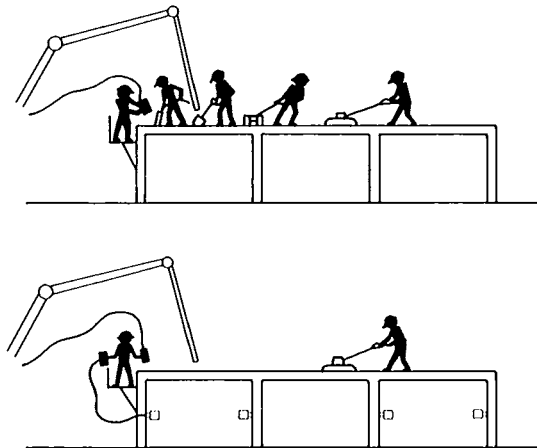


Fig. 8--Conventional internal and surface vibration compared with form vibration in tunnel forms.

with regard to achieving surfaces free from air voids. However, this is a complex problem in which layer thickness during placement, compaction, form material, type of form oil, etc. all come into play. The effects of all the factors involved are still insufficiently known.

Form vibration of superplasticized concrete has also been used with good results and to an increasing extent for the prefabrication of concrete building elements. As mentioned above, a superplasticizing admixture in combination with concrete of plastic consistency is often used in this case.

CONCLUSIONS

Superplasticized concrete with flowing consistency (slump > 8 in (200 mm) normally needs consolidation.

In superplasticized concrete the radius of action of an internal vibrator is 20-30 % greater than in concrete of plastic consistency, and the vibration time can be reduced by about 50 %. Compaction work can thus be reduced to about 25 % of the amount necessary for ordinary concrete.

In practice, however, the possible reduction of the number of vibrators has been found to be rather limited. The practical application has in many cases been to use an internal vibrator "one size" smaller than that used for ordinary concrete.

Observe especially the need for efficient vibration of superplasticized concrete in narrow congested forms. Internal vibrators with an appropriate frequency for ordinary concrete are also suitable for superplasticized concrete.

For form vibration of superplasticized concrete a minimum acceleration of 0.5 g is sufficient, compared to 1-2 g for stiff plastic to plastic consistencies. As a result, the number of external vibrators can be reduced. A lower noise level is also possible.

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Consolidation of Continuously Reinforced Concrete Pavement

By Mikael P.J. Olsen

Synopsis: Current consolidation practices and a recently completed Laboratory investigation to determine the effects of coarse aggregate factor, maximum aggregate size, vibrator spacing, and the method of vibrator mounting on the achieved consolidation of CRCP is reviewed. Also reviewed are the theory and principles of consolidation by internal vibration. The parameters found to be of importance are the vibrator spacing, concrete mix design, and acceleration in the concrete. A vibratory spacing of 24 inch (610 mm) is required to produce adequate consolidation. The concrete mix should contain coarse aggregate with a top size 1 1/2 inch (40 mm) and a coarse aggregate factor determined by the Fineness Modulus Method of mix design. The superplasticizers with or without retarders have to be used with great caution due to slump loss making it difficult to consolidate the stiff concrete mixes used in slipformed paving construction.

Keywords: aggregate size; coarse aggregates; compacting; concretes; consolidation; continuously reinforced pavements; density (mass/volume); fresh concretes; plasticizers; vibration; vibrators (machinery)

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INTRODUCTION

Concrete pavements, placed with travelling form pavers, generally are made with extremely stiff, low slump mixes. Although both internal "spud" vibrators and surface "pan" vibrators are used, the resulting concrete may contain regions of insufficiently consolidated concrete. This is especially troublesome in continuously reinforced concrete pavement (CRCP) where the layer of reinforcing steel at mid-depth prevents insertion of the internal vibrators below the steel. Thus, the bottom half of the pavement has been found to occasionally contain large voids which weaken the pavement and ultimately cause premature distress and failure.

This problem is neither new or unique. Since the introduction of vibration in the 1930's (1), the subject of proper consolidation has received increased interest and attention. But the problem is still not resolved. The major reasons why the problem has not been resolved are 1) mixes have changed in recent years and 2) the research findings on consolidation have not been applied to slipformed CRCP.

Consolidation imparts many benefits upon the properties of the concrete: 1) it reduces the undesirable air voids (entrapped air), 2) it allows for a lower water content of the mix (2), 3) it reduces the permeability of the hardened concrete (3), 4) it increases the bonding to and reduces the corrosion of the reinforcement (2, 4, 5, 6), 5) it reduces drying shrinkage (2), 6) it may increase freeze-thaw resistance (even if some air-entrained voids are removed (3), 7) it is mandatory at construction joints where there is a congestion of reinforcing steel (3).

