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Influence of early-age vibration on concrete strength

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Abstract

This report examines the strength of young and early age concrete that has been systematically exposed to horizontal, sinusoidal vibrations with varying vibration parameters. Specimens were subjected to vibrations of predefined vibration times (4–14 h) and the compressive strength was determined after a period of 28 days. It was found that the different parameters have no critical influence on compressive strength and that vibration prior to initial setting of the concrete can increase its strength. Additional information to examine the reasons for this increase was obtained by further investigations (nuclear magnetic resonance, x-ray diffraction, and thermogravimetric analysis).

KEYWORDS

compressive strength, early-age concrete, green concrete, vibrations, young concrete

1 | INTRODUCTION

There have been many research projects in the past that have investigated the influence of vibrations on young concrete. However, their effect on concrete strength has to date not been conclusively examined. One reason for this is that vibrations occur over a wide range of intensities, durations, and excitation frequencies. They can be powerful short-term vibrations of the kind caused by blasts, or constant and low-intensity vibrations resulting from road traffic. Moreover, concrete can have a range of compositions that influence its setting and hardening behavior.

Generally, revibration of fresh concrete leads to increased strengths[1–3] while the positive effect of postcompaction reaches its maximum in the induction period of the concrete and diminishes afterwards.[1,3,4] It is usually assumed that the critical period for potential damage is after the concrete has set, when it is no longer able to withstand the vibrations by virtue of its (semi)fluid nature, but before sufficient strength has been built up to withstand the vibrations. At this stage vibrations generate dynamic stresses, which can impact young and vulnerable concrete and damage the microstructure of the hardening cement stone, resulting in cracking. Hence, the focus of this research project is to investigate possible strength reductions at this age.

2 | BACKGROUND

For more than a century, scientists have been investigating the influence of vibrations on young and early-age concrete. Some of the first studies were conducted in 1918 by Scheidt et al.,[5] in which vibrations were either simulated by a dropping of a table in a predefined manner or applied by a vibrating table or an engine imbalance. During World War II, experiments were carried out in which young concrete was subjected to vibrations from the firing of anti-aircraft guns, among other things.[6] In other studies, vibrations were applied in laboratory settings using vibrating tables, hydraulic

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TABLE 1 Vibration parameters of construction vibrations.

Vibration type	Frequency (Hz)	Displacement (mm)	Velocity (mm/s)	Acceleration (m/s^2)
Typical vibration parameters				
Blasting[7]	0.1–200	2.5×10^{-4}–2,5	2.5×10^{-4}–500	1×10^{-3}–1
Construction[8]	0.5–200	1×10^{-4}–10	1×10^{-4}–1000	1×10^{-2}–100
Range of exemplary vibrations—pile driving				
Driving by impact[8–11]	0–100	N/A	0–150	N/A
Pile driving by vibration[8–10,12,13]	0–100	N/A	0–30	N/A
Range of exemplary vibrations—traffic				
Rail traffic[9,10]	0–100	N/A	0–1.3	NA
Road traffic[8,9,14–17]	0–40	0–1	0–23	0–0.4
Range of exemplary vibrations – demolition work				
Falling masses[8,9]	0–48	N/A	0–40	N/A
Pavement breaker[17]	10–30	N/A	0–15	0–1.5
Jackhammer[17]	40–90	N/A	N/A	0–0.3
Range of exemplary vibrations—compaction work				
Vibratory roller[8,17]	20–30	N/A	0–80	0–0.7
Vibro-plate compactor[17]	40–90	N/A	N/A	0–0.3
Vibroflotation[8]	N/A	N/A	0–10	N/A
Dynamic compaction[8,18]	0–35	N/A	0–100	N/A
Range of exemplary vibrations—tunneling				
Tunnel boring machine[8,19]	15–50	N/A	0–7	N/A

actuators, or a hammer or pendulum. Furthermore, many research projects have investigated the effect of really occurring vibrations induced by road traffic, pile driving, or blasting.

These studies can be divided into laboratory experiments and field investigations. One problem of field investigations is that their results are often not fully comparable, since the specimens are generally not subjected to the same curing conditions. Furthermore, conclusions can generally only be drawn for certain types of vibration. Hence, to date, there has been no systematic investigation that might lead to a generally valid statement.

