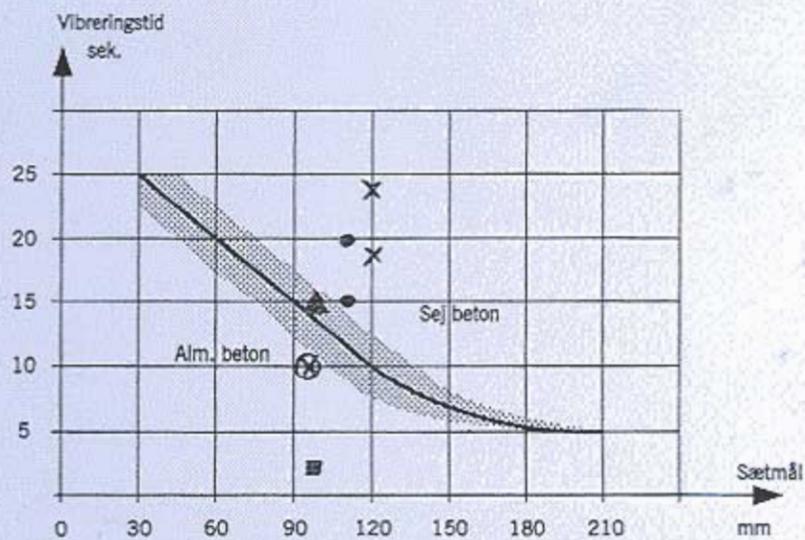




HETEK

Undersøgelse af stavvibrering



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Forord

Rapporten giver resultaterne fra HETEK opgave 5B, som er en registrering af vibrering med stavvibrator på 5 støbninger.

Baseret på undersøgelserne er vejledningen fra HUA-2 Projektet:

- Vibrering med stavvibrator, Vejledning.
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Vibreringsprojektet HUA-2, opgave 4 er dokumenteret i følgende publikationer:

- 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

Resumé

Der er registreret vibrering på 5 udvalgte støbninger:

- 1 Væg udstøbt på eksisterende fundament
- 2 Forspændt brodæk i butterfly profil
- 3 Prøvestøbning af kantbjælke og fundament
- 4 Skråvæg udstøbt på eksisterende fundament
- 5 Bundplade i kassedrager

Undersøgelserne viser at den anbefalede sammenhæng fra HUA-2 vejledningen mellem vibreringstid og sætmål er en rimelig anbefaling. Vibreringstiderne kunne formentlig reduceres med 20 til 30 %, men da luftporeanalyserne fra undersøgelserne også er acceptable for konstruktioner med længere vibreringstider, anses HUA-2 sammenhængen for at være tilfredsstillende.

Siden HUA-2 Vejledningen blev skrevet i 1994, er det blevet mere klart, at holdbarheden kan nedsættes væsentligt, hvis der overvibreres med stavvibrator. Svenske undersøgelser har påvist at frostbestandigheden ødelægges, hvis staven kommer for tæt på formoverfladen.

Baseret på ovenstående anbefales det, at der aldrig foretages nedstik nærmere formsiden end 3d regnet fra vibratorstavens symmetrilinie. Denne regel angives i den reviderede vejledning for stavvibrering.

1 Undersøgelsens formål

Formålet med undersøgelseerne er at få verificeret de vibreringstider, der er anbefalet i Vejledningen fra HUA-2 Projektet.

2 Ny viden

Siden HUA-2 vejledningen blev skrevet i 1994 er det blevet almindelig kendt at vibrering med stavvibrator kan ødelægge betonens makro-, mikro- og luftporestruktur og dermed holdbarheden af konstruktionernes dæklag.

På Storebælts Østbro var der store vanskeligheder med at opfylde kravene til mikrostruktur og luftporestruktur. Betonens frostbestandighed blev undersøgt ved Borås metoden SS 137244. Resultatet var overraskende dårligt idet ca. 20 % af de undersøgte borekerner fra konstruktionerne havde afskallinger større end $1,0 \text{ kg/m}^2$, hvilket er den maksimalt tilladelige afskalling for borekerner fra konstruktioner efter SS 137244.

Borekerner fra Øresunds landanlæg har samme tendens til mangelfuld luftporestruktur og frostbestandighed som på Storebælt.

En svensk undersøgelse udført af Lars Forssblad og Stig Sällström offentliggjort i Concrete International september 1995 viser en alarmerende sammenhæng mellem stavvibrering og manglende frostbestandighed ved prøvning efter SS 137244.

Udover denne HETEK opgave med registrering af vibreringstider har en dansk entreprenør gennemført en systematisk afprøvning af sammenhængen mellem afstanden til stavvibratoren og tabet af indblandet luft i betonen.

Storebælt og Øresund

Resultaterne fra Storebælt og Øresunds landanlæg viser, at der ikke er nogen klar sammenhæng mellem de traditionelle krav til luftporestrukturen og resultaterne fra frostprøvning efter metoderne SS 137244 og ASTM 666 for høj kvalitetsbeton med lavt vandcementforhold under 0,45.

Undersøgelser af fluorescensimprægnerede planslib af emner efter exponering efter henholdsvis SS 137244 og ASTM 666 tyder på at frost angrebene kommer, hvor der er revner eller porøsiteter ved den exponerede overflade. Hvis dette er rigtigt, vil frostbestandigheden af høj kvalitetsbeton først og fremmest afhænge af makro- og mikrostrukturens revner og porøsiteter og kun sekundært af luftporesystemet.

Andre aggressive miljøpåvirkninger vil på samme måde som frost kunne angribe ved revner og porøsiteter. Da høj kvalitetsbeton har en større tendens til revnedannelse på grund af et højere autogentsvind, vil høj kvalitetsbeton være mere følsom overfor overvibrering end almindelig beton.