Since internal vibration is the most popular means of mechanical consolidation, an understanding of the internal vibrator is necessary. An internal vibrator consists of a head containing an unbalanced weight (eccentric) which is driven by a motor and caused to rotate at very high speeds (7, 8). The forces transmitted to the concrete during vibration act at right angles to the head of the vibrator (Figure 1). An internal

internal vibrator must efficiently consolidate the concrete mixes used on the job. It should be chosen by its head diameter (based on the size of the coarse aggregate, slump, and desired radius of action), frequency (which determines the liquefaction of the concrete), and amplitude (which determines the radius of action) (7, 9). Consideration should also be given to the centrifugal force and the horsepower of the motor (7).

State-of-the-Art for Internal Vibration of CRCP

There is general agreement in the literature that vibrator spacing on gang-mounted paving machines is a function of the radius of action, which is determined by head size, frequency, acceleration, type of reinforcement, vibration time, and degree of consolidation required (3, 7, 10, 11). Vibrators are typically spaced from 14 to 24 inches (355 to 610 mm) resulting in 97 percent consolidation based on rodded unit weight (AASHTO T121) (3, 7, 10, 11, 12). Air entrainment has not been substantially affected by vibration, and the benefits attained by adding air entrainment remain intact (3, 11, 12).

Aggregate size, shape, and uniformity influence the percentage of entrapped air voids for a given level of consolidation (10, 13). No research has been found regarding a variation of the coarse aggregate factor and its subsequent effect on consolidation. Frequency of the internal vibrators, while in fresh concrete, should be maintained between 8,000 and 12,000 vpm with an optimum level of 10,800 vpm (3, 7, 9, 11, 12, 15). The amplitude in air should be held between 0.025 and 0.050 inch (0.6 and 1.3 mm) (7, 12).

Slump must be maintained in the range of 1 to 2 1/4 inch (25 to 60 mm) and optimally should lie between 1 1/2 and 2 inch (40 to 50 mm) (3, 11, 12). Segregation has been found to be of little concern during even prolonged periods of vibration on stiff mixes, but if it should become critical, then a lowering of the slump value is recommended (14). Continued vibration has been determined to have very little effect on strength, other than directly in the path of the vibrator (11, 12). While vibration of the reinforcing steel has been found to aid in the bonding of the concrete to the steel, the net result can be reversed if the vibration of the steel is performed excessively (4, 14).

A paving vibrator should optimally have a head diameter of 2 to 3 1/2 inch (50 to 90 mm), a 0.5 to 0.7 in-lb (0.02 to 0.08 N-m) eccentric moment, and a variable frequency (4, 7). The physical properties of the concrete have, however, more influence on consolidation than the properties of the vibrator (15). A paving machine should be operated between 10 to 20 fpm (1 to 6

m/minute, and optimally maintained between 12 to 14 fpm (3.6 to 4.3 m/minute) (12, 15). Vibrators should be mounted horizontally above the reinforcement and as close to mid-depth as feasible (11). No research has been found concerning the influence of the position of the vibrators within the horizontal plane or with respect to the direction of travel of the paving machine.

It has been determined that the presence of chemical or mineral admixtures will affect the rheological properties of a concrete mixture. With the advent of superplasticizers there is a lack of information concerning their implications in the CRCP industry. There is a need for an understanding of their benefits and limitations.

Review of Selected Important Parameters

Consolidation Versus Depth in Pavement. It has long been the concern of those interested in the consolidation of CRCP that the concrete in the bottom of the CRCP slabs was not receiving adequate consolidation when compared to the concrete in the top of the slab. This concern is based on the fact that in most cases a CRCP slab contains a heavy mat of reinforcing steel at mid-depth which only allows the paving vibrators to be submerged to a position above this plane. For this reason, the vibrators are located in the top half of the CRCP slabs. Many researchers also believe that the reinforcement tends to dampen the effect of the vibrations as they are transmitted to the bottom portion of the slab, and lower the quality of consolidation below the reinforcing steel. Some research in this area tends to reinforce this concern. A study released by the New York State Department of Transportation in 1977 states that the top of the CRCP pavements was consolidated better than the bottom (15). However, also included in the 1977 study was that the use of a mesh depressor was found to contribute to the consolidation process. Since the mesh depressor pushes the steel down through the top of the CRCP slab to mid-depth, this influence would be more prevalently detected in the top portion of the concrete slab. The degree of the mesh depressor's contribution was not presented, therefore, the conclusion that the top of the slab was consolidated better than the bottom due to better vibration could be subject to question.