A short compilation of common building vibrations is given in Table 1. A range of typical vibration parameters was available only for blasting and general construction vibrations, for other types of vibrations no general data could be found, so the vibrations are characterized on the basis of individual measurements. Due to the fact that these particular measurements were determined at a certain distance from the vibration source, higher vibration velocities may probably occur at a smaller distances. Moreover, the transmission mediums (e.g., soil properties) were influencing the measured magnitudes as well. Furthermore, by providing a frequency spectrum, the specification of predominant frequencies (e.g., 32 Hz in a case of pile driving by vibration) is omitted. Therefore, the references must be consulted for details.

An extensive summary of previous investigations and a compilation of different definitions of hardening concrete from fresh to hardened concrete, which is used likewise in this publication, is given in Ref. 20 The conclusion of Ansell and Silfwerbrand[20] is that the critical time for early-age and young concrete is generally after 3–14 h. The investigations described there are distinguished by vibration sources and types hence different vibrations can have varying characteristics.

Vibrations are generally classified as either periodic or nonperiodic. Nonperiodic vibrations are further subdivided into impulse loadings, such as explosions, and arbitrary loadings, for example, earthquakes. In contrast, periodic vibrations are caused by loadings that repeat at regular intervals. These include both harmonic (sinusoidal) oscillations and arbitrary periodic vibrations.[21]

This research focuses on periodic vibrations. A short survey of previous studies of the influence of periodic vibrations on young and early-age concrete is presented in the following, whereby only the latest publications—in English—of each author (or group of authors) are considered. As this publication focuses on the impact on compressive strength after 28 days, only this is presented, even though some authors have examined impacts after different loading times (e.g., 7 days) or different concrete characteristics (e.g., bond strength).

Harsh and Darwin[22] investigated the influence of vibrations on young and early-age concrete by simulating traffic-induced vibrations. So-called "repair concrete" for a laboratory bridge was set in sinusoidal vibration at a frequency of 4 Hz and an amplitude of 0.5 mm by means of a servo-hydraulic actuator. Vibration began 10 min after pouring and continued for a period of 30 h. In addition to this sinusoidal vibration, a single short-term peak excitation with a static amplitude of 13 mm and a frequency of 0.5 Hz was applied every 4 min to simulate truck traffic. This study showed that vibrated concrete with a lower slump built up higher strength, which was explained by a resulting additional consolidation, whereas vibrated concrete with a higher slump developed lower strength, probably due to segregation.

The experiment conducted by Hulzhizer[23] consisted of field tests in which young and early-age concrete was vibrated by blasts, as well as a laboratory test program using a vibrating table. The laboratory tests were conceived to simulate blasts, with vibrations applied 5 ± 0.5 s, in line with the minimum vibration duration of the vibrating table. The concrete cylinders were vibrated either 3, 6, 12, or 24 h after casting at frequencies of either 50, 100, or 150 Hz. The peak particle velocity was between 25.4 and 406.4 mm/s. Irrespective of the applied vibration or time point of excitation, there were both increases and decreases in strength, such that no clear trend could be identified.

Dunham et al.[24] aimed to identify the influence of vibrations on young concrete during the setting process. For this purpose, concrete cylinders were vibrated before the initial set (after 2 h), during setting (after 3.5 h) or after the final set (after 4.5, 5, or 6 h) using a vibrating table operating at a frequency of 60 Hz. The duration was either 1 or 2 min, and two different vibration levels (50–100 or 200–300 mm/s) were applied to simulate vibratory soil compactors. The study found that this type of vibration serves to increase and not decrease the compressive strength of the concrete. No trend was observed by varying the vibration parameters (velocity, duration, and point of time).

Tawfiq et al.[13] simulated the dynamic effect of pile driving by applying continuous vibration from a vibrating table to young and early-age concrete cylinders. In the first test group, vibration was applied directly after mixing for 21 h (until the final setting time), while in the second group, it was applied from the initial set (14 h 42 min) to the final setting time (20 h 35 min). The vibration frequency was not specified, and the velocity was either ~25, 51, 76, or 229 mm/s. The outcome was that samples vibrated continuously after mixing had equal or greater compressive strengths, while specimens vibrated from ~15 to 21 h had slightly lower strength than nonvibrated specimens. The authors of this publication did not mention whether a regular vibration was conducted directly after pouring, such that the increase in compressive strength could be explained as an effect of "normal" vibration and not necessarily of an applied (re-)vibration.

