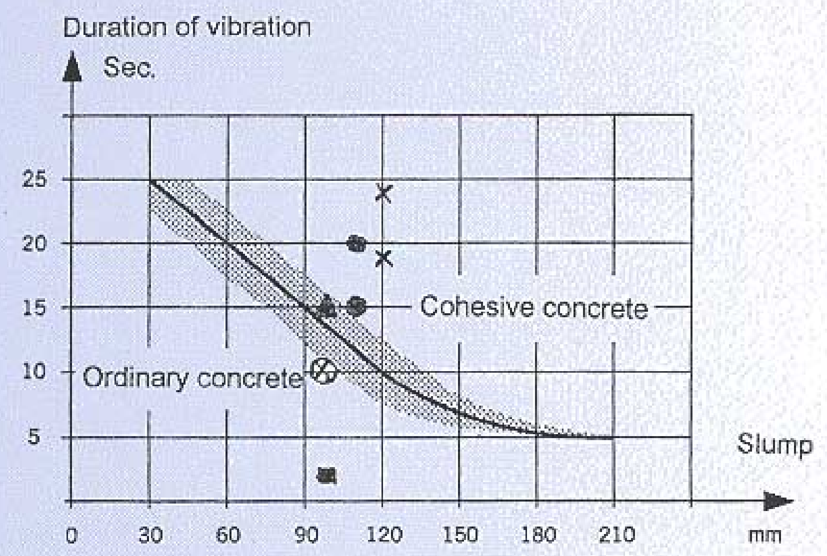
HETEK

Investigation of Poker Vibration



Report No.89
1997

Road Directorate Denmark Ministry of Transport

IRRD Information

Title in Danish	Undersøgelse af stavvibrering
Title in English	Investigation of poker vibration
Authors	Jens Frandsen og Karin-Inge Schultz
Subject	Concrete Execution
Key words	Poker vibration Vibration Consolidation Compaction Casting Pouring
Abstract	The investigation comprise recording of poker vibration on 5 selected sites.
UDK	691.32
ISSN	0909-4288
ISBN	87 7491 797-8

List of Content

Enclosures:

Report from Sweden, Concrete International September 1995

Scope

The report summarises the results from HETEK Project 5B, which are recording of poker vibration on 5 different sites.

Based on the investigations is the recommendation from the HUA-2:

- Vibrering med stavvibrator, Vejledning.
  Dansk Betoninstitut A/S september 1995.
  ISBN: 87-89962-14-1

revised and published as a recommendation from the Road Directory.

- HETEK
  Recommendation on Poker Vibration
  Vejdirektoratet 1997
  ISBN:87 7491 794-3

The vibration project in HUA-2 is documented in the following publications:

- Anvisning i brug af højkvalitetsbeton til udsatte anlægskonstruktioner.
  Dansk Betoninstitut A/S september 1995.
  ISBN: 87-89962-13-3.

- Vibrering HUA-2, Opgave 4.
  Dansk Betoninstitut A/S september 1995.
  ISBN: 87-89962-003-6

Summary

Recording of poker vibration has been made on the following selected types of structures:

- 1 Wall casted on existing foundation
- 2 Prestressed bridge girder
- 3 Trial casting of edge beam and foundation
- 4 Sloped wall casted on exiting foundation
- 5 Bottom slab in box girder

The investigations indicate that the recommended relation between duration of vibration and slump given by the HUA-2 Recommendation is acceptable. The durations could possibly be reduced by 20 to 30 %, but as the air void structures from the investigations are acceptable also from the longer durations, the relation from HUA-2 is considered satisfactory.

Since the HUA-2 Recommendation was written in 1994 it has become more evident that the durability can be significantly reduced if over vibration is made by a poker. Investigations from Sweden has indicated that the frost resistance is damaged if the poker comes too close to the surface of the form.

Based on above we recommend never to insert the poker closer to the form surface than 3d from the centerline of the poker. This rule will be stated in the revised recommendation for poker vibration.

1 Aim of the investigation

The aim of the investigation is to verify the durations of vibration recommended in the HUA-2 Recommendation.

2 New knowledge

Since the HUA-2 Recommendation was written in 1994 it has been widely known that vibration by a poker can damage the microstructure and air void structure of the concrete and by this the durability of the structures cover to the reinforcement.

On the East Bridge of Storebælt there was great difficulties in obtaining the requirements to the micro structure and the air void structure in the concrete. The frost resistance was investigated by the Borås method SS 137244. The result was surprisingly bad as 20 % of the investigated cores from the structures had scaling higher than 1,0 kg/m^2, which is the requirement for cores taken from structures in accordance with SS 137244.

Cores from the land works of Øresund in Denmark showed the same tendency of lack of sufficient air void structure and frost resistance as on Storebælt.

A Swedish investigation made by Lars Forssblad and Stig Sällström published in Concrete International September 1995 indicate an alarming relation between poker vibration and lack of frost resistance tested in accordance with SS 137244.

In addition to this HETEK project on recording of duration of vibration a Danish contractor has carried out a systematic testing of the relation between the distance to the poker and the loss of entrained air in the concrete.

Storebælt og Øresund

The results from Storebælt and the land works of Øresund shows that there is no obvious relation between the traditional requirements to air void structure and the results from frost resistance tested in accordance with the test methods SS 137244 and ASTM 666 for high quality concrete with low water cement ratio below 0.45.

Investigation of flourocens impregnated plane sections of specimens after exposure to SS 137244 and ASTM 666 indicate that frost attack is located at cracks and porosities at the exposed surface. If this is correct frost resistance of high quality concrete will mainly depend on the cracks and porosities of the micro structure and only secondary of the air void structure.

Other aggressive environmental conditions will in the same way be able to attack at cracks and porosities. As high quality concrete has a higher tendency to cracking due to the higher autogenous shrinkage, high quality concrete will be more sensible to over vibration than normal concrete.

Poker vibration has a high influence on both the micro structure and the air void structure and will therefor be a significant factor for the durability of concrete structures.

The investigations of frost resistance on Storebælt resulted in investigations of the applied vibration methods, and made A/S Storeforbindelsen support the HUA-2 Project which comprised investigation of vibration and resulted in the recommendation on poker vibration.

Swedish Investigations

The Swedish investigations of poker vibration was published in September 1995 on almost the same time as the recommendation from the HUA-2 Project.

The durations of vibration recommended is in the same order as in the HUA-2 recommendation, between 5 and 25 sec. And it is mentioned that for high flowable concrete with a slump of 200 mm the duration of vibration can be reduced to 50 %.

The influence on the concrete quality of poker vibration is investigated by the following methods:

- density
- strength
- permeability
- chloride permeability
- air content
- frost resistance

The most significant results are obtained by frost testing in accordance with SS 137244, The results are shown in figure 1 from table 1 of the Swedish paper.

Table 1 — Results of freeze-thaw tests in salt solution*

Vibrator insertion with 10 sec. duration in the center of the form					
Test section	Weight loss, scaling, in kg/m² at different freeze-thaw cycles				
	7	14	28	42	56
Center of vibrator insert	0.6	1.6	3.2	4.5	6,0
	Very low frost resistance				

*Insertions with 58 mm (2.25 in.) internal vibrator in forms 600 x 600 x 450 mm (24 x 24 x 18 in.)

Vibrator insertion with 20 sec. duration in the center of the form					
Test section	Weight loss, scaling, in kg/m² at different freeze-thaw cycles				
	7	14	28	42	56
Center of vibrator insert	0.9	2.7	6.0	8.8	11,6
	Very low frost resistance				
100 mm (4 in.) from insert center	0.3	0.6	1.8	2.0	2,2
	Low frost resistance				
200 mm (8 in.) from insert center	0.2	0.3	0.4	0.4	0,4
	Good frost resistance				

*Insertions with 58 mm (2.25 in.) internal vibrator in forms 600 x 600 x 450 mm (24 x 24 x 18 in.)