Stavvibreringen har stor indflydelse på både makro-, mikrostrukturen og luftporesystemet i betonen og vil derfor være en afgørende faktor for betonkonstruktioners holdbarhed.

Undersøgelserne af frostbestandigheden på Storebælt ledte til undersøgelse af de anvendte vibreringsmetoder og var medvirkende til, at A/S Storebæltsforbindelsen støttede projektet HUA-2, som omfattede undersøgelser af stavvibrering og resulterede i vejledningen i stavvibrering.

Svenske undersøgelser

De svenske undersøgelser af stavvibrering blev offentliggjort i september 1995 på nogenlunde samme tid som vejledningen fra HUA-2 projektet.

Der anbefales samme størrelsesorden af vibreringstid som i HUA-2 vejledningen, mellem 5 og 25 sek, og det anføres at vibreringstiden kan halveres ved anvendelse af flydebetoner med sætmål af størrelsesordenen 200 mm.

Stavvibreringens indflydelse på betonkvaliteten er undersøgt ved følgende metoder:

- densitet
- styrke
- permabilitet
- chlorid permabilitet
- luftindhold
- frostbestandighed

Mest markante resultater er opnået ved frostprøvning efter SS 137244, resultaterne er vist i figur 1 fra artiklens tabel 1.

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/m ² 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/m ² 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/m ² 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.)

Figur 1 Resultater tabel 1 fra de svenske undersøgelser

Kravet til maksimal tilladelig afskalling efter SS 137244 er 0,5 kg/m² for laboratorieprøver og 1,0 kg/m² for borekerner fra konstruktioner.

Med en vibreringstid på 10 sek. vil afskallingen på prøver taget umiddelbart op ad stavvibratoren være 6,0 kg/m², hvis vibreringstiden fordobles til 20 sek. fordobles afskallingen til 11,6 kg/m².

Med en vibreringstid på 20 sek. vil afskallingen reduceres fra 11,6 kg/m² til 2,2 kg/m² i afstanden 100 mm fra staven svarende til ca. 2d, og til 0,4 kg/m² i afstanden 200 mm fra staven svarende til ca. 4d.

Det er efter disse resultater kun beton med en afstand på 4d til nærmeste nedstik, som vil opfylde kravene efter SS 137244. HUA-2 vejledningen anbefaler en afstand til formsiden på 2d til 3d, altså lidt på den usikre side.

Holdes staven tæt på formsiden viser de svenske resultater, at prøverne går istykker efter 28 cykler, og at prøvningen ikke kan gennemføres til de krævede 56 cykler.

Konklusionen på de svenske undersøgelser er klar. Hvis dæklaget i en betonkonstruktion skal være frostbestandig må stavvibratoren aldrig komme nærmere formsiden end 4d.

Danske undersøgelser

En dansk entreprenør har i 1996 undersøgt sammenhængen mellem vibreringstiden og luftindholdet i betonen på en højkvalitetsbeton.

Små bjælker med dimensionerne 500 x 500 mm og længde 2300 mm blev vibreret med en 66 mm stavvibrator 200 Hz i indmålte afstande fra formsiden på 100 mm og 200 mm.

Betonen havde målt før vibreringen et luftindhold på 6,5 %, et sætmål på 120 mm og en temperatur på 17 °C.

Resultaterne er vist i figur 2.

Vibreringstid	Afstand fra center af stav til formside	
	100 mm	200 mm
sek.	Total luftindhold %	Total luftindhold %
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

Figur 2 Sammenhæng mellem luftindhold og afstand til stavvibrator

Resultaterne viser, at den indblandede luft vibreres ud af betonen. Hvis luftindholdet skal være tilfredsstillende ved formsiden, skal afstanden fra center af staven til formsiden være mindst 200 mm svarende til 3d ved en vibreringstid på over 5 sek.

3 Registreringer HETEK 5B

3.1 Undersøgelse 1

Konstruktionstype

Den undersøgte konstruktionsdel er en væg udstøbt på et eksisterende fundament. Væggens dimensioner er højde x tykkelse x længde: 1,80 m x 0,40 m x 20,0 m. Armeringen består af Y16 pr. 150 mm lodret i begge sider, og Y12 pr. 300 mm vandret i begge sider. Dæklaget er 35 mm og tolerance på + 5 mm. De anvendte afstandsklodser er 40 mm.

Udlægning og vibrering

Udlægningen er tilfredsstillende.

Nedstiksafstanden samt afstanden til formsiden er som anbefalet i HUA-2 vejledningen. Mikrostrukturen i dæklaget er tilfredsstillende, hvilket viser, at vibreringstiden og vibratorens afstand til formen er korrekt.

Vibreringstiden pr. nedstik på 7 - 8 sek. for et sætmål på 120 mm er ligeledes som anbefalet i HUA-2 vejledningen, men nedstiksybden er langt større end anbefalet, hvorved den totale vibreringstid, dvs. inklusiv genvibrering, bliver større. Det anbefales, at nedstiksybden samt vibreringstiden i HUA-2 vejledningen følges.

3.2 Undersøgelse 2

Konstruktionstype

Den undersøgte konstruktionsdel er et forspændt brodæk med butterfly profil og følgende dimensioner, bredde x længde x højde: 8,0 x 64,6 x 1,54 m midt på tværsnittet og 0,40 m i siderne. Dimensionen af kantbjælkerne er ca. 0,46 x 0,50 m. Dæklaget er 30 mm med tolerance på + 10 mm, de anvendte afstandsklodser er 35 mm.

Kantbjælkerne er armeret med bøjler T12 pr. 200 mm og 14 T20 i længderetningen fordelt langs bøjlerne. Brodrageren er armeret med T16 pr. 200 mm i længderetningen i top og bund samt T12 pr. 200 mm i tværretningen i top og bund. Derudover er der ilagt forankringskabler samt diverse ekstra armering i form af bøjler mv.