Siwula et al.[11] applied vertical vibrations to cylinders for 15 min using a hydraulic actuator. The frequency was 20 Hz and the velocity ~13, 51, 127, 254, 381, or 508 mm/s respectively. The vibration was applied either in the first 4–6, 12–14, 24–26, or 72–74 h. The vibrations generally reduced the compressive strength, but in some cases there were also increases. Due to the independency of the strength difference and vibration velocity or time there was also no conclusion found.

Freyne and Watkins[25] investigated the influence of vibration between initial and final set. Concrete cylinders were subjected to vibration on a vibrating table at various intensities and durations and at different ages. The velocities were either 13, 25, 38, or 50 mm/s, the duration was 10, 20 or 30 min, and the vibration was applied after 2, 4 or 6 h. Two different coarse aggregates (limestone and river gravel) were used. As in the other studies, both positive and negative strength differences were noted, irrespective of the vibration parameters, and there was no conclusive outcome.

Hong and Park[16] applied vibrations to fresh, early-age and young concrete for 3, 6, 9, 12, or 24 h using a hydraulic actuator. The vibrations applied in the laboratory had a frequency of 5 Hz and velocities of 3, 4.5, 6, or 10 mm/s, so as to simulate vehicle-induced vibrations during bridge widening. Due to the immediate occurrence of traffic in bridge widening, the vibration was applied directly after concreting in the laboratory studies. This research project found that peak particle velocities of 10 mm/s can decrease compressive strength by up to 25%, which might be caused by segregation. Velocities of 3 and 4.5 mm/s generally neither affected nor increased the compressive strength, whereas at a particle velocity of 6 mm/s both increases and decreases in strength were observed. The duration of the vibration seems to matter only marginally.

Table 2 summarizes the various studies described above. The literature is arranged by peak particle velocity, with the declared increases or decreases in strength added ("ca." indicates that the values were taken from diagrams/graphs). A comparison of these publications is rather difficult due to the different testing methods applied. However, there is a slight tendency suggesting that an interaction at early vibration times with a combination of higher frequencies and higher velocities increase the compressive strength but otherwise there is no trend observable.

TABLE 2 Recent publications relating to harmonic vibration tests conducted on young and early-age concrete.[11,13,16,22–25]

Author(s)	Vibration generator	Vibration time (h)	Frequency (Hz)	Velocity (mm/s)	Strength decrease (%)	Strength increase (%)
Hong and Park	Hydraulic actuator	0–24	5	3–10	−24.8	+ 20.3
Harsh and Darwin	Hydraulic actuator	0.17–30.17	0.5–4	13–36	−7.7	+ 4.1
Freyne and Watkins	Vibrating table	2–6	N/A	13–50	−5.8	+ 4.9
Tawfiq et al.	Vibrating table	0–21	N/A	25–229	ca. −9	ca. +10
Dunham et al.	Vibrating table	2–6	60	50–300	N/A	+13
Hulzhizer	Vibrating table	3–24	50–150	25–406	ca. −6.5	ca. +15
Siwula et al.	Hydraulic actuator	4–72	20	13–508	ca. −10	ca. +6%

3 | EXPERIMENTAL INVESTIGATIONS

3.1 | Scope

The aim of this research project was to determine the impact of individual (e.g., frequency only) and combined vibration parameters on young concrete. Due to the existing mathematical correlations between sinusoidal vibration parameters (see Section 3.3) all vibrations applied were harmonic. The project focused solely on compressive strength since this is the most relevant parameter in concrete design.