Vibrator insertion with 20 sec. duration close to a form side					
Test section	Weight loss, scaling, in kg/m² at different freeze-thaw cycles				
	7	14	28	42	56
Concrete surface at vibrator insert point	1.5	5.6	11.6	Test ended	
	Very low frost resistance				

*Insertions with 58 mm (2.25 in.) internal vibrator in forms 600 x 600 x 450 mm (24 x 24 x 18 in.)

Figure 1 Results table 1 from the Swedish investigations

The requirement to maximum scaling in accordance with SS 137244 is 0.5 kg/m² for laboratory specimens and 1.0 kg/m² for cores taken from structures.

With a duration of vibration of 10 sec. Surfaces taken emidiatly at the poker position have a scaling of 6.0 kg/m², if the duration is doubled to 20 sec. The scaling will double to 11.6 kg/m².

With a duration of vibration of 20 sec., the scaling will reduce from 11.6 kg/m² to 2.2 kg/m² in a distance of 100 mm from the poker corresponding to aproximatly 2d, and to 0.4 kg/m² in a distance of 200 mm from the poker corresponding to aproximatly 4d.

Based on these result it is only concrete with a distance of 4d to the nearest insertion of the poker that will fulfill the requirements in SS 137244. The HUA-2 Recommendation recommends a minimum distance of 2 to 3d to the form surface, which accordance to above is a little on the unsafe side.

If the poker is held close to the form side, the Swedish results shows that the test specimens are broken in the test after 28 cycles and that the testing can not completed to the required 56 cycles.

The conclusion on the Swedish investigations or obvious. If the cover to the reinforcement in a concrete structure shall be frost resistance, the poker shall never be inserted closer to the form surface than 4d.

Danish Investigations

A Danish contractor has in 1996 investigated the relation between duration of vibration and loss of entrained air in a high quality concrete.

Small beams with dimensions 500 x 500 mm and a length of 2300 mm were vibrated with a 66 mm poker 200 Hz in measured distances from the form side of 100 mm and 200 mm.

The concrete had before vibration an air content of 6.5 %, a slump of 120 mm and a temperature of 17 °C.

The results are shown in figure 2.

Duration of vibration	**Distance from centre poker to form surface**	
	100 mm	**200 mm**
sec.	**Total air content %**	**Total air content %**
0	-	5,1
5	4,1	4,3
15	2,7	3,5
30	1,6	3,5
45	1,5	3,1
50	1,2	4,1

Figure 2 Relation between duration of vibration and distance to form surface

The results indicates that the entrained air is vibrated out of the concrete. If the air content shall be acceptable the distance from centre of poker to the form surface shall be minimum 200 mm corresponding 3d at a duration of vibration of more than 5 sec.

3 Records HETEK 5B

3.1 Investigation 1

Type of structure

The structure is a wall casted on an existing foundation. The dimension of the wall is 1.8 x 0.4 x 20.0 m. The reinforcement are Y16 per 150 mm vertical in both sides and Y12 per 300 mm horizontal in both sides. The cover is 35 mm with a tolerance of 5 mm. The spacers are 40 mm.

Placing and vibration

The placing is satisfactory.

The distance of insertion and the distance to the form surface are as recommended in the HUA-2 Recommendation.
The microstructure in the cover is satisfactory, which indicate that the duration of vibration and the pokers distance from the form surface are correct.

The duration of vibration per insertion 7 to 8 sec. For a slump of 120 mm is also in accordance with the HUA-2 Recommendation, but the depth of insertion is far deeper than recommended, which means that the total duration of vibration including the revibration is higher. We recommend that the depth of insertion and the duration of vibration recommended by HUA-2 are followed.

3.2 Investigation 2

Type of structure

The structure is prestressed bridge girder with butterfly cross section with the following dimensions 8.0 x 1.54 m. The dimensions of the edge beam is 0.46 x 0.50 m. The cover is 30 mm with a tolerance of 10 mm, the spacers are 35 mm.

The edge beams are reinforced with T12 per 200 mm and 14 T20 in the longitudinal direction distributed along stirrups. The girder is reinforced with T16 per 200 mm in the longitudinal direction in top and bottom and T12 per 200 mm perpendicular in top and bottom. In addition to this the girder is supplied with tendons and extra reinforcement in the form of stirrups.

Placing and vibration

The placement is satisfactory but the thickness of the layers could be increased by 10 to 15 cm, corresponding a thickness of 80 % of the poker length, as recommended in the HUA-2 Recommendation /3/. By doing this the revibration of the layer below would automatically be reduced by 5 to 10 cm, when the poker is used so that the top of it can be seen.

The insertion distances are as recommended by the HUA-2 Recommendation.

The used duration of vibration 10 sec. At a slump of 100 mm is a bit lower than recommended by the HUA-2 Recommendation, but acceptable. We estimate that the recommended duration can be reduced.

3.3 Investigation 3

Type of structure

The structures are trial casting of 3 edge beams supplemented by 2 foundations made for a bridge contract on the Øresund Land Works.

Placing and Vibration

The placing is satisfactory.

The duration of vibration with the ø 48 mm poker was 15 sec. with an insertion distance of 0.4 m which is as recommended by the HUA-2 Recommendation for a slump of 100 mm, but we estimate that the duration could be reduced to 10 sec.

The duration of vibration with the ø 25 mm poker was 5 sec. with an insertion distance of 0.2 m is shorter than recommended by the HUA-2 Recommendation, but we estimate that it could be increased to 10 sec.

3.4 Investigation 4

Type of structure

The structure is a sloped wall casted on an existing foundation. The dimensions of the wall is 2.85 to 3.00 m with a thickness of 0.50 m.

The reinforcement is T20 per 200 mm vertical in both sides increased to 100 mm on the lower third of the wall and T12 per 100 mm horizontally.

In addition T25 in top of the wall and U-stirrups per 200 mm in top of the wall and per

100 mm in the bottom of the wall, the U-stirrups covers 2 m of the wall hight.

The cover is 30 mm with a tolerance of 10 mm, the spacers are 35 mm.

Placing and vibration

The placing was not satisfactory. The free fall was up to 3 m for the lower layer and the pump pipe was supported by the reinforcement in the inside of the wall which has resulted in separation in the concrete causing the unacceptable macro- and microstructure in the concrete. The placing method could be improved by using guides for the pump pipe central in the wall.

The thickness of the layers was 45 to 80 cm which are very thick layers. In order to get the whole layer and secure connection to the previous layer there was vibrated in several depths at each insertion. But this makes systematically vibration very difficult. We recommend to reduce the thickness corresponding the length of the poker as recommended in the HUA-2 Recommendation. In addition we recommend to use vibrator guides in the centre line of the wall to obtain a more uniform vibration in the wall and avoid that the poker comes too close to the in side of the wall.

As vibration has taken place in several depths at the same insertion it is very difficult the real duration of vibration in the areas. We estimate that the duration has been 15 to 20 sec. Which is 5 to 10 sec. More than recommended by the HUA-2 Recommendation. Based on the air void analysis we estimate that a duration of 10 sec. would be suitable.

The distance of insertion has especial in the lower layers with extra reinforcement been higher than recommended by the HUA-2 Recommendation.

3.5 Investigation 5

Type of structure

The structure is a bottom slab in a box girder. The cross section is 4.54 x 0.25 m with a length of 46.77 m. The cover is 35 mm with a tolerance of 5 mm, the spacers are 40 mm.

The reinforcement are Y20 per 150 mm in the longitudinal direction in both sides of the slab the perpendicular reinforcement are in the top side Y16 per 200 mm and in the bottom side Y 20 per 200 mm. In both sides are starterbars Y20 per 200 mm with a length of 1400 mm.

Placing and vibration

The placing is satisfactory.

The distance of insertion is in accordance with the HUA-2 Recommendation for difficult reinforcement. If the reinforcement is evaluated as normal the distance could be increased by 2d, but with the design of the rebar net its reasonable to vibrate in every second opening as done.

The duration of vibration is 2 sec. Which is 10 sec. Less than recommended by the HUA-2 Recommendation for a slump of 90 mm, but the results of the core analysis are acceptable. The influence of the beam vibrator unknown but based on the core analysis there is no difference between top and bottom. The duration of vibration could be reduced to 5 sec.