While concerns for the effectiveness of consolidation in the bottom of CRCP slabs are valid, there are also reasons to believe that, in fact, the concrete in the lower portion of the slab is subject to better consolidation than that in the top. It is generally accepted that concrete in the lower portion of a structure, such as that of a column, results in higher strength than the concrete above it. This is due to the loading produced

by the overburden which aids in the consolidation of the concrete under it. The upper concrete's weight helps to force the solid material down and either move the air up or compress it into smaller voids. This same effect can be applied to what happens during the consolidation of a thick concrete pavement.

Another factor to consider, is the force field which is produced by the paving vibrator. As can be seen from Figure 1, a paving vibrator produces forces at right angles to its head. Understanding that the vibrator is submerged in the top section of the CRCP leads to the conclusion that the forces acting on the concrete above the vibrator are acting upward. This will tend to force the concrete above the vibrator upward and counteract the forces of gravity that normally aid the consolidation process. As a result the consolidation will be inhibited and tend to produce a greater concentration of voids in the concrete above the vibrator.

In eight tests performed during a laboratory investigation at Texas A&M University, the concrete at the bottom of the simulated CRCP slabs was of significantly higher quality than that at the top of the slabs (5). The reasons for this finding were attributed to the weight of the overburden of concrete, air moving upward from the bottom of the slabs while the concrete is in the liquid state during vibration and getting trapped in the upper portion when the internal friction of the mix is restored. Other contributing factors include the upward forces produced in the concrete above the vibrators and dragging of the vibrators through the upper portion leading to a higher air void content in their paths, particularly if the paving speed is excessive (5).

Consolidation Versus Vibrator Spacing. Numerous research studies have determined that vibrator spacing on gang-mounted paving machines has a pronounced effect on the degree of consolidation attained in CRCP (3, 7, 11, 12, 14). The radius of action of a vibrator is defined as the distance away from a vibrator that the concrete can be adequately consolidated during the time period the vibrator remains in a particular position.

When investigating the spacing requirements of paving machine vibrators it is not enough to simply study the radius of action of a single vibrator submerged in fresh concrete. This method of study makes it impossible to determine the overlapping effect of the vibratory patterns experienced when two vibrators are mounted at various spacings. For this reason, a laboratory investigation designed to depict actual field conditions must incorporate the same vibratory patterns emitted by gang-mounted paving vibrators; thus, two or more vibrators must be studied simultaneously at various spacings. Another factor of importance is to insure that the vibrators used be of the same design and produce practically identical vibrators in the fresh concrete.

Research has shown that consolidation and strength decreases with an increase in the distance away from a single vibrator (3, 11, 12). For this reason, it can be assumed that the worst possible condition for consolidation effort will be located at the centerline between the spacing of two vibrators. Therefore, when studying the effects of various spacing requirements, data should be gathered at the center of the space between the vibrators, and an analysis made to determine if the reduction of void content is great enough to require a smaller spacing.

Data collected at Texas A&M University revealed that there was little statistical difference between void content of the concrete consolidated with any of the following three vibrator spacings, 12, 18, and 24 inch (305, 460, and 610 mm) (5).

Consolidation Versus Method of Mounting Paving Vibrators. Most current construction standards for CRCP specified a vibrator spacing of no more than 24 inch (610 mm) on slip-form paving machines (5). This 24 inch (610 mm) maximum spacing requirement is intended to be applied to the spacing of paving vibrators when mounted so that they are parallel to the direction of travel (see Figure 2a).

Presently, many CRCP paving contractors mount their vibrators perpendicular to the direction of travel (Figure 2b) rather than the conventional way (Figure 2a). For this reason, it is clear that some research is necessary in order to determine the effect of this mounting procedure.