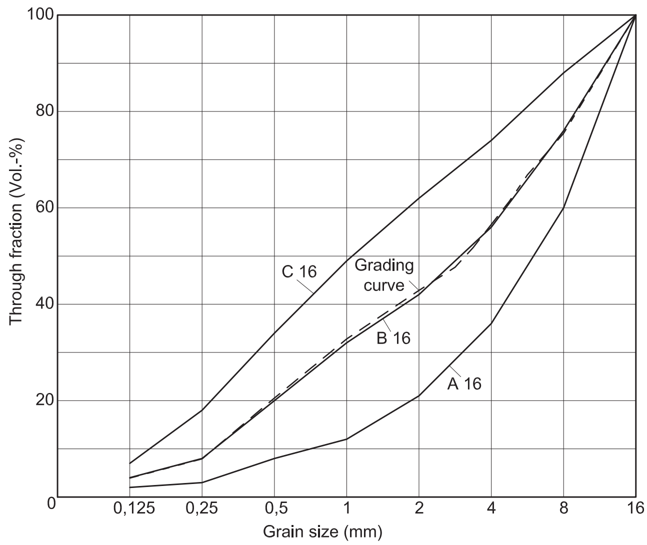

FIGURE 1 Concrete grading curve

3.2 | Concrete

3.2.1 | Cement

The concrete was made from normal hardening Portland cement (CEM I 42.5 N according to DIN EN 197-1[26]) with an arithmetic mean compressive strength of 52.3 MPa after 28 days, which was determined according to DIN EN 196-1.[27] The clinker phase fraction of the Portland cement consisted of:

- 67.1 wt.% tricalcium silicate (C_3S)
- 7.4 wt.% dicalcium silicate (C_2S)
- 12.8 wt.% tricalcium aluminate (C_3A) and
- 3.8 wt.% tetracalcium aluminoferrite (C_4AF)

The setting times of the cement were determined according to DIN EN 196-3[28] as 2 h 40 min (initial setting time) and 3 h 35 min (final setting time). These times differ in part from the setting time of the concrete due to the lower water/cement ratio of the cement paste (w/c = 0.27) and the absence of aggregate, which reduces the relative hydration heat. The Blaine fineness of the cement determined according to DIN EN 196-6[29] was 2790 cm^2/g.

3.2.2 | Concrete mixture

In order to avoid interactions with concrete admixtures and/or concrete additives, no concrete admixtures or additives were used. The concrete was made with a water/cement ratio of 0.50. The aggregate consisted of quartz sand and quartz gravel. The grain size distribution was selected according to the regular grading curve B16 in DIN 1045-2[30] (Figure 1).

The aggregate mass was estimated from the calculated material volumes, as follows:

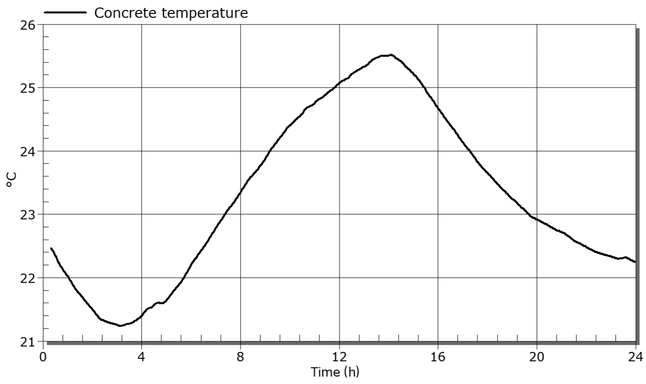

FIGURE 2 Development of concrete temperature over the first 24 h.

- 1713.5 kg/m^3 aggregate
- 411.4 kg/m^3 cement
- 205.7 kg/m^3 water

3.2.3 | Concrete properties

Flow was measured according to DIN EN 12350-5[31] and slump according to DIN EN 12350-2,[32] resulting in average flow values of 450 mm and slump values of 40 mm. Furthermore, concrete setting was determined according to DIN EN 480–2,[33] resulting in an initial setting time between 4 h 10 min and 4 h 20 min and a final setting time between 4 h 50 min and 5 h 10 min.

The hydration progression was determined simply by measuring the hydration heat. The concrete temperature was measured during initial hydration at the center of a concrete cube (Figure 2), which was stored under the same conditions as the specimens in the subsequent experiments (Section 3.4).

