VIBRATION EFFECT ON THE CONCRETE STRUCTURE

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Concrete is still the most important building material. With up-to-date research tools (X-ray, electron microscope, derivatograph, etc.) the factors acting on the concrete structure, the mechanism and kinetics of concrete setting, could be discovered. From an empirically manufactured material, concrete has became more and more a material produced reckoning with its known physical and chemical features.

In spite of many practical experiences and theoretical results, it is a much debated problem whether *ulterior vibration* acting on concrete is favourable or unfavourable. Inherent uncertainties hampered generalization of its application as a technology. Reexamination of the problem was imposed by the fact that in construction and maintenance, concreting has to be carried out under conditions where traffic vibrations act on the green concrete.

1. Mechanism and kinetics of cement hydration

The *setting* and *hardening* of cement involve very complex physical and chemical processes, where calcium silicate hydrates, calcium alumina hydrates develop and $Ca(OH)_2$ is released. At the present state of science, both the gel theory of *Michaelis* and the crystal theory of *Le Chatelier* are true — as proved by *Powers* through electron microscopy — namely the initial gel structure becomes later crystallized.

According to electron microscopic tests by *Locher* and *Richartz*, hydrate products seen in Fig. 1 are formed in the cement mortar at 20 °C in the first hours of cement hydration.

From the aspect of this research work, processes taking place during cement setting and influencing it are of primary importance.

Latest investigations divided the *setting time of cement* into *four phases*.

The *first phase* is hydrolysis concomitant to solution. Hydration of the free lime and the reaction of C_3A with water and $CaSO_4$ involves a sudden heat generation. A saturated lime solution develops, favourable for the solution

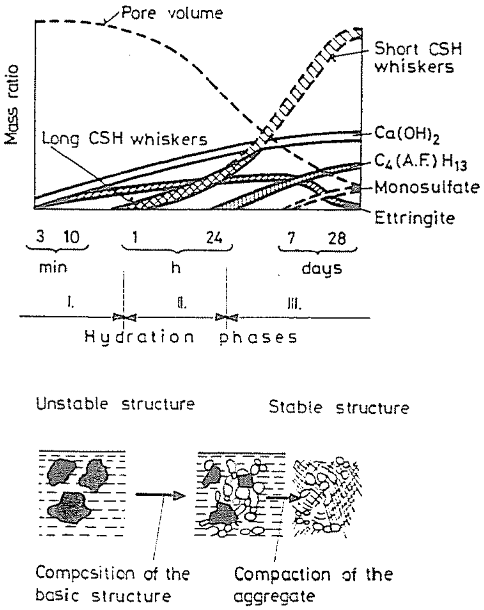

Fig. 1. Timely development of hydrate products after Locher and Richartz

of the C_3S grains. The developing jelly-like structure has a certain rigidity but no strength.

The *second phase* is characterized by a thin gel membrane enveloping the clinker grains and restraining the hydration process. This period is characterized by an induction time with almost no heat generation following the initial sudden temperature increase. This phase includes the first minimum of the direct tension curve. The Ca^{++}-ion content of water pressed out of the paste suddenly increases, hexagonal crystals appear under the microscope, which *Zimonyi* supposed to be $Ca(OH)_2$. The mortar grows increasingly stiff as demonstrated by the Vicat needle. This period is considered to be the beginning of setting.

In the meanwhile the osmotic pressure causes the gel membrane to split, the clinker grains get again water. The *third phase* of setting begins. This period is also characterized by substantial heat generation.

The fourth phase, the end of setting, is difficult to interpret. *Zimonyi* suggested it to last from the second wave valley of the entire tension curve and the time of the first temperature maximum following the induction time.

The setting time, i.e., the hydration rate is influenced by the temperature, the specific cement surface, the water/cement ratio of the concrete and the admixtures.