There are several factors that should be considered when studying the effects of mounting the vibrators perpendicular to the direction of travel. Figure 1 reveals that the forces generated by a paving vibrator act at right angles to the head. This is of importance in that no vibrational forces are produced beyond the head of the paving vibrator. Also depicted in this figure is the effect of where the eccentric weight is located within the head of the vibrator. It is this eccentric weight that produces the forces of vibration. Since the eccentric is located in the front half of the vibrator, the majority of the forces it produces are emitted from this part of the vibrator. The back half of the vibrator's head does transmit some of the vibrational forces, but they are of a smaller magnitude than those emitted from the front half of the vibrator's head. Therefore, paving vibrators mounted perpendicular to the direction of travel should be mounted at a maximum spacing equal to the length of their head. Ideally, vibrators mounted in this fashion should be mounted so that they overlap half of the length of the vibrator's head.

Another factor due consideration involves the effect of the speed of the paving train when vibrators are mounted perpendicular rather than parallel to the direction of travel. Figure 3b shows that the speed of the paving train is a function of the

length of the effective part of the vibrator (the eccentric). Research has shown that for this method of mounting the optimum paving speed is between 12 to 14 fpm (3.7 to 4.3 m/minute) (12). By turning the vibrators perpendicular to the direction of travel, the paving speed is a function of twice the effective radius of action (diameter of action) of a single vibrator submerged in fresh concrete (Figure 3a). Since this diameter of action is probably different than the length of the effective part of the vibrator (the eccentric), it could be expected that the paving speed would need to be reduced when the vibrators are turned perpendicular to the direction of travel in order to achieve the same level of consolidation. If the paving train speed was kept the same, it would be assumed that the concrete consolidated by the vibrators mounted perpendicular would be of lower quality than that vibrated by the conventional method. The diameter of action of a single vibrator moved through fresh concrete must be determined in order to recommend a speed for a paving train with vibrators mounted perpendicular.

In a laboratory study performed at Texas A&M University, there was a significant difference between the air void content and strength of concrete slabs vibrated using one perpendicular mounted vibrator versus two parallel mounted with a spacing of 24 inches (610 mm) (5). The concrete subjected to 104°F (40°C) temperature with only one vibrator produced poor quality concrete with large air pockets and poor liquefaction. Only the area around the vibrator at a distance of about 4 to 5 inches (100 to 130 mm) from the surface of the vibrator seemed to be adequately consolidated (5). However, this finding was not duplicated in a field project. The reasons are attributed to the additional vibration provided by the pan vibrator immediately following the gang mounted spud vibrators, and the lower air temperature (80°F (26°C) versus 104°F (40°C) in the laboratory).

Consolidation Versus Coarse Aggregate Factor. The coarse aggregate factor is one way of describing the composition of a concrete mix. It is defined as the ratio of the bulk volume of coarse aggregate to the total volume of concrete, and it depends on the maximum size of the aggregate and on the grading of the fine aggregate (8). The shape of the coarse aggregate particles does not directly enter the relation since, for instance, a crushed aggregate has a greater bulk volume for the same weight (i.e., lower bulk density) than a well-rounded aggregate. Thus, the shape factor is automatically taken into account in the determination of the bulk density (8).

When designing a concrete mix, the optimum ratio of the bulk volume of coarse aggregate to the total volume of concrete (coarse aggregate factor) is chosen based on the maximum size of the aggregate and the grading of the fine aggregate (fineness modulus). However, when the degree of consolidation, or the desired void content of the hardened concrete, is critical to

the mix designer, then this property must also be considered. It is understood that the volume of coarse aggregate contained in a given concrete volume will influence the subsequent void content of that mix. This can be described by examining the properties of a fine and coarse grained mixture (Figure 4) (16).

Figure 4 represents three combinations of a fine and coarse grained mixture. A mixture that contains little or no fines (Figure 4a) has stability due to the grain-to-grain contact of the coarse materials (16). However, this mixture inherently contains voids between the coarse grains due to a lack of fines necessary to fill all of the voids between contact points. A concrete mixture that has too high a coarse aggregate factor, or too high a volume of coarse aggregate, will tend to have a low density and a high void content irrespective to the degree of consolidation.

A mixture that has adequate fines to fill all of the voids between the coarse grains will still gain its strength from grain-to-grain contact, but with increased shear resistance (Figure 4b) (16). A concrete mix with the optimum coarse aggregate factor will have a high density, a low permeability and increased shear strength. The degree of consolidation will become increasingly important to this mix to assure that the fines are allowed to flow into all of the voids between the coarse grains. Once the concrete has undergone the initial slumping during the consolidation process, it will be important to continue vibration until the entrapped air present in the mortar has been allowed to escape. This condition should lead to the optimum consolidation attainable for a given set of concrete materials.