Note that Figure 2 shows the actual temperature of the concrete (°C) in a semiadiabatic measurement and not the heat evolution rate (g/[h·K]). Isothermal or adiabatic measurement of the hydration heat (for example with a hydration heat calorimeter) would falsify the heat development of the concrete cubes due to the influence of temperature on the chemical processes. This method therefore best represents the actual temperature affecting all used specimens.

The vibration time points of 4, 6, 8, 10, 12, and 14 h after adding water to the dry concrete mixture were selected in accordance with Figure 2 and the evaluation by Ansell and Silfwerbrand.[20] So, the first vibration time is closely related to the initial set of the concrete, while most of the vibration times are within the acceleration period of the cement, during which the chemical reactions progress rapidly, and the final two times are already during the deceleration period of the cement, which is associated with a regression of the chemical reaction rate.[34] The compressive strengths of the concrete cubes were tested for the selected vibration time points according to DIN EN 12390-3[35] to get an impression of the concrete strength at these times. Table 3 shows the results:

After 28 days, the concrete cubes without vibrations had a compressive strength of 47.8–53.9 MPa and an arithmetic mean value of 50.9 MPa.

3.3 | Test setup

Horizontal vibrations were applied to the young and early-age concrete by an LDS V721 series shaker (V721 M8-CE) of Brüel & Kjær, controlled by a linear power amplifier (PA1000L) in connection with a field power supply (FPS10L). An overview of the test setup is depicted in Figure 3. Further information about the test setup is in Figure S1.

Acceleration was measured using piezoelectric CCLD accelerometers (Type 4507 B002) made by Brüel & Kjær. The acceleration data were exported via two front ends through a switch to the software “BK Connect.” Because the experimental design did not include a vibration controller, the frequency was fixed and the vibration magnitude was adjusted indirectly by measuring the acceleration. By virtue of the sinusoidal vibrations, the individual vibration parameters could be calculated for a constant location and varying time as follows[8]:

$$u(t) = U \cdot \sin(\omega \cdot t + \text{const.}) \quad (1)$$

$$\dot{u}(t) = U \cdot \omega \cdot \cos(\omega \cdot t + \text{const.}) \quad (2)$$

$$\ddot{u}(t) = -U \cdot \omega^2 \cdot \sin(\omega \cdot t + \text{const.}) \quad (3)$$

with $u(t)$, displacement (m); $\dot{u}(t)$, velocity (m/s); $\ddot{u}(t)$, acceleration (m/s^2); U, amplitude (m); ω, circular natural frequency (1/s).

Since only the maximum values are relevant, and the difference between sine and cosine is merely an angular phase shift, the trigonometric functions can be omitted. Thus, $\omega = 2\pi f$ leads to the following equations:

$$v = \dot{u}_{\max} = U \cdot \omega = U \cdot 2\pi f \quad (4)$$

$$a = \ddot{u}_{\max} = U \cdot \omega^2 = U \cdot 4\pi^2 f^2 \quad (5)$$

with f, frequency (Hz).

Hence, if one vibration parameter increases, every parameter will increase as a function of each other.

TABLE 3 Compressive strength of concrete (MPa) at different vibration time points.

Point in time	4 h	6 h	8 h	10 h	12 h	14 h
Single values	0.08	0.15	0.42	0.82	1.77	3.33
	0.08	0.15	0.45	0.79	1.77	3.54
Arithmetic mean values	0.08	0.15	0.44	0.81	1.77	3.44

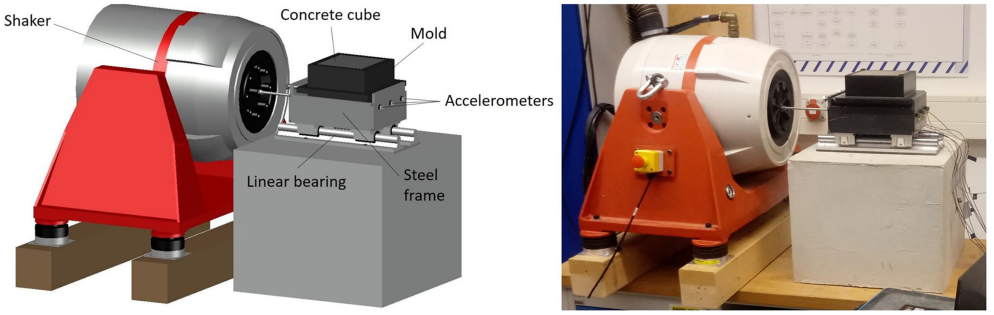

FIGURE 3 Test setup (schematic drawing and photograph of the assembled experimental setup)

TABLE 4 Vibration parameters of the testing scope.