2. Publications on ulterior vibration

Most of the research works were concerned with the possibility of using, and practical utility of, ulterior vibration as a technology. Many tests were carried out abroad [1, 2, 3, 4, 5, 6], it was discussed at conferences and standards ACI 614—44—49 and DIN 4235 permitted ulterior vibration with certain restrictions. In this country Weiss carried out a few laboratory tests and great many pilot plant experiments, underlying a recommendation [10] on the method of ulterior vibration.

The following conclusions were drawn from ulterior vibration experiments:

a) Already the tests by *Abrams* on varying the mixing time gave a hint that a prolonged mixing is accompanied by a wet post-grinding process, increasing the early strength of the concrete. A similar process occurs during ulterior vibration.

This post-grinding process explains why ulterior vibration has always a greater effect on the initial than on the final strength. This is partly why several short-time vibrations by *Shestoperov* were far more efficient than a single ulterior vibration. Namely with several ulterior vibrations the soaked surface layer of the cement grain scales off repeatedly, enhancing the grain refinement.

The same wet post-grinding process is responsible for the observed lower effectiveness of ulterior vibration for high early strength cements compared to standard cements. Namely if the high early strength of the cement is achieved by finer grinding, there is less probability of further refinement.

b) The success of ulterior vibration is partly due to its compacting effect.

Already *Féret* recognized the influence of porosity on strength reflected also by concrete design formulae. According to the present state of knowledge starting from a high grade aggregate, strength depends on the hardened cement, both on its binding power and porosity. Yet the initial porosity is a function of the water/cement ratio and of the compactness, depending, in turn, on the paste saturation of the concrete and on the compaction degree. An ulterior vibration increasing the compactness (reducing the porosity) improves the strength.

c) These effects can only be achieved, however, if vibration fluidizes the concrete mix as stated already by *Novikov*. Weiss [10] writes about the occurrence of this state that the right time for ulterior vibration depends on the quality and quantity of the applied cement, on the water/cement ratio, the mobility of the mix and the water absorption of the shuttering, on the temperature and other weathering effects. Other authors are of a similar opinion. These statements are though true but meaningless for the practicing engineer.

At any rate they express that the effect of ulterior vibration is in connection with the complicated process of cement hardening, a function, in turn, of the enumerated factors. This complicated process may be responsible for the disuse of ulterior vibration in technology. A practical result may be expected from research connecting the effect of ulterior vibration with the setting time, characteristic of cement hydration. This is more conceivable, because the cement setting time can be determined as a function of the influencing factors. At most, setting time of cement rather than of concrete is determined by means of the standard instrument.

d) In a certain initial stage of setting, the *volume of hydrate products is bigger* than that of the original cement grain but smaller than the joint volume of the cement grains and the water used. Thus, compacting the concrete in a condition of partial hydration results in a higher compactness, still forwarded by the mobility of cement in gel state and the better compactibility of smaller cement grains.

e) *The technology of ulterior vibration did not generalize.* On the other hand, the *setting concrete is* increasingly *exposed to constant vibrations* although much smaller than those emitted by a vibrator used in ulterior vibration. In lack of publications on relevant research, tests were continued in this direction, in possession of the ulterior vibration test results.

3. Bridge deck vibrations in reconstruction and their simulation

Membrane vibrations of horizontal bridge decks can be considered as critical. Determination of the amplitude-frequency characteristics (vibration patterns) in the frequency range $f = 30$ Hz to 1 kHz has been demonstrated to be sufficient. Since these change in time as a function of traffic, only the limits of the range had to be changed.

From the aspect of bridge tests, places where the vehicle traffic caused the greatest dynamic vibrations (expansion joints, defects of the smooth road surface) were considered as critical.

Tests were made by a *Brüel and Kjaer* recording and analysing vibrometer system. Measurement results were tape recorded on the site and evaluated in the laboratory.

All three measuring spots on the bridge exhibited vibration acceleration maxima in the frequency range around 31.5 Hz. Accordingly the characteristic frequency of the vibrating table simulating the vibration conditions on the bridge had to be in the range $f_a = 22.27$ Hz to 44.55 Hz.

Therefore the vibrating table had to be made suitable for simulating the recorded bridge vibrations and also their 60, 30, 15 and 7.5-fold, to permit simulation of vibrational conditions of other structure types subject to other types of traffic.