4 Duration of vibration and slump

The relation between slump at vibration and the recorded duration of vibration are shown in Table 4.1 together with the air content of the concrete.

	Duration of vib. sec.	Total air in concrete, %	Slump mm
Investigation1:			
Layer 2	19	7,2 [1)]	120 [1)]
layer 3	24	7,2 [1)]	120 [1)]
Investigation 2:			
girder	10	5,4 [2)]	100 [2)]
edge beam	10	5,4 [2)]	100 [2)]
Investigation 3:			
foundation	15	6,2 [3)]	100 [3)]
Investigation 4:			
layer 1	20	7,2 [4)]	110 [4)]
layer2	15	7,2 [4)]	110 [4)]
layer3	15	7,2 [4)]	110 [4)]
Investigation 5:			
bottom slab	2	6,7 [5)]	90 [5)]

[1)] Before pump, estimated based on measurement at the batching plant

[2)] Average of 15 measuerements after pump on site

[3)] After pump on site

[4)] Before pump on site, measured for layer 2-3

[5)] Average of 8 measurements on site

Table 4.1 Relation between slump and recorded durations of vibration

The recorded durations of vibrations are plotted in the corresponding diagram from the HUA-2 Recommendation in figure 4.1

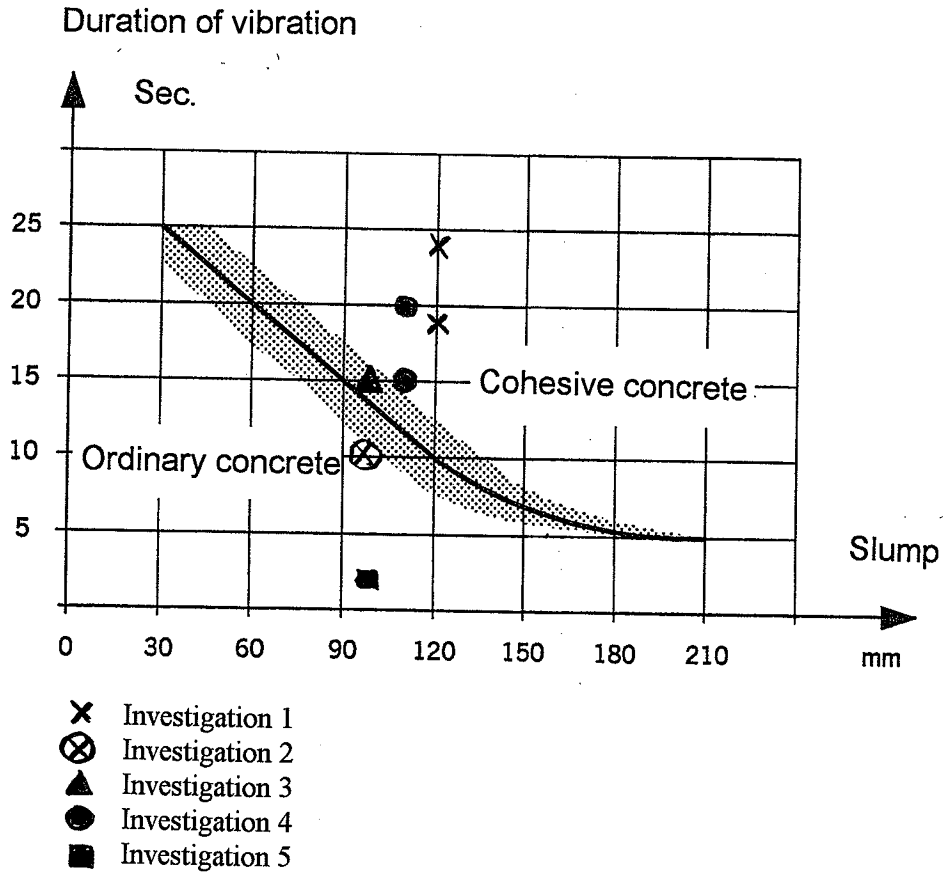


Figure 4.1 Relation between duration of vibration and slump

The results indicate that only concrete with a slump between 100 and 200 mm have been used in the investigations. The durations of vibration are distributed between 10 and 25 sec. With one result at 2 sec.

5 Core analysis

Cores from the structures are investigated by fluorecens impregnated plane sections, thin sections and air void analysis.

Table 5.1 shows those results from plane- and thin sections which are estimated to be influenced by vibration a which have influence on the durability.

Table 5.2 shows the results from the air void analysis.

	Core No.	Thin section	Impregnated plane section				
		Pasta homogeneity	Bleeding and pasta seperation	Cracks	Dispersion of coarse aggreg.	Entrapped air	
Investigation 1:							
layer 2	A1	0,3	1	1	0	0	
layer 2	A2	0,1	1	1-2	0	0	
layer 2	A3	0,3	1	1	0	0	
layer 3	A4	0,5 [1]	1	1-2	0	0	
layer 3	A5	0,1	1	1	0	0	
layer 3	A6	0	1	0-1	1	0	
Investigation 2:							
girder	B1	1 [1]	-	-	2	-	
girder	B2	1,6 [1]	2	1	0	1	[2]
girder	B3	1,6 [1]	1-2	1	0	1	
edge beam	K1	0,7 [1]	-	-	0	-	
edge beam	K2	0,9 [1]	1	1	1	1	
edge beam	K3	1,1 [1]	2-3	3	0	1	
Investigation 4:							
layer 1, inner surface	I/I1	1,7 [1]	3	2-3	0	0	[2]
layer 1, outer surface	I/I4	2,2 [1]	3	2	2	1	[2]
layer 2, inner surface	II/II1	1,5 [1]	2	1	0	0	
layer 2, outer surface	II/II2	2,2 [1]	3	2-3	1	1	[2]
layer 3, inner surface	III/III1	1,1 [1]	1-2	1	3	0	
layer 3, outer surface	III/III4	2,3 [1]	1-2	1	1	1	[2]
Investigation 5:							
bottom slab	E1	0,4	1(-2)	1	0	1	
bottom slab	E2	0,3	1	1	0	0	
bottom slab	E3	1,0 [1]	0-1	1-2	0	1	

[1] Raised capillary porosity and bleeding along fine and coarse aggregates
[2] Bonding slip along part of the reinforcement

Table 5.1 Results from plane- and thin sections which are estimated to be influenced by vibration a which have influence on the durability.

	Core No.	Total air in concrete, %	Air in 'kitmasse', %			Spec. surface mm^{-1}
			Total	< 0.35 mm	> 0.35 mm	
Investigation 1:						
layer 2	A1	5,9	17,4	14,4	3	41
layer 2	A2	4,8	14,5	11,8	2,7	37
layer 2	A3	6,7	19,4	16,5	2,9	41
Average layer 2		*5,8*	*17,1*	*14,2*	*1,8*	*40*
layer 3	A4	5,3	15,8	14	1,8	42
layer 3	A5	5	15	13,2	1,8	45
layer 3	A6	4,4	13,4	12,2	1,2	46
Average layer 3		*4,9*	*14,7*	*13,1*	*1,6*	*44*
Investigation 2:						
girder	B1	5,1	15,8	9	6,8	28
girder	B2	3,9	12,8	9,2	3,6	37
girder	B3	3,5	11,2	8	3,2	36
Average girder		*4,2*	*13,3*	*8,7*	*4,5*	*34*
edge beam	K1	6,6	19,2	13,1	6,1	28
edge beam	K2	5,9	17,9	8,8	9,1	23
edge beam	K3	2,2	7	5,1	1,9	34
Average e. b.		*4,9*	*14,7*	*9*	*5,7*	*28*
Investigation 3:						
foundation	1	1,8	6,6	3,8	2,8	28
foundation	2	3,7	12,7	8,2	4,5	30
foundation	3	5,3	17,3	9,4	7,9	24
Average		*3,6*	*12,2*	*7,1*	*5,1*	*27*
Investigation 4:						
layer 1, sample I1	I	2,3	7,8	6,8	1	45
layer 1, sample I2	I	3,9	12,4	8,6	3,8	32
layer 1, sample I3	I	4,6	14,4	10,,3	4,1	35
layer 1, sample I4	I	4,6	14,4	10,3	4,1	36
layer 2, sample II1	II	4,3	13,1	9,8	3,3	35
layer 2, sample II2	II	4,1	13	8,8	4,2	36
layer 3, sample III1	III	2,6	8,5	6,9	1,6	41
layer 3, sample III2	III	5,3	16,3	10,2	6,1	29
layer 3, sample III3	III	4,6	14,4	10,9	3,5	39
layer 3, sample III4	III	5,1	16,3	11,8	4,5	35
Investigation 5:						
bottom slab	E1	6,5	18,9	15,1	3,8	36
bottom slab	E2	6,6	19,7	16,5	3,2	38
bottom slab	E3	5,7	17,4	13,1	4,3	34
Average		*6,3*	*18,7*	*14,9*	*3,8*	*36*

Table 5.2 Results from the air void analysis.