Experimental series number	Frequency (Hz)	Displacement (mm)	Velocity (mm/s)	Acceleration (m/s^2)	Variance (%)
Experimental series No. 0: specimens without vibration					
0	0	0	0	0	0
Experimental series No. 1: specimens with constant frequency					
1–1	20	0.10	12.5	1.57	+10
1–2	20	0.14	17.7	2.22	+5
1–3	20	0.40	50	6.28	+4
1–4	20	1.13	141.4	17.77	+4
1–5	20	1.59	200	25.13	+3
Experimental series No. 2: specimens with constant displacement					
2–1	7.07	0.40	17.7	0.8	+10
2–2	10	0.40	25	1.57	+11
2–3 (=1–3)	20	0.40	50	6.28	+4
2–4	40	0.40	100	25.13	+3
2–5	56.57	0.40	141.4	50.27	+1
Experimental series No. 3: specimens with constant velocity					
3–1	5	1.59	50	1.57	+10
3–2	7.07	1.13	50	2.22	+9
3–3 (=1–3)	20	0.40	50	6.28	+4
3–4	56.57	0.14	50	17.77	+2
3–5	80	0.10	50	25.13	+2
Experimental series No. 4: specimens with constant acceleration					
4–1	7.07	3.18	141.4	6.28	+7
4–2	10	1.59	100	6.28	+7
4–3 (=1–3)	20	0.40	50	6.28	+4
4–4	40	0.10	25	6.28	+5
4–5	56.57	0.05	17.7	6.28	+6

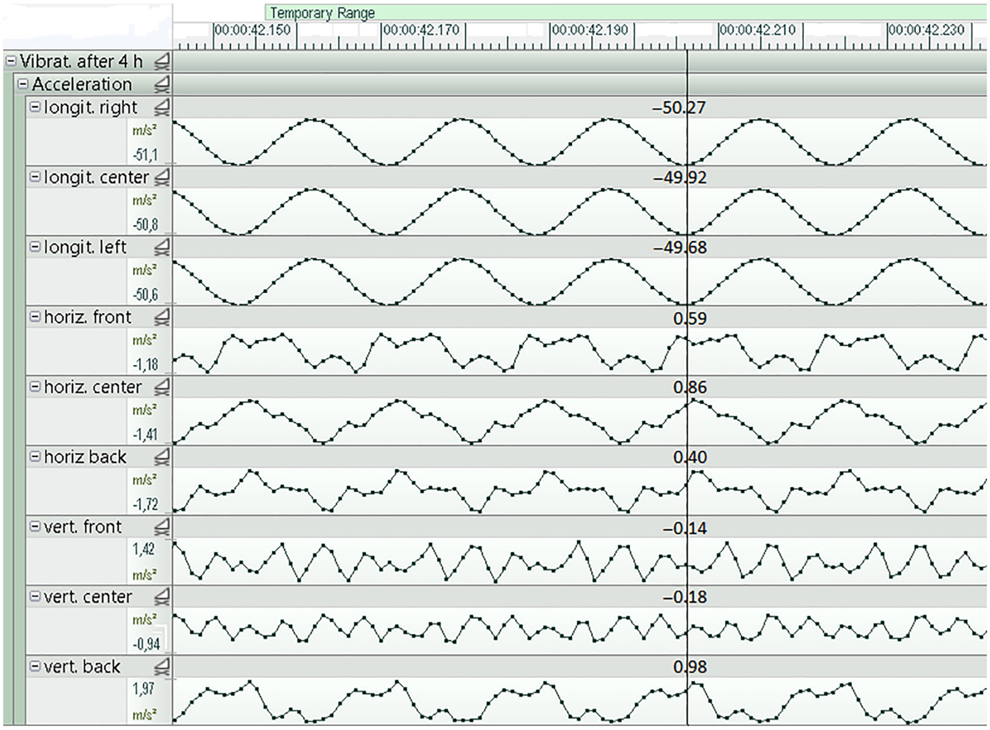

FIGURE 4 Accelerations in the various orthogonal directions.