A mixture that contains a large amount of fines, or too low a coarse aggregate factor, has no grain-to-grain contact and the coarse aggregate merely "floats" in the mixture (Figure 4c) (16). A concrete mixture under these conditions will have a low density and a higher void content due to the entrapped air contained in the fines. Consolidation of this mix would have to be continued excessively in order to allow the entrapped air to rise to the surface. Since the coarse aggregate is free to float in the mix, and since the mortar is what carries the vibration after the initial slumping, this would tend to cause settlement of the coarse aggregate and an accumulation of fines on the surface.

From this discussion, it is obvious that an optimum coarse aggregate factor exists for a given set of concrete materials in order to achieve the highest degree of consolidation desired should also be considered, in addition to the maximum aggregate size and the fineness modulus, when choosing a coarse aggregate factor in the mix design procedure.

There presently exists one possible method for predicting the optimum coarse aggregate factor based on the materials to be

used. The Fineness Modulus Method of mix design is based on the concept that aggregate proportions and gradations can be used to design a concrete batch. Design tables and a design example for the Fineness Modulus Method of mix design can be found in Appendix A. In a recent study conducted at Texas A&M University, it was proven that among the three coarse aggregate factors investigated (0.76, 0.80, and 0.85) the best consolidation was achieved for the mix with a 0.80 coarse aggregate factor (5). When checking the mix design, using the Fineness Modulus Method, the same coarse aggregate factor was determined.

Consolidation Versus Coarse Aggregate Size. The choice of coarse aggregate maximum size is usually made prior to any considerations of the mix design. In reinforced concrete the maximum size aggregate which can be used is governed by the width of the section and the spacing of the reinforcement. It has also been accepted that the maximum size of the coarse aggregate will influence the void content of the hardened concrete; therefore, the desired void content of the concrete must also be considered when choosing the maximum coarse aggregate size.

It has generally been considered desirable to use as large a maximum size of aggregate as possible. However, it now seems that the improvement in the properties of concrete with an increase in the size of the aggregate does not extend beyond 1 1/2 inch (40 mm) so that the use of larger sizes may not be advantageous (8). This has been verified by tests with aggregates up to 1 1/2 inch (40 mm) maximum size and beyond. Experimental results show that above the 1 1/2 inch (40 mm) maximum size the gain in strength due to the reduced water requirement is offset by the detrimental effects of lower bond area (so that volume changes in the paste cause larger stresses at the interface) and of discontinuities introduced by the very large particles, particularly in rich mixes (8). In a study performed at Texas A&M University, a reduction of the maximum size aggregate from 2 1/2 to 1 1/2 inch (65 to 40 mm) enhanced consolidation of the concrete (4).

Recently, the need to further reduce the 1 1/2 (40 mm) top size requirement has been investigated. As expected the 1 1/2 inch (40 mm) top size produced practically the same void content regardless of the maximum aggregate sizes studied (3/4, 1, and 1 1/2 inch (20, 25, and 40 mm) (5). The slabs with 1 1/2 inch (40 mm) top size furthermore had the highest strength for a given void content confirming that 1 1/2 inch (40 mm) is the optimum top size of the coarse aggregate for the purpose of consolidation and strength.

Consolidation Versus Superplasticizers. Superplasticizers are a relatively new family of admixtures which can either be used as high-range water reducers or be incorporated to produce "flowing" concrete. They were introduced into North America in 1976 and since then a number of research laboratories have been developing data on their effect on hardened concrete (17).



There are three possible ways in which superplasticizers may be used in concrete (17):

1. To produce concrete with a very low water/cement ratio. This will develop high strength concrete since the water content is reduced while the cement content remains the same. The loss in workability due to the decrease in the water content is compensated for by the superplasticizing agent.
2. To produce concrete with reduced cement content. The same strengths can be obtained by lowering both the cement and water contents so that the water/cement ratio is maintained. Again, the loss in workability is compensated for by the superplasticizing agent.
3. To produce flowing concrete. Superplasticizers may be added, with no change in the mix proportions, simply to increase the slump and produce a more flowable mixture.

Since, in slip-form construction, the slump of the concrete mixture must be maintained, the only advantage in using superplasticizers would be to either conserve cement and produce equally strong concrete (as in method 2) or lower the water content and produce stronger concrete (as in method 1).