4. Tests simulating the real bridge vibration conditions (1st series)

The generator (RZ 464034—01) constructed for the experiment was driven by a DC motor through a flexible shaft to permit frequency changes. Main technical parameters of the equipment were as follows:

Vibrating table area: 700 × 800 mm
Vibrating table mass (with generator): 82.5 kg
Mould size: 900 × 550 × 220 mm
Mould mass: cca 150 kg
Concrete mass: about 250 kg
Excitation frequency: 22 Hz to 44, 55 Hz (68.2 Hz) adjustable
Exciting force: 7.18 N —800.0 N (adjustable)
Mass moment of eccentric body: 0.0367—0.433 cmkg (adjustable in 10 grades).

The damping factor of the specially designed equipment is practically negligible and the exciting frequency is the multiple of the overall frequency. Thus the frequency acceleration is described by the following simplified relationship:

$$a = \frac{m_0 r_0 w^2}{m} \; [\mathrm{m/s^2}].$$

The experimental reinforced concrete model is shown in Fig. 2.

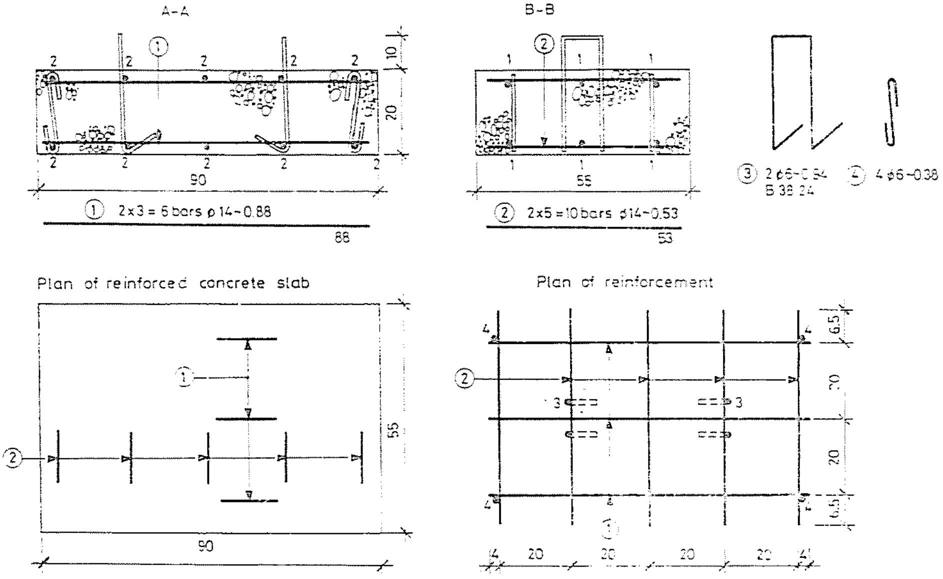

Fig. 2. The experimental reinforced concrete slab model (1st test). *Materials:* Steel: B 60.40 (∅14). Concrete: B 400 — 15 K

Characteristics of the green concrete:

Concrete grade: B 400 —16/K
450 kg/m^3 of portland cement 450 from Vác
Water/cement ratio: 0.45—0.47
Concrete composition: 1 : (0.45—0.47) : (3.8—3.9)
Grading according to Fig. 3.