Investigation 4 has a bad pasta homogeneity, cracks and uneven distribution of coarse aggregates, but the air void structure is acceptable. The recorded defects are caused by the placing method in the sloped wall.

Except investigation 1 all investigations indicate problems with the pasta homogeneity.

Except investigation 1 all investigations indicate problems with bleeding and paste separations.

Investigation 1 and 4 have many cracks evaluated by plane sections.

The distribution of coarse aggregates is acceptable except in investigation 4.

All investigations have a low content of entrapped air which indicate that the vibration has been sufficient or more than sufficient.

The air void structure is acceptable for investigation and 5. The remaining investigations have single cores with too little air, especial investigation 3 shows 2 cores with low air content.

6 Conclusions

It is difficult to record duration of vibration when the thickness of the placed layers are bigger than the recommended 80 % of the poker, and when the poker is inserted too deep into the previous layer.

The operators have the same problem in evaluating if the result is good when they are using this method. The operators should be trained in only to vibrate the actual layer and the connection to the layer below.

It is is normal practice to insert the poker too deep into the previous layers. By this there is risk of overvibration of some areas.

The operators have no knowledge of the relation between the complexity of the form and distance of insertion.

The operators have some knowledge of the relation between slump and duration of vibration.

The investigations indicate that the recommended relation between slump and duration of vibration in the HUA-2 Recommendation indicated in figure 4.1 is suitable. The durations could be reduced with 20 to 30 % but as the air void analysis from the investigations are acceptable also from longer durations, we recommend to accept the HUA-2 relation.

This is supported by the Danish investigations presented in chapter 2 figure 2 which indicate that the entrained air is only seriously reduced at duration of vibration of 30 sec. And above at a slump of 120 mm.

It is is documented that the durability of the concrete is damaged in the insertion and the area close to the insertion. In order to secure durable concrete structures it is therefor important never to insert the poker in the cover or the imediatly neighbourhood. The HUA-2 Recommendation recommends a distance of 2 to 3d where d is the diameter of the poker. Based on the Swedish investigations presented in chapter 2 the distance should be 4d. The Danish investigations presented in chapter 2 shows that an adequate quantity of air is remaining after vibration in a distance of 3d.

Based on above we recommend never to vibrate with insertions closer to the form surface than 3d from the centre line of the poker. This rule will be stated in the revised recommendation for poker vibration.

Enclosure

Concrete Vibration — What's Adequate?

by Lars Forssblad and Stig Sällström

It is a well-established fact that careful and thorough consolidation of concrete is necessary. This is especially important for large structures such as bridges, dams, power plants, harbor and offshore structures, but also for concrete that has to fill special requirements such as high strength or a particular surface appearance.

Inadequate consolidation can cause porous and nonhomogeneous conditions as well as local defects. Such imperfections are a special problem if they occur in the surface or surface layers of a structure. Poor consolidation can lead to frost damage as well as reinforcement corrosion and other chemical attacks, primarily as a consequence of penetration into the concrete by aggressive matters such as water, chlorides, carbon dioxide, and oxygen. A well-consolidated surface layer of the concrete is thus especially important for the quality and service life of the concrete structure.

In contract documents, the demands for sufficient concrete vibration are normally formulated in a very general way; for example, requiring a "consolidation resulting in a dense homogeneous concrete." As a consequence of such general specifications, wide variations occur in the performance of the concrete vibration on job sites. In Swedish bridge construction, several cases were reported in the 1980s where insufficient consolidation resulted in serious defects, necessitating extensive repair and, in one case, total demolition and reconstruction.

In order to establish more realistic guidelines as to what should be considered as an adequate amount of internal vibration under various conditions, a number of field studies have been carried out in Sweden during recent years.[1,2,3] The results of these studies are summarized in the following.

Vibration effort

In the investigations described here, the amount of vibration has been defined as the "vibration effort." This is equal to the effective time of vibration per concrete volume as measured in seconds per cubic meter or yard (s/m^3; s/yd^3). This measure, originally introduced by the U. S. Bureau of Reclamation,[4] has later been used in Sweden in studies of concrete vibration.

If the same type of internal vibrator is used, the effective time of vibration also indicates the compaction energy transmitted to the concrete. The vibration effort thus represents a summarizing measure of the transmitted compaction energy. The measure is, however, dependent on the compaction effect

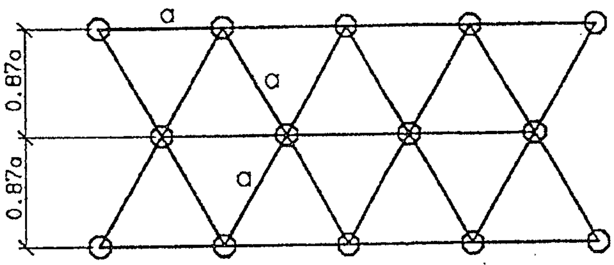


Fig. 1 — Plan for internal vibration with even distribution of the insert points. (a) is the distance between the points.

of the actual vibrator in use and, to great degree, is related to the size of the tube diameter.

The vibration effort depends on the number of vibration insertions, the duration of such insertions, and the volume of the concrete that is cast. A simple relationship is obtained:

$$V_e = \frac{n \cdot T}{V} \qquad \text{Eq. 1}$$

where V_e = vibration effort, s/m^3 (s/yd^3)
n = number of vibration insertions
T = duration of insertions, s
V = cast volume, m^3 (yd^3)

The duration of the insertions T is defined here as the time the vibrator is operating in final immersed position, and does not include the time for its sinking and raising.

For structures cast in horizontal layers of a definite thickness, the following relation is valid, assuming an even distribution of the insertions over a large casting area (Fig. 1).

$$V_e = \frac{2 \cdot T}{h \cdot a^2 \cdot \sqrt{3}} \qquad \text{Eq. 2}$$

where h = layer thickness, m (yd)
a = distance between insertions, m (yd)

For example, with a layer thickness of 0.4 m the expression is simplified to:

$$V_e = 2.89\frac{T}{a^2} \qquad \text{Eq. 3}$$

In this case, the diagram in Fig. 2 indicates the vibration effort as related to the spacing and duration of the insertions.

When choosing a certain vibration effort, Fig. 2 data can be used for guidance as to suitable spacing and duration of the

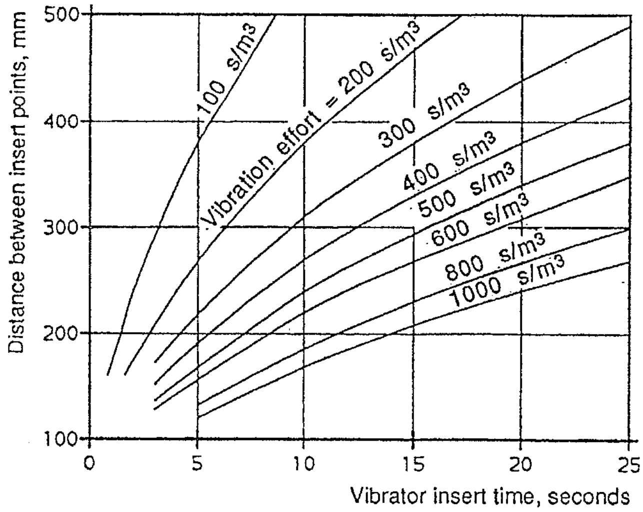


Fig. 2 — The distance between insert points and vibrator insert time are depicted here. Large casting area, concrete cast in layers of 0.4 m.