While research has shown that superplasticizers (when used to reduce water content) cause no increase in segregation or bleeding, and no significant influence on the setting time of the fresh concrete, they do promote a high rate of slump loss (17) and may increase freeze-thaw scaling of the hardened concrete surface in the presence of deicing agents (18). This rapid rate of slump loss in superplasticized concrete is a serious disadvantage and research is being conducted to find a solution to the problem. Presently, concrete containing a superplasticizer will provide a large increase in slump, but this increase is of short duration, and within 30 to 60 minutes the concrete reverts back to the original consistency (17). This phenomenon is accentuated with elevated temperatures.

Currently, there are various methods available for counteracting the problems of rapid slump loss caused by the addition of superplasticizers. One solution involves the use of set retarding admixtures that can be obtained with the superplasticizers. The purpose of these set retarders is to retard the rate of hardening of the concrete, thereby reducing the rate of slump loss.

The previously mentioned research study, conducted at Texas A&M, provided additional insight into the use of superplasticizers in CRCP concrete mixes (5). Among the findings were that at the elevated temperature used (104°F (40°C)), the slump loss encountered produced poorly consolidated concrete when only

one transverse mounted vibrator was used (5). It was extremely difficult to maintain the vibrator within the concrete mix during vibration of the stiff mix and additional time had to be used to liquefy the concrete. Due to the stiff consistency, the response from accelerometers installed at the bottom of the slabs showed a pattern consistent with the minimal amount of liquefaction observed and the difficulty of vibrating such mixtures. Similar results were found when using a water reducing agent in combination with a retarder, but to a lesser extent. Since the field results with conventional concrete mixtures yielded adequate strength and consolidation when using the present transverse mounting of the spud type vibrators in combination with the pan vibrator, the difficulties encountered in the laboratory with superplasticized concrete may or may not be reproduced.

Summary and Conclusions

As for any other type of concrete structure, the consolidation of CRC pavements is of great importance for the strength and durability of the concrete. Several variables and aspects related to the consideration of CRCP have been discussed and the findings of various laboratory and field investigations revealed. Among the findings are that the degree of consolidation varies with the depth of the pavement with the greatest consolidation usually occurring at the bottom portion. A vibrator spacing of 24 inch (610 mm) is adequate to consolidate the concrete when the vibrators are mounted parallel to the direction of travel. The current practice of mounting the spud vibrators perpendicular to the direction of travel generally results in poorer consolidation of the concrete in the laboratory. In the field, however, the pan vibrator used to provide a leveled pavement surface provides extra vibration and aids in the consolidation process by further compacting the concrete. Any detrimental effects in the consolidation provided by the internal vibrators might thus be reduced by the additional vibration produced by the pan vibrator.

The Fineness Modulus Method of mix design determines the coarse aggregate factor which is needed to optimize consolidation. Furthermore, a coarse aggregate top size of 1 1/2 inch (40 mm) provides both good strength and desirable contributions to the quality of consolidation.

In order to use superplasticized concrete for slip-formed CRC pavements, careful consideration has to be given to the possibility of rapid slump loss. Such slump losses can affect the consistency of the fresh concrete to the extent that consolidation is not possible with the vibratory equipment being used on a paving machine. In addition, delays in construction becomes particularly critical with these mixes.



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APPENDIX A

MIX DESIGN BY FINENESS MODULUS METHOD

The relative quantities of the aggregates (per cubic meter) only, are determined in this method whereas the quantities of the cement and water are determined by other methods. This method is based on the fact that for given aggregate, cement content and slump, the strength of the concrete increases with the increase of the fineness modulus.

This connection exists up to a certain modulus from which on a decrease in strength results and the mix is less workable. This modulus that gives the concrete its maximum strength is called the "Optimal Fineness Modulus". This design is based on the principal that the aggregate mix should be proportioned to give the optimal modulus. The optimal modulus as a function of the cement content and nominal maximum size aggregate is presented in the following table.

Example (per cubic meter)

Data: X = Coarse Aggregate: $\gamma_{ca} = 2.68$; FM = 6.8

Maximum Size: 3/4"

Y = Medium Coarse: $\gamma_{mca} = 2.67$; FM = 4.8

Maximum Size: 1/2"

Z = Fine Aggregate: $\gamma_{fa} = 2.63$; FM = 1.4

Cement $\gamma_c = 3.12$

The mix is given light vibration

$\frac{X}{Y} = \frac{2}{1}$ (assumption - or by dry rodding, this ratio gives the maximum unit weight).

Air Content = 1.5 percent

By ACI method it was found that the cement content is 278 kg/m³ and the volume of water is 200 liters (200 kg). Therefore, the optimal Fineness Modulus is 4.75 + 0.1 = 4.85.