Udlægning og vibrering

Udlægningen er tilfredsstillende, men lagtykkelsen skønnes at kunne øges 10 - 15 cm, svarende til en lagtykkelse på ca. 0,8 x længden af stavvibratoren, som anbefalet i HUA-2 vejledningen. Herved ville genvibreringsdybden i det underliggende lag automatisk mindskes til 5 - 10 cm, når staven holdes, så toppen kan ses.

De anvendte nedstiksafstande er som anbefalet i HUA-2 vejledningen.

Den anvendte vibreringstid på 10 sek. for et sætmål på 100 mm er lidt lavere end anbefalet i HUA-2 vejledningen, men tilfredsstillende. Det skønnes, at den anbefalede vibreringstid kan nedsættes.

3.3 Undersøgelse 3

Konstruktionstype

Den undersøgte konstruktionsdel er prøvestøbning af 3 kantbjælker suppleret med prøvestøbning af 2 fundamenter i forbindelse med udførelse af en broentreprise på Øresunds landanlæg.

Udlægning og vibrering

Udlægningen er tilfredsstillende.

Vibreringstiden med \varnothing 48 mm staven 15 sek. pr. 0,4 m er som anbefalet i HUA-2 vejledningen for et sætmål på 100 mm, men skønnes at kunne sættes ned til 10 sek.

Vibreringstiden med \varnothing 25 mm staven 5 sek. pr. 0,2 m er kortere end anbefalet i HUA-2 vejledningen, men skønnes at kunne øges til 10 sek.

3.4 Undersøgelse 4

Konstruktionstype

Den undersøgte konstruktionsdel er en skråvæg udstøbt på et eksisterende fundament. Væggens dimensioner er (højde x tykkelse x længde) : 2,85 - 3,00 m x 0,50 m x ca. 9 m. Der udover består væggen af ca. 5 m væg, hvorover væggens højde falder fra ca. 3 m til ca. 1 m, denne del indgår ikke i undersøgelsen.

Armeringen består af T20 pr. 200 mm lodret i begge sider, dog pr. 100 mm på væggens nederste tredjedel på indersiden, og T12 pr. 100 vandret i begge sider.

Derudover er der ekstra armering i form af T25 i toppen af væggen og U-bøjler T20 pr. 200 mm i toppen af væggen og pr. 100 mm i bunden af væggen, U-bøjlerne længde udgør ca. 2 m af væggen højde.

Dæklaget er 30 mm med tolerance på 10 mm, de anvendte afstandsklodser har en tykkelse på 35 mm.

Udlægning og vibrering

Udlægningen er ikke tilfredsstillende. Faldhøjden har været op til ca. 3 m for det nederste lag og udpumpningsmetoden, hvor pumpe-slanger har været støttet mod armeringen i væggen inderside, har medført separation af betonen, som er en medvirkende årsag til den uacceptable mikro- og makrostruktur i betonen. Udlægningsmetoden kunne forbedres ved at isætte støberuser til pumpe-slanger centralt i væggen.

Den anvendte lagtykkelse har været 45 - 80 cm, hvilket er meget tykke lag. For at få vibreret hele laget samt sikret sammenvibrering med det underliggende lag er der vibreret i flere dybder ved hvert nedstik, men ved denne metode er det svært at sikre en systematisk vibrering. Det anbefales derfor at nedsætte lagtykkelsen, så den tilpasses vibratorstavnens længde, som anbefalet i HUA-2 vejledningen. Samtidig anbefales det ved en skråvæg, at isætte vibratorledere i væggen centerlinie for at få en mere jævn vibrering i væggen og undgå, at vibratorstaven kommer for tæt på formen i væggen inderside.

Da der ved de enkelte nedstik er vibreret i flere dybder, er det svært at vurdere den faktiske vibreringstid i de enkelte områder. Men det skønnes, at vibreringstiden har været 15 - 20 sek., hvilket er 5 - 10 sek. mere end anbefalet i HUA-2 vejledningen. Baseret på luftporeanalyserne bør vibreringstiden nedsættes, og det skønnes, at en vibreringstid på 10 sek. som anbefalet i vejledningen vil være passende.

Nedstiksafstanden har specielt i de nederste lag, hvor der er ilagt ekstra armering, været større end anbefalet i HUA-2 vejledningen. For stor nedstidsafstand giver dårlig komprimering og kan være årsag til den høje pastapåværelse konstateret i tyndslibsanalyserne.

3.5 Undersøgelse 5

Konstruktionstype

Den undersøgte konstruktionsdel er bundpladen i et hult brodæk med butterfly profil. Bundpladen har følgende dimensioner, (bredde x længde x højde): 4,54 x 46,77 x 0,25 m. Dæklaget er 35 mm med tolerance på + 5 mm, de anvendte afstandsklodser er 40 mm.

Armeringen består af Y20 pr. 150 mm i længderetningen i pladens over- og underside og Y16 pr. 200 mm i tværretningen i pladens overside samt Y20 pr. 200 mm i pladens underside. I begge sider i længderetningen er der ilagt strittere Y20 pr. 200 mm i pladens overside. Den totale længde af stritterne er 1400 mm.

Udlægning og vibrering

Udlægningen er tilfredsstillende.

Den anvendte nedstiksafstand svarer til det, der i HUA-2 vejledningen anbefales for en svært armeret beton med mindre omfang af svært tilgængelige områder. Vurderes konstruktionen derimod at være normalt armeret kunne nedstiksafstanden godt øges med 2 x stavens diameter. Men betragtes armeringsnettets udformning er det fornuftigt at foretage nedstik i hver anden åbning i nettet, som udført.