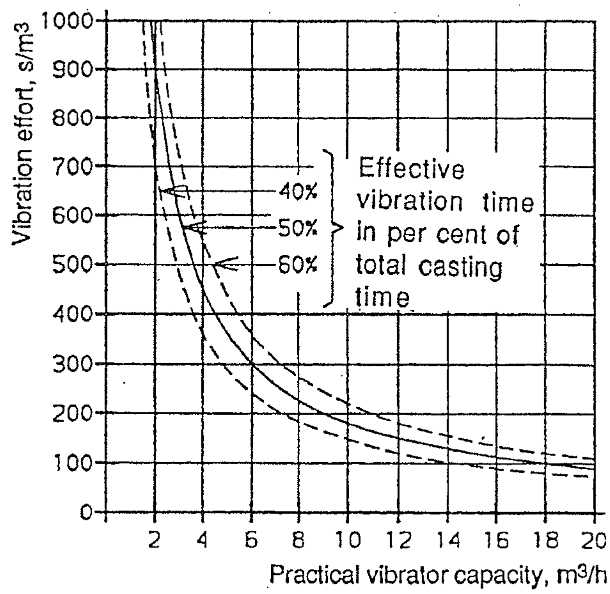


Fig. 3 — Relationship between vibration effort and practical vibrator capacity.

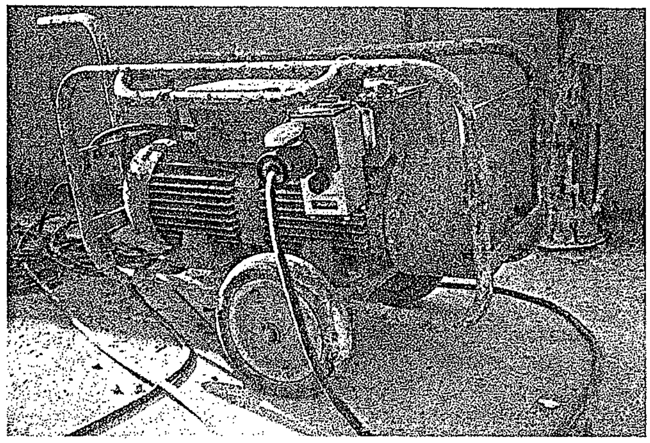


Fig. 4 — Vibration time meter coupled to frequency converter.

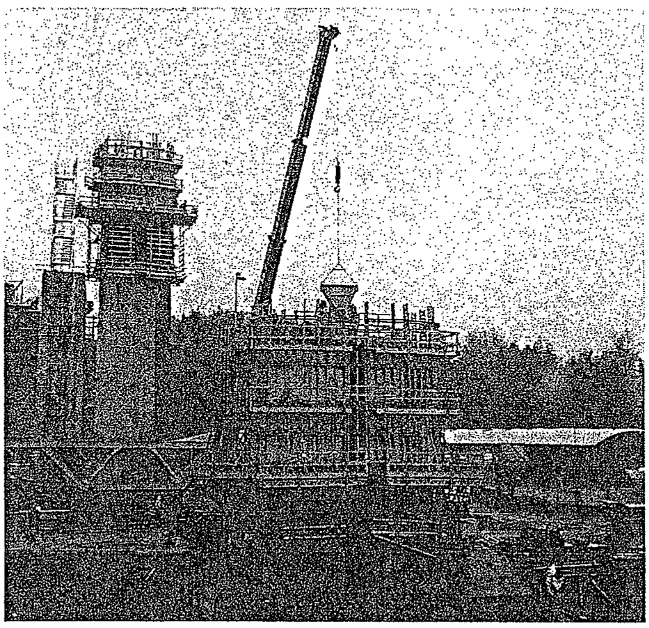


Fig. 5 — Casting of a bridge pier of a railway bridge south of Stockholm.

vibrator insertions. However, the practical limitations relating to maximum spacing and duration must be considered.

Relationships

An inverse relation exists between vibration effort in seconds per cubic meter/yard and practical casting capacity C in m^3/hr (yd^3/hr) of an internal vibrator. Efficiently used, an internal vibrator runs from 60 to 70 percent of the total time of a casting operation, according to field studies. Considering the running time while not in an inserted position, mainly in the lowering and raising between the insertions, the effective time of vibration in concrete is reduced to 40 to 60 percent of the total casting time.

Assuming the efficient time of vibration in concrete amounts to 50 percent of the total casting time, that is, 1800 s/hr, the following relationship between vibration effort V_e (s/m^3 [s/yd^3]) and practical casting capacity of an internal vibrator C (m^3/hr [yd^3/hr]) is obtained:

$$V_e = \frac{1800}{C} \quad ; \quad C = \frac{1800}{V_e} \qquad \text{Eq. 4}$$

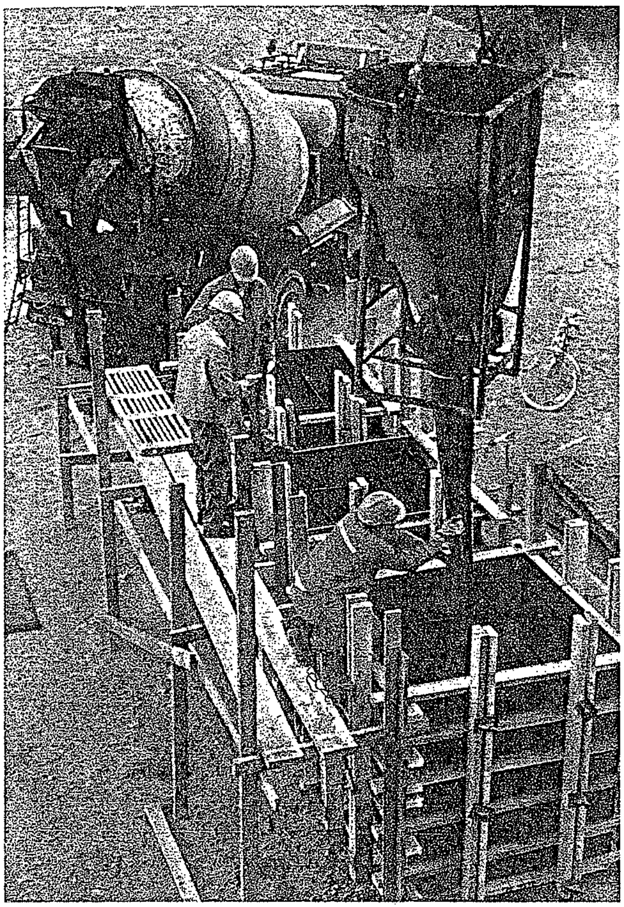


Fig. 6 — Special forms were used for field tests of different vibration efforts.

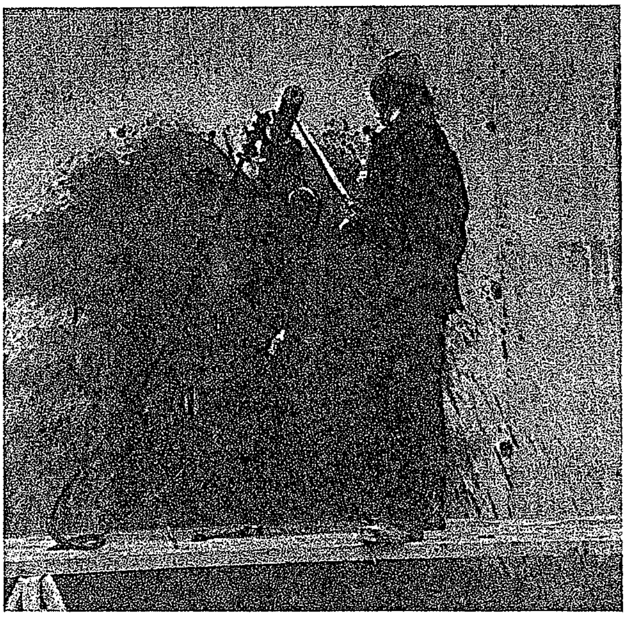


Fig. 7 — Core drilling for the tests.