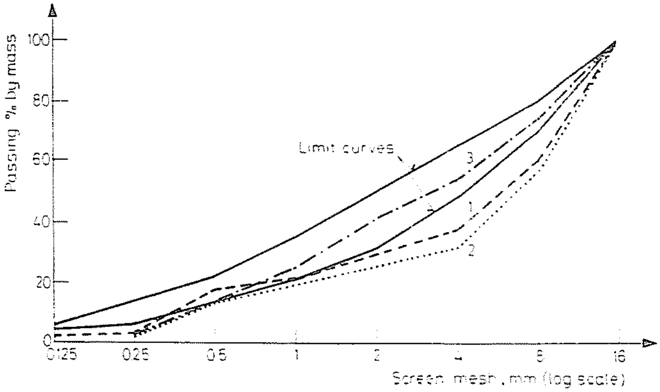

Fig. 3. Grading curves

Table 1

Characteristics of green concrete and the revibration

No.	Concrete Composition c : w : a	Aggregate mark	Green concrete		a mm/s^2	Ulterior vibration data		Vibration time, hours
			slump cm	spread cm		Hz	Age of concrete at the beginning of vibration, hours	
I	1 : 0.47 : 3.9	1	13.5	43.5	control	—	—	—
II	1 : 0.47 : 3.9	1	7.0	36.0	130	31.5	2	6
III	1 : 0.47 : 3.9	1	15.0	44.0	210	38.5	2	6
IV	1 : 0.47 : 3.9	1	18.0	37.5	130	31.5	2	16
V	1 : 0.45 : 3.9	1	14.0	43.0	130	31.5	2	12
VI	1 : 0.47 : 3.8	2	18.5	46.5	210	38.5	2	12
VII	1 : 0.47 : 3.8	2	15.0	41.0	(vibrating table) 18 330	50.0	2 4 6	1’ 1’ 1’
VIII	1 : 0.45 : 3.8	2	13.0	38.0	(vibrating table) 11 660	50.0	6 8	1’ 1’
IX*	1 : 0.45 : 3.8	3	14.0	40.0	1 500	68.2	2	4
X	1 : 0.45 : 3.8	3	13.0	39.0	1 500	68.2	6	4
XI	1 : 0.45 : 3.8	3	11.0	38.0	1 500	68.2	5	10

* Schmidt-hammer test after removal of the soft surface layer!

The concrete was placed as usual on the vibrating table then exposed to ulterior vibration according to Table 1.

5. Ulterior vibration tests (2nd series)

The compacting tool used for testing the ulterior vibration effect accompanied by vibration accelerations — that are high compared to vibrations measured on the bridge — comprised either the original shutter vibrator type Z-15 (1st series), or a shutter vibrator type VZ 100 (2nd series) as generator with the following characteristics:

Technical parameters of shutter vibrator type Z-15:

Mass of table (with generator): 122.5 kg
Exciting frequency: 50 Hz
Exciting force: 6867-14 700 N (adjustable)
Mass moment of the eccentric body: 0.075 to 0.16 kgm.

Technical parameters of shutter vibrator type VZ 100:

Mass of table (with generator): 95 kg
Exciting frequency: 48 Hz
Exciting force: 550 to 9100 N (adjustable)
Mass moment of the eccentric body: 0.11 kgm.

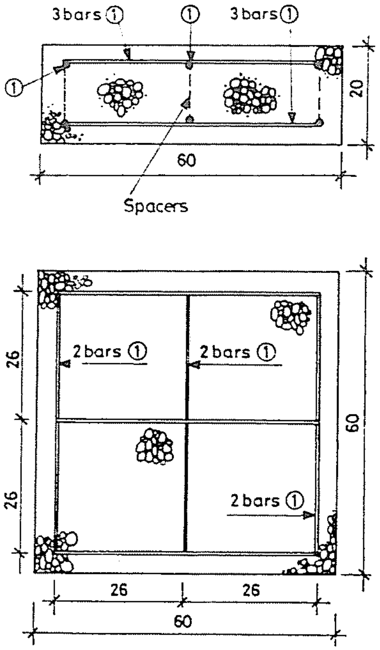

Fig. 4. **The experimental reinforced concrete slab model (2nd test). Each slab is reinforced by 2×6 = 12 deformed bars ① made into top and bottom fabric reinforcement**

Concrete:

300 kg/m^3 of cement 450 ppc 10
Aggregate No. 2 in Fig. 3
Concrete grade: B 280 – 16/K
Water/cement ratio:
Concrete I: $W/C = 0.65$ (pump concrete)
Concrete II: $W/C = 0.55$ (rigid-plastic).