Den anvendte vibreringstid pr. nedstik på 2 sek er ca. 10 sek. lavere end den i HUA-2 vejledningen anbefalede for et sætmål på 90 mm, men resultatet af laboratorieundersøgelserne er tilfredsstillende. Virkningen af bjælkevibratoren er ikke kendt, men ud fra de foretagne laboratorieanalyser, synes der ikke at være nogen markant forskel mellem den øvre og nedre del af kernerne. Vibreringstiden for et sætmål på 90 mm skønnes at kunne nedsættes med 5 sek.

4 Vibreringstid og sætmål

Sammenhængen mellem betonens sætmål ved vibreringen og den registrerede vibreringstid er vist i Tabel 4.1 sammen med betonens luftindhold.

	Vib. tid sek.	Total luft i beton i %	Sætmål mm
Undersøgelse 1:			
lag 2	19	7,2 ¹⁾	120 ¹⁾
lag 3	24	7,2 ¹⁾	120 ¹⁾
Undersøgelse 2:			
brodrager	10	5,4 ²⁾	100 ²⁾
kantbjælke	10	5,4 ²⁾	100 ²⁾
Undersøgelse 3:			
Fundament	15	6,2 ³⁾	100 ³⁾
Undersøgelse 4:			
lag 1	20	7,2 ⁴⁾	110 ⁴⁾
lag 2	15	7,2 ⁴⁾	110 ⁴⁾
lag 3	15	7,2 ⁴⁾	110 ⁴⁾
Undersøgelse 5:			
bundplade	2	6,7 ⁵⁾	90 ⁵⁾

¹⁾ Værdi før pumpe, skønnet ud fra måling på fabrik

²⁾ Gn. snit af 15 målinger efter pumpe på byggeplads

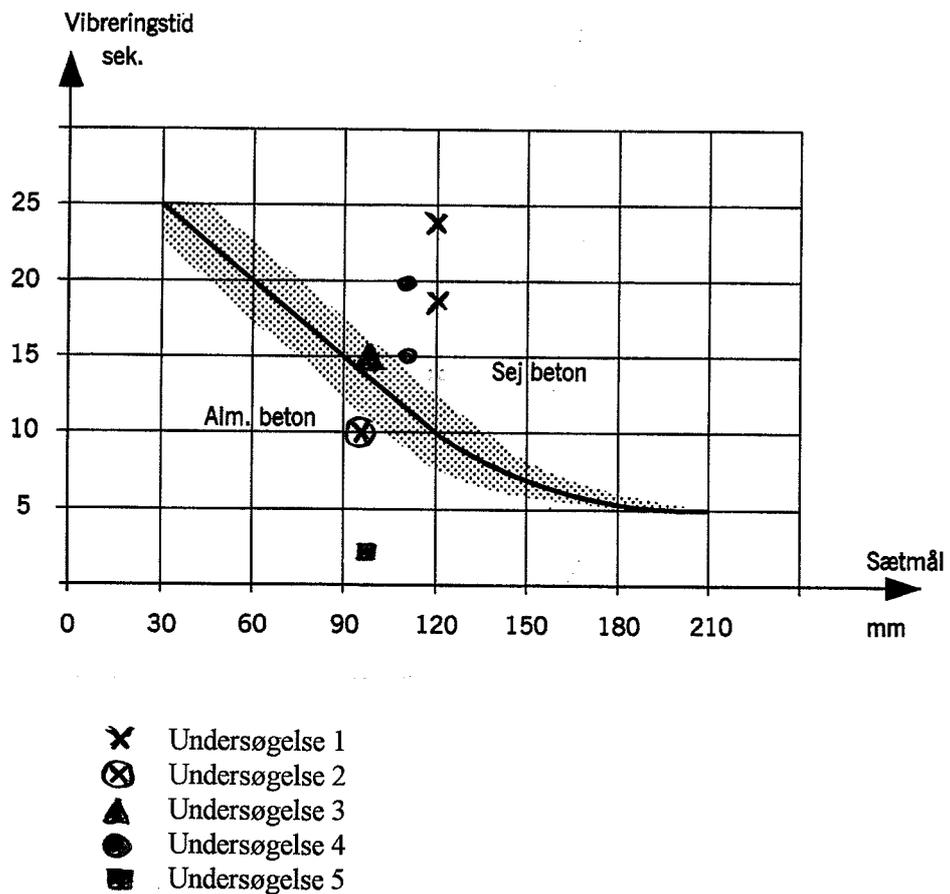
³⁾ Værdi efter pumpe på byggeplads

⁴⁾ Værdi før pumpe på byggeplads, 1 måling ved lag 2-3

⁵⁾ Gn. snit af 8 målinger på byggeplads

Tabel 4.1 Sammenhæng mellem sætmål og registrerede vibreringstider.

De registrerede vibreringstider er plottet i det tilsvarende diagram fra HUA-2 vejledningen i figur 4.1.



Figur 4.1 Sammenhæng mellem vibreringstider og sætmål

Resultaterne viser, at der er anvendt beton med sætmål mellem 100 og 120 mm ved alle de undersøgte støbninger. Vibreringstiderne ligger spredt mellem 10 og 25 sek., med et enkelt resultat på 2 sek.

5 Analyse af borekerner

Borekerner fra konstruktionerne er undersøgt ved fluorescensimpregnede planslib, tyndslib og luftporeanalyser.

Tabel 5.1 viser de af resultaterne fra plan- og tyndslib, der skønnes at påvirkes af vibreringen, og som har indflydelse på holdbarheden.

Tabel 5.2 viser resultaterne af luftporeanalyserne.