A vibration effort of, for example, 300 s/m³ corresponds to a practical casting capacity of 1800/300 = 6 m³/hr per vibrator. The relationships between vibration effort and practical vibrator capacity are shown in Fig. 3 for 40, 50, and 60 percent efficient vibration time.

Vibration time meter

In major concrete work, the applied vibration effort should be measured and documented. For the projects reported here, a vibration time meter was developed in cooperation with the Swedish company Dynapac (Fig. 4).

This meter, coupled between an electrical internal vibrator with an in-head motor and its frequency converter, records the total running time during a specific casting operation. To obtain the effective vibration time in concrete, a reduction factor has to be applied for the time the vibrator is operating in air between the insertions.

In field studies this reduction factor has been determined to be 0.7 to 0.9, where 0.7 is valid for deeper forms and 0.9 for slabs.

As a result, a verification can be obtained for the total effort of the internal vibration in a casting operation. In turn, this verification may be a suitable part of the overall quality assurance program for concrete construction.

Field studies

The field studies were generally carried out on typical Swedish bridge constructions with a required concrete compressive strength of 40 to 45 MPa (5800 to 6500 psi). Normally, an entrained air content of 5 to 6 percent is specified. However, tests of concrete with only small amounts of entrained air were also included in the investigations. In the studies, the slump values varied from the normally applied range of 75 to 125 mm (3 to 5 in.) up to 200 to 240 mm (8 to 10 in.). Maximum aggregate size was 32 mm (1.25 in.).

The purpose of the studies was to ascertain the amount of vibration needed for adequate or full consolidation under various practical conditions. For this purpose, different vibration efforts were systematically applied within a range from 75 s/m³ (57 s/yd³) up to a maximum of 1200 s/m³ (920 s/yd³). This also covered the extreme values of the vibration efforts.

The internal vibrators used for the compaction of the concrete were exclusively electrical with the motors in the head and with a tube diameter of 55 to 60 mm (2.25 to 2.5 in.).

Different vibration efforts were applied to the concrete in certain test sections (Fig. 5) or in special test forms (Fig. 6). After normal curing and hardening of the concrete, test spec-

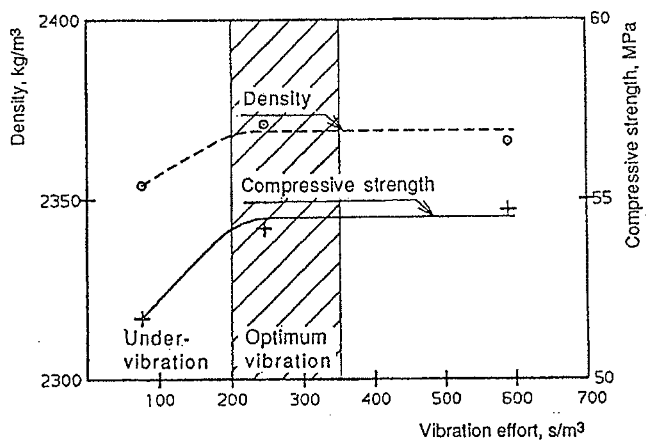


Fig. 8 — Relationship of vibration effort, density, and compressive strength are shown here. The air-void content is 2.5 percent.

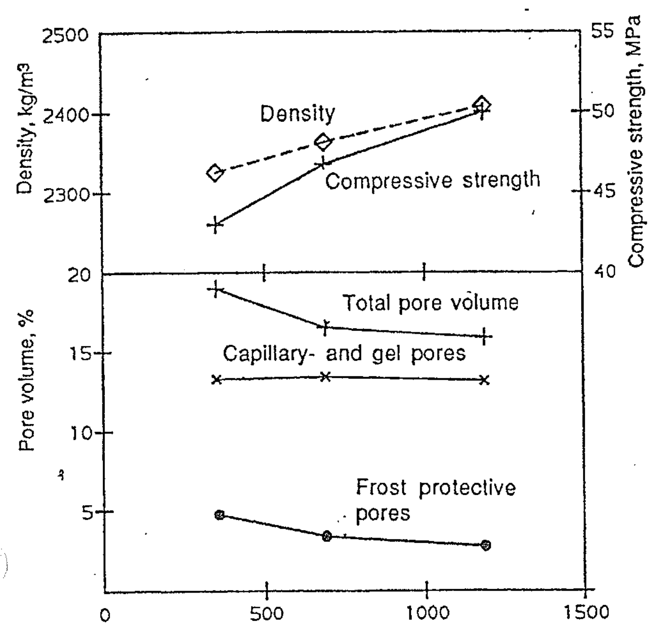


Fig. 9 — Relationship between vibration effort, density, pore volume, and compressive strength depicted here. This was air entrained concrete with 5 to 6 percent air content. (See Reference 5.)

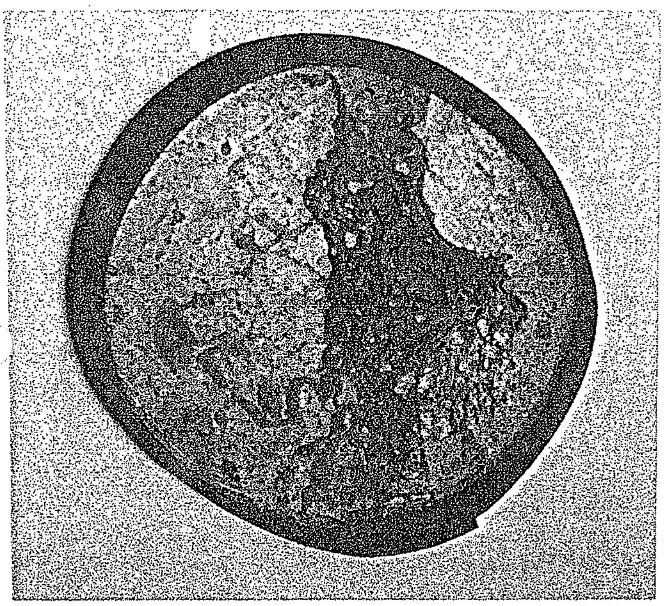


Fig. 10 — Freeze-thaw test showing uneven scaling effect at a vibrator insertion. Core diameter is 125 mm (5 in.).

imens were taken out of the structure by means of core drilling (Fig. 7). The cores were then tested for such conditions as density, strength, resistance to freezing and thawing, water permeability, and resistance to chloride penetration.

Density, compressive strength

Insufficient vibration (undervibration) results in concrete with remaining entrapped air pockets and pores. These voids reduce density, strength, and durability. An increased vibration effort will lift the density to a level where the remaining

Fig. 11 — Testing in special forms was carried out to determine the influence of vibrator insertion on frost resistance.

air-void content has dropped to 1 to 1.5 percent for concrete without entrained air.

Fig. 8 depicts results for concrete with a small amount of entrained air. In this case, the total air-void content is 2.5 percent. Here, a prolonged vibration effort from 250 s/m^3 to 600 s/m^3 (190 to 460 s/yd^3) did not significantly increase density or compressive strength, as determined on cores taken from the hardened structure.

For concrete with an air-void content of 5 to 6 percent, a prolonged vibration of 1200 s/m^3 (920 s/yd^3) resulted in a maximum density increase of 3 percent (Fig. 9). The corresponding strength increase was 12 percent. Further studies, however, showed that this was due to an undesirable reduction in the amount of small entrained air pores.

Freezing, thawing

Freeze-thaw tests of cores from inner parts of the structures cast with air-entrained concrete showed large variations. Conducted with salt water, these tests resulted in data illustrating very good frost resistance in some cases but low values in others.

The test method was the Swedish standard 137244, which means freezing and thawing in contact with a 3 percent $NaCl_2$ solution, measuring the scaling on an exposed surface. An uneven distribution of the scaling effect over the surfaces of some tested cores as shown in Fig. 10 indicates that internal vibration may seriously affect the air-void system in areas close to the vibrator insertions.