For each test one slab of 60×60×20 cm was made with a top and bottom reinforcement fabric (Fig. 4), as well as 5 cubes of 20 cm edge length. A ∅ 14 mm smooth reinforcing bar grade B 38.24 was embedded into the centre of two cubes for pull-out tests, whereas the three other cubes were used to determine the 28-day compressive strength.

The hardening process was checked both on the slab and the cubes by the nondestructive *Schmidt hammer* method at 1, 2, 3, 7,14 and 28 days of age. The bond strength was determined on 14-day reinforced cubes by the pull-out test. Temperature change of the slab concretes was measured by silicon film diode thermocouples to establish the cement setting time from the actual concrete temperature, to be considered as an exact basis to start the vibration in the tests.

The reinforced concrete slabs were compacted first in the usual way on a vibrating table, then both concrete types were subjected to three different ulterior vibrations in 4 vibration grades each.

Vibration grades:

No.	Vibration acceleration m/s^2	Exciting force N
1	10	4500
2	5	2200
3	2.5	1100
4	1.25	550

Start of ulterior vibration:

1	immediately after concreting
2	at the beginning of setting
3	at the end of setting.

Within each vibration range the specimens were subjected to periodical ulterior vibrations, that is, three cycles of vibration for 2 hours, followed by 1 hour of rest.

6. Conclusions drawn from the tests, and suggestions

Rather than to decide over the technological problem of applying ulterior vibration, the research aimed at providing a theoretically founded, serviceable proposal for the practical case of less intensive but permanent vibrations. Based on the above, the effect of vibrations on green and hardened concrete — both under actually measured and simulated vibration conditions — may be summed up as follows:

a) As a *general tendency* it may be stated that for vibrations of 1.25 to 10 m/s^2 acceleration affecting the cement or concrete before complete setting, no unfavourable structural change prejudicial to either the concrete strength or the reinforcement bond has to be expected. The setting time may be stated referring to both the paste consistency change and the temperature changes during setting.

b) The tests showed the effect of vibration on the green concrete to depend on both the concrete consistency and the vibration acceleration. The strength of earth-moist concrete was nearly identically affected by vibration grades 1 to 3 whereas for plastic pumpable concretes, grade 2 was the most advantageous. Consistency acts in a way to increase the setting time of concrete compared to that determined on a paste of standard density. This is in agreement with the substantial strength increase of cement paste upon ulterior vibration applied after the end of setting as against earth-moist concrete. The effect of cooling is anticipated to be similar.

c) More intensive vibrations were generally more effective in compaction manifest by both the strength and the hardening rate. Concretes less compact from any cause (higher water/cement ratio, less ulterior compaction) underwent slower initial hardening.

d) Two to three hours after the start of applying vibration of small acceleration, hair-cracks were observed to appear on the surface, which closed later on. Such cracks were observed during the reconstruction of the *Petőfi bridge*, chiefly above the reinforcement. Provided they do not disappear spontaneously it is effective to apply a surface vibration when the surface begins to become dull.

e) Strength was tested both on cubes and on reinforced concrete slabs. Lateral displacement of the concrete in cubes was found to be inhibited, indicating more favourable compacting conditions than in flat slabs. This is why measurement results on the slab are accepted as design values.

f) These experiences can be used advantageously in construction. Purposeful selection of post-compacting conditions by ulterior vibration — taking the cement setting time into account — is likely to improve the concrete quality. Thereby the economy of construction is improved, against the present practice of safety margin represented by one grade higher concrete than necessary.

g) The test results are in no contradiction with conclusions drawn from the references.

Summary

Concrete is an important building material increasingly prepared relying on physical and chemical regularities. The actually much debated problem whether post-vibration of concrete is beneficial or harmful is of practical importance for building and reconstruction projects.

The effect of post-vibration has been investigated on r.c. slab models under real vibrational conditions measured on a bridge, and under their multiples, varying vibration parameters and concrete age. Conclusions have been drawn from published data, strength test results and structural characteristics, leading to suggestions for the building practice.

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* In Hungarian
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