	Kerne nr.	Tyndslib	Imprægneret planslib			
		Pasta-homogenitet	Bleeding og pastaseparation	Revner	Stenfordeling	Indkapslet luft
Undersøgelse 1:						
lag 2	A1	0,3	1	1	0	0
lag 2	A2	0,1	1	1-2	0	0
lag 2	A3	0,3	1	1	0	0
lag 3	A4	0,5 ¹⁾	1	1-2	0	0
lag 3	A5	0,1	1	1	0	0
lag 3	A6	0	1	0-1	1	0
Undersøgelse 2:						
brodrager	B1	1 ¹⁾	-	-	2	-
brodrager	B2	1,6 ¹⁾	2	1	0	1 ²⁾
brodrager	B3	1,6 ¹⁾	1-2	1	0	1
kantbjælke	K1	0,7 ¹⁾	-	-	0	-
kantbjælke	K2	0,9 ¹⁾	1	1	1	1
kantbjælke	K3	1,1 ¹⁾	2-3	3	0	1
Undersøgelse 4:						
lag 1, inderside	I/I1	1,7 ¹⁾	3	2-3	0	0 ²⁾
lag 1, yderside	I/I4	2,2 ¹⁾	3	2	2	1 ²⁾
lag 2, inderside	II/II1	1,5 ¹⁾	2	1	0	0
lag 2, yderside	II/II2	2,2 ¹⁾	3	2-3	1	1 ²⁾
lag 3, inderside	III/III1	1,1 ¹⁾	1-2	1	3	0
lag 3, yderside	III/III4	2,3 ¹⁾	1-2	1	1	1 ²⁾
Undersøgelse 5:						
bundplade	E1	0,4	1(-2)	1	0	1
bundplade	E2	0,3	1	1	0	0
bundplade	E3	1,0 ¹⁾	0-1	1-2	0	1

¹⁾ Forøget kapillarporøsitet og bleeding langs sand og sten

²⁾ Vedhæftning til armering synes dårlig

Tabel 5.1 Resultaterne fra plan- og tyndslib, der skønnes at påvirkes af vibreringen, og som har indflydelse på holdbarheden.

	Kerne nr.	Total luft i beton i %	Luft i kitmasse i %			Spec. overfl. mm ⁻¹
			Total	< 0.35 mm	> 0.35 mm	
Undersøgelse 1:						
lag 2	A1	5,9	17,4	14,4	3	41
lag 2	A2	4,8	14,5	11,8	2,7	37
lag 2	A3	6,7	19,4	16,5	2,9	41
<i>Gn. snit lag 2</i>		5,8	17,1	14,2	1,8	40
lag 3	A4	5,3	15,8	14	1,8	42
lag 3	A5	5	15	13,2	1,8	45
lag 3	A6	4,4	13,4	12,2	1,2	46
<i>Gn. snit lag 3</i>		4,9	14,7	13,1	1,6	44
Undersøgelse 2:						
brodrager	B1	5,1	15,8	9	6,8	28
brodrager	B2	3,9	12,8	9,2	3,6	37
brodrager	B3	3,5	11,2	8	3,2	36
<i>Gn. snit brodrager</i>		4,2	13,3	8,7	4,5	34
kantbjælke	K1	6,6	19,2	13,1	6,1	28
kantbjælke	K2	5,9	17,9	8,8	9,1	23
kantbjælke	K3	2,2	7	5,1	1,9	34
<i>Gn. snit kantbj.</i>		4,9	14,7	9	5,7	28
Undersøgelse 3:						
fundament	1	1,8	6,6	3,8	2,8	28
fundament	2	3,7	12,7	8,2	4,5	30
fundament	3	5,3	17,3	9,4	7,9	24
<i>Gn. snit</i>		3,6	12,2	7,1	5,1	27
Undersøgelse 4:						
lag1, prøve I1	I	2,3	7,8	6,8	1	45
lag1, prøve I2	I	3,9	12,4	8,6	3,8	32
lag1,prøve I3	I	4,6	14,4	10,3	4,1	35
lag1, prøve I4	I	4,6	14,4	10,3	4,1	36
lag 2, prøve II1	II	4,3	13,1	9,8	3,3	35
lag 2, prøve II2	II	4,1	13	8,8	4,2	36
lag 3, prøve III1	III	2,6	8,5	6,9	1,6	41
lag 3, prøve III2	III	5,3	16,3	10,2	6,1	29
lag 3, prøve III3	III	4,6	14,4	10,9	3,5	39
lag 3, prøve III4	III	5,1	16,3	11,8	4,5	35
Undersøgelse 5:						
bundplade	E1	6,5	18,9	15,1	3,8	36
bundplade	E2	6,6	19,7	16,5	3,2	38
bundplade	E3	5,7	17,4	13,1	4,3	34
<i>Gn. snit</i>		6,3	18,7	14,9	3,8	36

Tabel 5.2 Resultaterne af luftporeanalyserne.

Undersøgelse 4 viser en dårlig pastahomogenitet, bleeding, revner og uens stenfordeling, men luftporestrukturen er acceptabel. De registrerede defekter er forårsaget af udlægningsmetoden i den skrå væg, der har forårsaget separationer.

Bortset fra undersøgelse 1 viser de øvrige undersøgelser problemer med pastahomogeniteten.

Bortset fra undersøgelse 1 viser de øvrige undersøgelser problemer med bleeding og pastaseparationer.

Undersøgelse 1 og 4 har mange revner bedømt på planslib.

Stenfordelingen er generelt i orden bortset fra undersøgelse 4.

Ingen af undersøgelseerne har problemer med indkapslet luft, hvilket viser, at vibreringen har været tilstrækkelig ved alle undersøgelser.

Luftporestrukturen er tilfredsstillende ved undersøgelse 1 og 5. Ved øvrige undersøgelser har enkelte kerner for lidt luft, specielt undersøgelse 3 viser 2 meget lave luftindhold.

6 Konklusioner

Det er vanskeligt at registrere vibreringstider, når lagtykkelsen af betonen er større end de anbefalede 80 % af vibratorstaven, og når vibratoren stikkes for dybt ned i foregående lag.

Operatørene har samme problem med at vurdere, om resultatet er godt, når de vibrerer på denne måde. Operatørene bør undervises i kun at vibrere det aktuelle lag og sammenvibrerer det med det underliggende lag.