This could explain the inconsistent frost-resistance. The local influence of vibrator insertions was confirmed by special tests in smaller forms where the duration of the inserts was varied between 5 and 20 seconds as shown in Fig. 11. In all

Table 1 — Results of freeze-thaw tests in salt solution*

Vibrator insertion with 10 sec. duration in the center of the form					
Test section	Weight loss, scaling, in kg/m² at different freeze-thaw cycles				
	7	14	28	42	56
Center of vibrator insert	0.6	1.6	3.2	4.5	6,0
	Very low frost resistance				

*Insertions with 58 mm (2.25 in.) internal vibrator in forms 600 x 600 x 450 mm (24 x 24 x 18 in.)

Vibrator insertion with 20 sec. duration in the center of the form					
Test section	Weight loss, scaling, in kg/m² at different freeze-thaw cycles				
	7	14	28	42	56
Center of vibrator insert	0.9	2.7	6.0	8.8	11,6
	Very low frost resistance				
100 mm (4 in.) from insert center	0.3	0.6	1.8	2.0	2,2
	Low frost resistance				
200 mm (8 in.) from insert center	0.2	0.3	0.4	0.4	0,4
	Good frost resistance				

*Insertions with 58 mm (2.25 in.) internal vibrator in forms 600 x 600 x 450 mm (24 x 24 x 18 in.)

Vibrator insertion with 20 sec. duration close to a form side					
Test section	Weight loss, scaling, in kg/m² at different freeze-thaw cycles				
	7	14	28	42	56
Concrete surface at vibrator insert point	1.5	5.6	11.6	Test ended	
	Very low frost resistance				

*Insertions with 58 mm (2.25 in.) internal vibrator in forms 600 x 600 x 450 mm (24 x 24 x 18 in.)

the tests, a reduced frost resistance was obtained where the vibrator was inserted and up to a certain distance from the vibrator (Table 1). The observed maximum distance for such an influence was about 100 mm (4 in.). The influence on the frost resistance was substantially increased as the time of insertion was prolonged.

The local influence of vibration with an internal vibrator on the air-void system and frost resistance has also been confirmed by tests in the United States.[6,7] In tests with internal vibration just beside the form side, the frost resistance of the surface was drastically reduced. In certain cases, vibration with small types of internal vibrators between a reinforcement and the form may be motivated by the demand for a dense and pore-free surface. For air-entrained concrete, internal vibration close to the form side should be restricted where a high frost resistance of the surface is required.

In many structures, reinforcement at vertical surfaces makes it necessary to keep a minimum distance of 100 to 150 mm (4 to 6 in.) between the centerline of the vibrator tube and the form surface. Under this condition, it seems possible to achieve an effective air-void system in the surface layer of the structure.

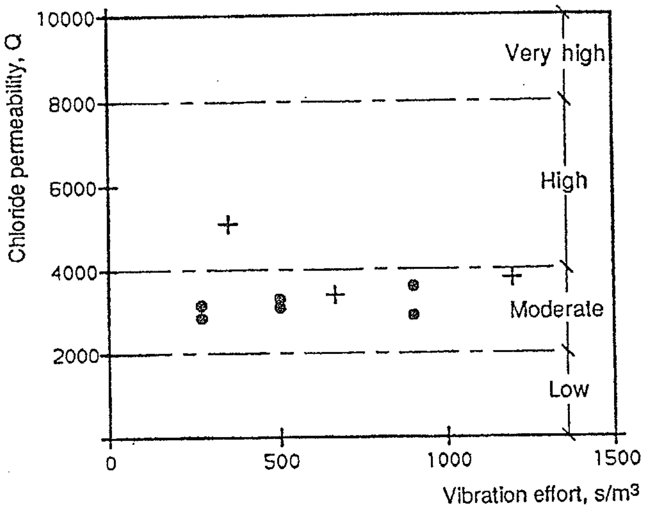


Fig. 12 — Relationship between vibration effort and chloride permeability.

At vertical or horizontal surfaces which run the risk of frost damage, a limitation of the insertion time to 10 to 15 seconds combined with shorter spacing of inserts as indicated in Fig. 2 can be recommended to decrease the influence on the air-void system.

The risk for frost damage in vertical surfaces normally is small due to a low moisture content in the concrete. Exceptions are structures exposed to water and salt splash.

Permeability

In the field studies, water permeability was ascertained by examining cores drilled out in the hardened concrete. The permeability was measured by the depth of penetration into the concrete at a pressure of 0.8 MPa (120 psi). Prolonged vibration up to 1200 s/m³ (920 s/yd³) did not have any significant influence on the water permeability. However, low vibration efforts (undervibration) were not included in these test series.

Chloride permeability was also measured on cores drilled out of the hardened concrete. The AASHTO method T277-831, "Rapid Determination of the Chloride Permeability of Concrete," was used (Fig. 12). The influence of the vibration effort was principally the same as in the water permeability tests.

Surface voids

The studies have mainly confirmed the existing experience that an increased vibration effort reduces the number of air voids in the concrete surfaces. In the upper parts of the vertical surfaces, a certain number of air voids at high vibration efforts were found when plastic concrete was used. Revibration is recommended as a means to increase the density and improve the surface appearance in the upper parts of concrete structures.

With highly plastic or flowing consistency and adequate vibration, all surfaces, including upper parts, were practically free of air voids.

The number of surface air voids, commonly known as bugholes, can be substantially reduced by an increased vibration effort. Specifications that call for a limitation of the number of air voids contribute to a greater security in obtaining satisfactory consolidation of the surface layers of a structure.

Table 2 — Guide values for adequate vibration effort and practical vibrator capacity for different casting conditions*

Degree of difficulty	Adequate vibration effort		Practical vibrator capacity	
	(s/m³)	(s/yd³)	(m³/h)	(yd³/h)
Simple castings: Large open forms easily accessible	200-300	150-230	6-10	8-13
Castings of medium difficulty: Walls, columns, beams, slabs with normal reinforcement density	300-400	230-310	4-6	5-8
Difficult castings: Narrow beams and walls with dense reinforcement, also prestressed	400-600	310-460	3-4	4-5

* Concrete of plastic consistency (slump 75-125 mm [3-5 in.]) vibrated with internal vibrators with a diameter of 55-60 mm (2.25-2.50 in.).
NOTE: For superplasticized concrete with a slump about 200 mm (8 in.) the vibration can be reduced by 50 percent and the corresponding practical vibrator capacity increased by 100 percent.

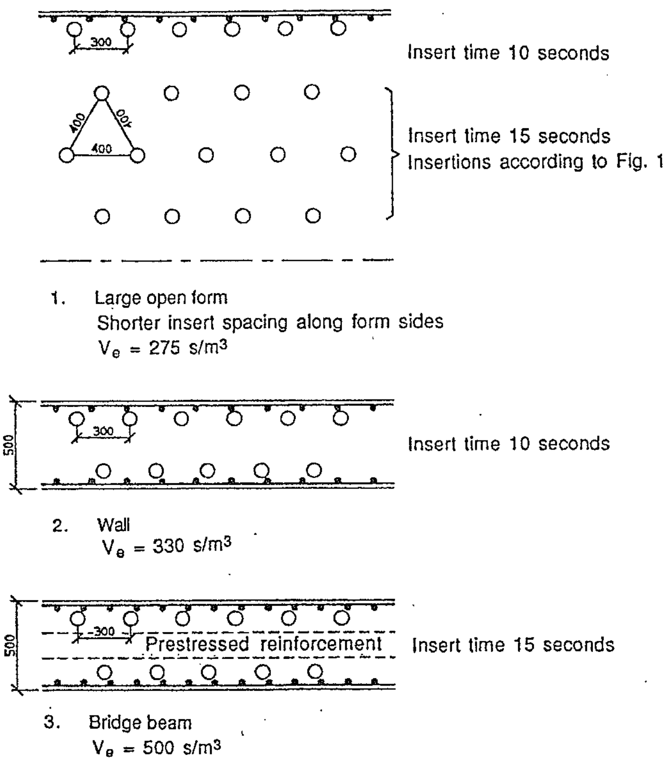


Fig. 13 — Large open form, wall, and bridge beam examples of vibration plans. Concrete had a plastic consistency when vibrated at 55-60 mm (2.25-2.5 in.).