Det er en ganske udbredt fejl at stikke vibratoren for langt ned både i det underliggende lag og adskillige af de foregående lag. Ved denne praksis risikeres det meget nemt, at områder overvibreres.

Der er ingen viden om sammenhængen mellem formens sværhedsgrad og nedstiksafstanden hos operatørene.

Der er nogen viden om sammenhængen mellem betonens sætmål og vibreringstiden hos operatørene.

Undersøgelseerne viser, at den anbefalede sammenhæng fra HUA-2 vejledningen mellem vibreringstid og sætmål vist på figur 4.1 er en rimelig anbefaling. Vibreringstiderne kunne formentlig reduceres med 20 til 30 %, men da luftporeanalyserne fra undersøgelserne er acceptable også fra de støbninger, hvor længere vibreringstider end anbefalet er anvendt,

anses HUA-2 sammenhængen for at være tilfredsstillende.

Dette støttes af de danske undersøgelser refereret i afsnit 2, figur 2, hvoraf det ses, at den indblandede luft først for alvor tabes ved vibreringstider på 30 sek. og der over ved et sætmål på 120 mm.

Det er dokumenteret, at betons holdbarhed ødelægges i nedstikspunktet og området tæt ved nedstikket. For at sikre holdbare betonkonstruktioner er det derfor vigtigt, at der aldrig foretages nedstik i konstruktionens dæklag og umiddelbare nærhed. I HUA-2 vejledningen anbefales en afstand til formsiden på 2 til 3d, hvor d er vibratorstavens diameter. Baseret på de svenske undersøgelser refereret i afsnit 2 bør afstanden være 4d. De danske undersøgelser refereret i afsnit 2 viser, at der stadig er en rimelig mængde luft tilbage ved vibrering i en afstand af 3d.

Baseret på ovenstående anbefales det, at der aldrig foretages nedstik nærmere formsiden end 3d regnet fra vibratorstavens symmetrilinie. Denne regel angives i den reviderede vejledning for stavvibrering.

Bilag

Concrete Vibration — What's Adequate?

by Lars Forsblad 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

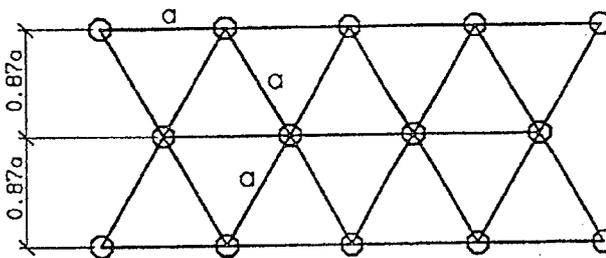


Fig. 1 — Plan for internal vibration with even distribution of the insert points. (a) is the distance between the points.

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:

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

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).

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

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:

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

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

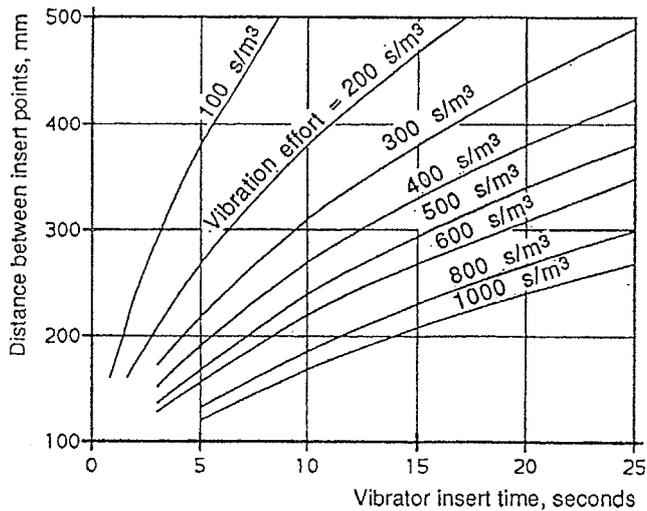


Fig. 2 — The distance between insert points and vibrator insert time are depicted here. Large casting area, concrete cast in layers of 0.4 m.

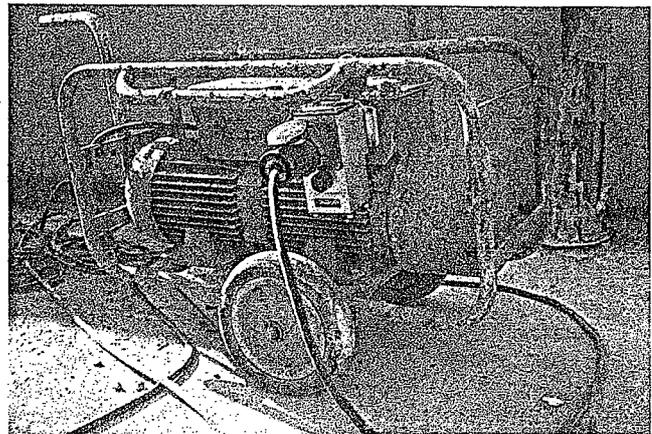


Fig. 4 — Vibration time meter coupled to frequency converter.

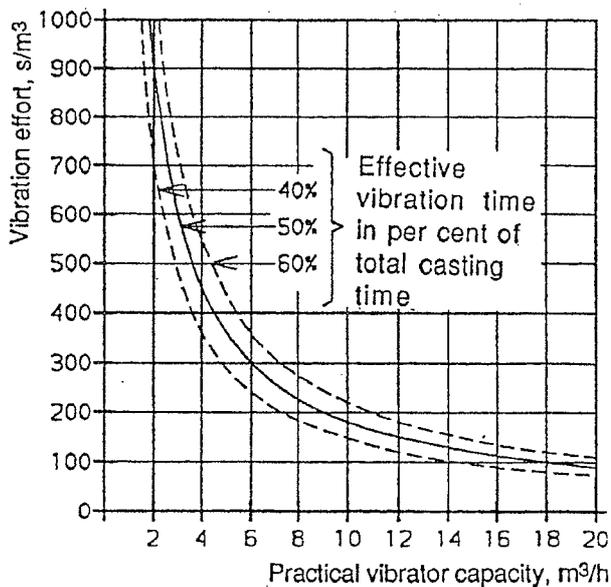


Fig. 3 — Relationship between vibration effort and practical vibrator capacity.

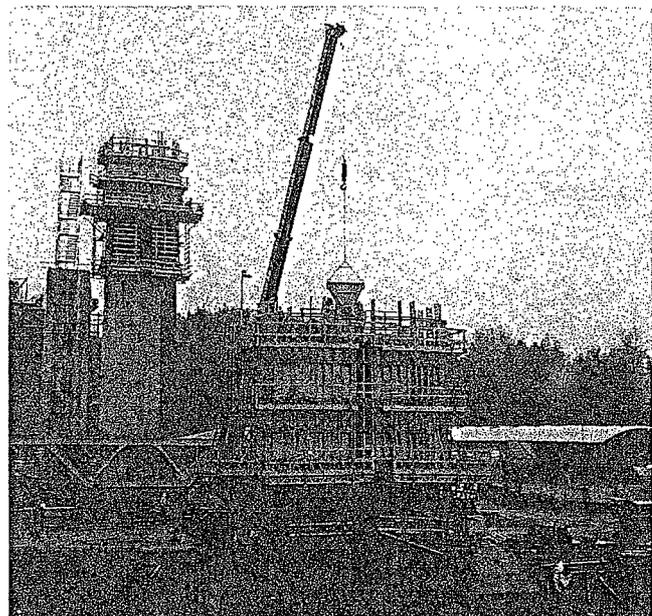


Fig. 5 — Casting of a bridge pier of a railway bridge south of Stockholm.

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:

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

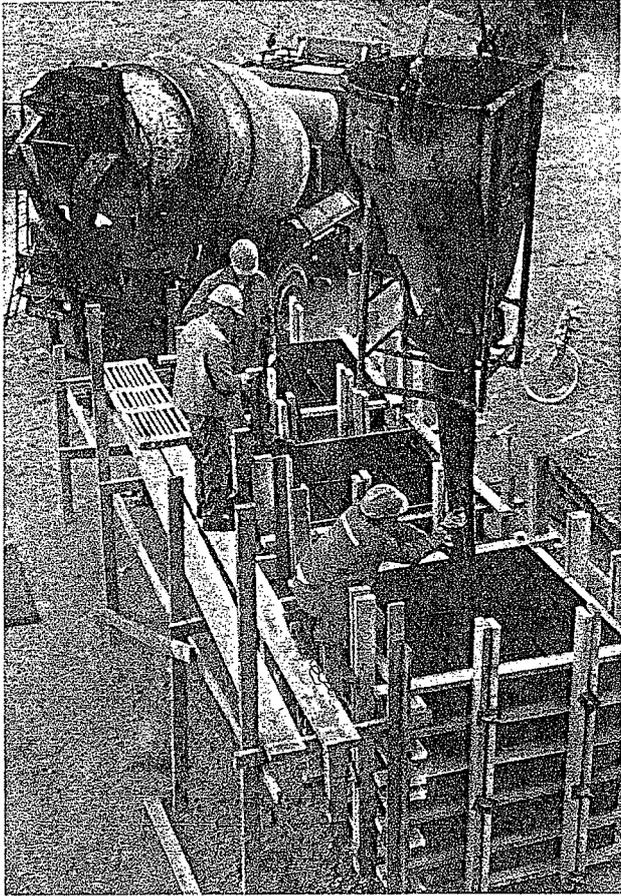


Fig. 6 — Special forms were used for field tests of different vibration efforts.

A vibration effort of, for example, 300 s/m^3 corresponds to a practical casting capacity of $1800/300 = 6 \text{ m}^3/\text{hr}$ 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



Fig. 7 — Core drilling for the tests.

ive 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/m^3 (57 s/yd^3) up to a maximum of 1200 s/m^3 (920 s/yd^3). 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-

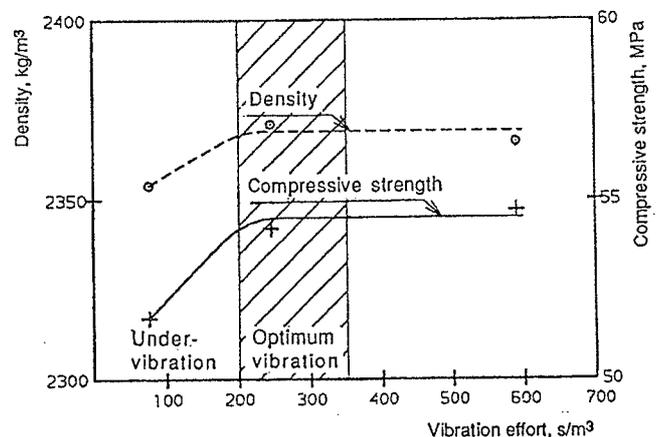


Fig. 8 — Relationship of vibration effort, density, and compressive strength are shown here. The air-void content is 2.5 percent.