Overvibration

As mentioned previously, insufficient vibration (undervibration), can seriously influence the homogeneity and quality of a structure.

Also a very large vibration effort (overvibration), may result in loss of quality. The possible influence on the entrained air-void system has been discussed.

The risk for segregation of the concrete mix must also be taken into account. In one of the field studies, dark "pour" lines were formed in vertical concrete surfaces, probably caused by segregated layers of cement paste in borderlines between the successively placed concrete layers. The presence of "pour" lines was decreased with a reduction of the vibration effort from initially 600 s/m³ to about 300 s/m³ (460 s/yd³ to 230 s/yd³). However, the field studies have mainly confirmed the established rule that the risk for defects due to undervibration are definitely higher than those of overvibration.

Workable mixtures

In present Swedish practice, bridge projects are normally cast with concrete with a plastic consistency, a slump of about 100 mm (4 in.). In some cases, however, more fluid mixtures have been used.

For most concrete structures, more workable concrete mixtures may be desirable. This will reduce the need for vibration, the risk for casting defects will be lower, and the number of surface air voids can be substantially lowered. With more fluid mixtures, it is easier to place the concrete in horizontal layers of uniform and limited thickness, an important condition for a good final result. From an ergonomic point of view, a reduced vibration effort is highly desirable.

A change of the consistency from a slump of about 100 mm (4 in.) to a more workable concrete with a slump about 200 mm (8 in.) may reduce the necessary vibration effort by 50 percent when the placing conditions are the same, as shown in the field studies.[1,3]

The large, complex offshore structures in the North Sea were mostly cast with flowing concrete with a slump of over 200 mm (8 in.).

The recent ACI Committee 309 document, "Guide to Consolidation of Concrete in Congested Areas,"[8] recommends flowing concrete for advanced concrete work in narrow and densely reinforced forms.

Site procedures

For large concrete constructions, the casting procedures should be especially well planned and prepared with care. Detailed plans should be made for the different casting sections and for vibration performance.

Special meetings with the supervisors and workers responsible for the casting should be held and, at the start of a job, a meeting to discuss consolidation of concrete is recommended. Audio-visual presentations are helpful.

Vibration efforts

The amount of necessary vibration is primarily influenced by the following factors:

- Basic quality requirements for the hardened concrete,
- Degree of difficulty with placing conditions, form dimensions, amount of reinforcement, type of embedments, and other possible problems, and
- Type of concrete defined by workability and consistency of the mixture.

Some guidelines are given in Table 2 with regard to the choice of adequate vibration efforts for different placing conditions in high-quality concrete work.

These guidelines are based on field tests as well as practical experience in Sweden.

With respect to the data in Table 2, it should be noted that, for superplasticized concrete with a slump of about 200 mm (8 in.), the vibration effort can be reduced by 50 percent and the corresponding practical vibrator capacity increased by 100 percent.

In addition, an approximate relationship exists between the radius of action and the tube diameter of an internal vibrator.[9] For internal vibrators with diameters of other than 55 to 60 mm (2.2 to 2.4 in.), corrections of the vibration effort and practical vibrator capacity can be made with a factor of $(D/57)^2$ where D is the diameter of the vibrator tube in mm. For example, $D = 70$ mm. Correction factor $(70/57)^2 = 1.51$. Divide vibration effort by 1.51 and multiply vibrator capacity by 1.51.

Vibration plans

After choosing a suitable vibration effort, plans showing the positions and durations of the vibration insertions should be prepared. Suitable spacings and durations can be selected with guidance of the Fig. 2 diagram.

A check of the vibration effort can be made with the formula $V_e = n \cdot T/V$ previously described in the section headed "Vibration effort."

With 55 to 60 mm (2.25 to 2.5 in.) internal vibrators to be used in plastic concrete, the distances between the insertions should not exceed 400 mm (16 in.), corresponding to seven times the tube diameter. The duration of the insertions should normally amount to between 10 and 20 seconds. With air-entrained concrete, the durations should be limited to 10 to 15 seconds when vibration is performed close to vertical or horizontal surfaces to avoid disturbing the air void system. Some examples of vibrating plans are shown in Fig. 13. The examples show castings with different degrees of difficulty.

In narrow and congested sections the ordinary vibrators have to be supplemented with vibrators of a small diameter.

Checking results

After the first casting of a structure performed according to plan, a careful inspection of its appearance should be made.

For major structures, a test of the hardened concrete, especially its surface layer, may be desirable. In-situ permeability tests are under development as are other nondestructive testing methods. At present, however, core drilling is the primary method of checking results of the consolidation. For example, cores with a diameter of 50 to 100 mm (2 to 4 in.) can be drilled to a depth of similar measurements with comparatively light and simple equipment. The cores can be investigated by ocular inspection and tested for density, compressive strength, permeability, resistance to freezing and thawing, and other conditions.

Conclusions

As previously noted, some guidelines have been established with respect to the necessary amount of concrete vibration for castings of different degrees of difficulty. The amount of vibration has been expressed by the "vibration effort," equal to the effective time of vibration per concrete volume measured in seconds per cubic meter or cubic yard.

The guidelines may be especially applicable for large concrete projects for which casting operations should be carefully planned, prepared, and carried out.

Acknowledgments

Major portions of the field studies were performed in close cooperation with NCC, a leading Swedish contracting firm. Economical support for the projects was received from SBUF, the Development Fund of the Swedish Building Branch.

References

1. Forssblad, L.; Leckstrom, P.; and Sällström, S., "Optimal vibreringsinsats vid betonggjutningar, slutrapport," (Optimum amount of concrete vibration), Report of SBUF, the Development Fund of the Swedish Building Branch, Stockholm, 1993.

2. Alemo, J., and Grandas, J.A., "Optimal vibreringsinsats for anlaggningsbetong," (Optimum amount of concrete vibration in dam construction), Vattenfall, Stockholm, 1989.

3. Peterson, O.; Johansson, A.; and Granhed B., "Optimal konsistens for brobetong," (Optimum concrete consistency in bridge construction), Swedish Cement and Concrete Research Institute, Stockholm 1992.

4. "Concrete Manual," U. S. Bureau of Reclamation, 8th edition, 1975.

5. Vuorinen, J., "Application of Diffusion Theory to Permeability Tests on Concrete," Part I and II, *Magazine of Concrete Research,* V. 37, No. 132, September 1985.

6. Simon, M. J.; Jenkins, R. B.; and Hover K. C., "The Influence of Immersion Vibration on the Void System of Air Entrained Concrete," *Durability of Concrete: G. M. Idorn International Symposium,* SP-131, American Concrete Institute, Detroit, 1992.

7. Stark, D. C., "Effect of Vibration on the Air-Void System and Freeze-Thaw Durability of Concrete." *Research and Development Bulletin,* Portland Cement Association, Skokie, 1986.

8. ACI Committee 309, "Guide to Consolidation of Concrete in Congested Areas (ACI 309.3R-92)," American Concrete Institute, Detroit, 1992.

9. ACI Committee 309, "Behavior of Fresh Concrete During Vibration (ACI 309.1R-93)," American Concrete Institute, Detroit, 1993.

Received and reviewed under Institute publication policies.

Forssblad

Sällström

Lars Forssblad, an ACI member, is a former member of ACI Committee 309, Consolidation of Concrete. He was research director for Dynapac, the Swedish firm which specializes in compaction equipment for concrete, soil, and asphalt. He joined Dynapac in 1959 after being involved in several Swedish hydropower and dam projects.

Stig Sällström, also an ACI member and a consultant in Stockholm, Sweden, is a former concrete specialist for the Swedish State Power Board. From 1976 to 1989 he was technical director of that nation's ready-mixed concrete and gravel/crushed stone associations.