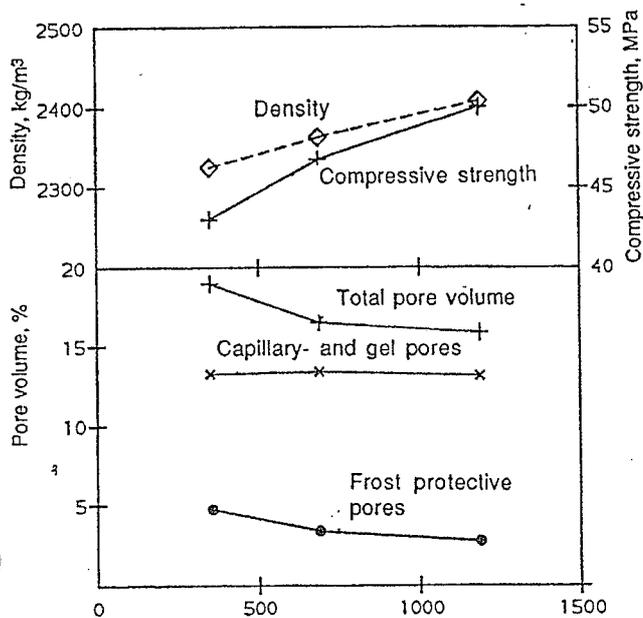


Fig. 9 — Relationship between vibration effort, density, pore volume, and compressive strength depicted here. This was air entrained concrete with 5 to 6 percent air content. (See Reference 5.)



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

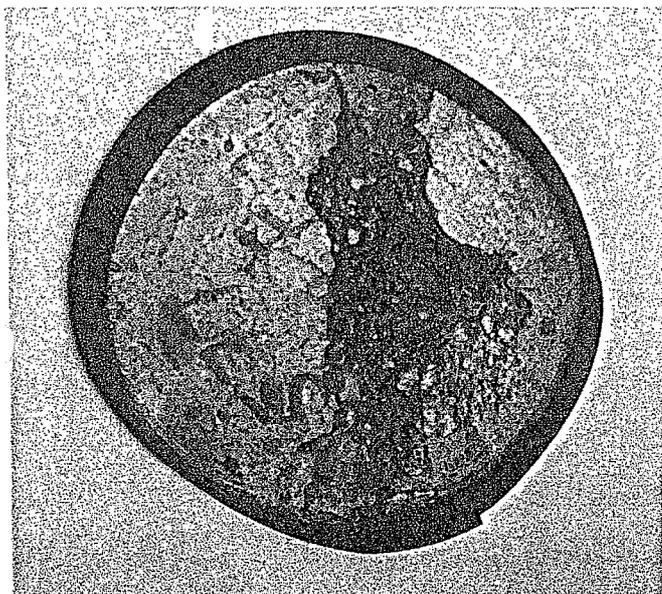


Fig. 10 — Freeze-thaw test showing uneven scaling effect at a vibrator insertion. Core diameter is 125 mm (5 in.).

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

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/m³ to 600 s/m³ (190 to 460 s/yd³) 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/m³ (920 s/yd³) 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 NaCl₂ 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/m ² 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/m ² 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/m ² 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.

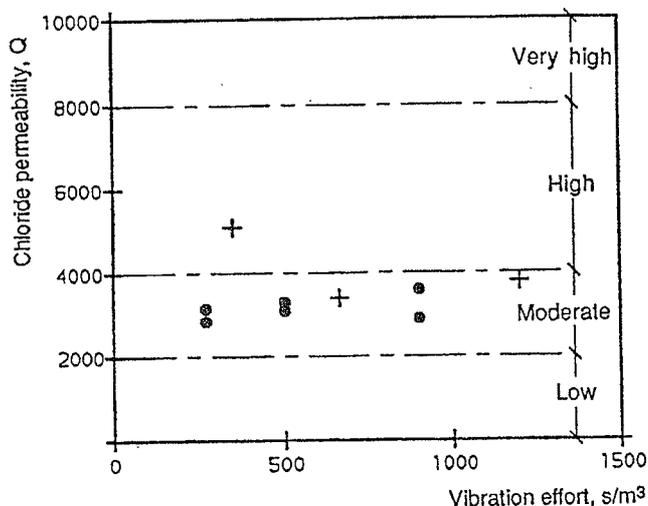


Fig. 12 — Relationship between vibration effort and chloride permeability.

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/yard³) 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/m ³)	(s/yd ³)	(m ³ /h)	(yd ³ /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.

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.).

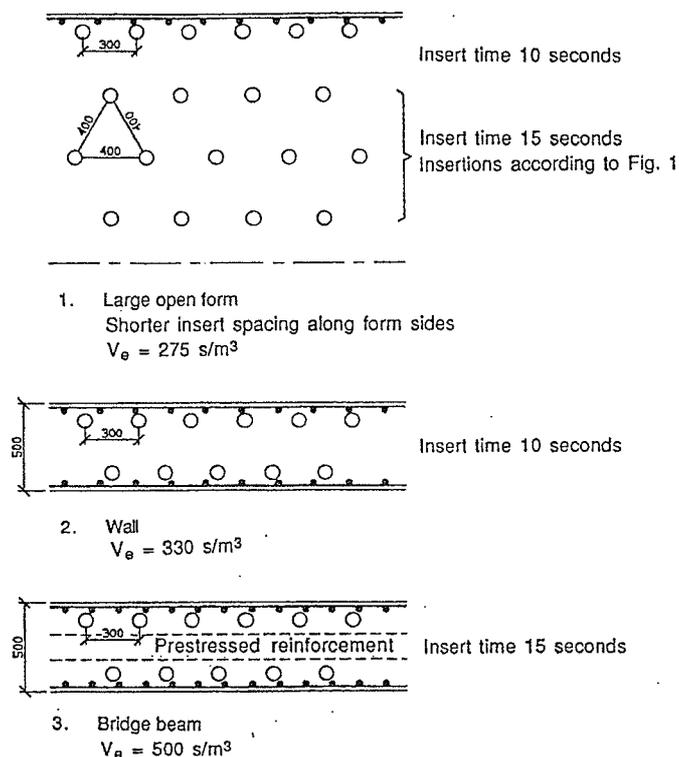


Fig. 13 — Large open form, wall, and bridge beam examples of vibration plans. Concrete had a plastic consistency when vibrated at 55-60 mm (2.25-2.5 in.).

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

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