Owing to these individual dependencies, the applied vibration parameters were selected to exclude the influence of individual values (Table 4). So, every third part of a testing series is the same and was only made once. This test series is mentioned within each experimental series since the respective vibration parameters were varied upwards and downwards based on this value.

These parameters result in the most relevant vibration intensities in engineering practice, especially for longer periodic vibrations with smaller magnitudes (cf. Table 1). Hence, 5 min were chosen as the duration representing a continuous vibration. The study thus considers long and steady vibrations of lower intensities such as pile driving or traffic vibrations rather than short impact excitations such as blasting.

Since frequency was the only parameter that could be fixed in the test setting, acceleration was regulated manually. The variation of this acceleration (Table 4) was determined in the middle of the longitudinal direction, as this represents approximately the mean value of this direction. Here, the variation could only be determined by the maximum value of each oscillation. However, since approximately the intended acceleration has been set, it is assumed that the downward variation is as great as the upward variation. Generally, the higher the acceleration was, the more accurately it could be set. In addition to the longitudinal, horizontal transverse and vertical accelerations were also measured. The locations of the accelerometers are shown in Figure S1. Figure 4 shows an extract of the applied vibration of the experimental test series 2–5 with an acceleration of ca. 50 m/s^2.

The main outcome is that there is a distinct sine wave in the direction of excitation and the vibration in the secondary directions (horizontal and vertical) is also periodic, but not harmonic. Generally, the acceleration in the secondary directions of every experimental test series constituted less than 10% of the acceleration in the excited direction. This indicates that the impacting acceleration is approximately equal to the longitudinal vibration and the accelerations in other directions are negligibly low.

3.4 | Procedure

Concrete cubes with an edge length of 15 cm were used in these experiments. Two series of 14 specimens were made for each of the 18 different experimental series (cf. Table 4), which differ by the loading direction. This results in a total of 504 specimens.

After the water was added to the dry concrete mix, the concrete was mixed for 2 min by a compulsory mixer. The molds were then filled randomly from the same batch of concrete and compacted for 30 s by a vibrating table. They were then transported into an air-conditioned room with a temperature of 20°C ± 2°C and a relative humidity of 60% ± 10%, where they were stored and subjected to vibration by the shaker. It had been determined

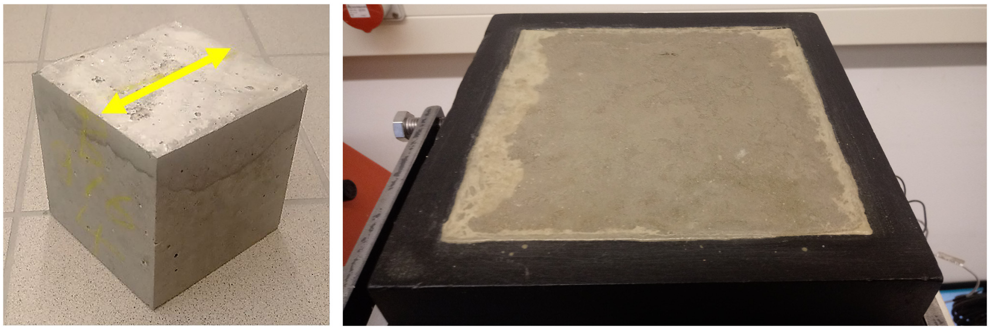

FIGURE 5 Vibration-induced liquefaction and visible differing texture/color following the vibration.

in previous investigations that this transport of the fresh concrete does not affect its strength.

After 4, 6, 8, 10, 12, and 14 h, two concrete samples were subjected to the predefined horizontal sinusoidal vibrations (Table 4). One cube was vibrated shortly before the selected time and the other one immediately thereafter. To do this, the molds were placed into the steel frame of the test setup and fixed by two screws with a torque of 2 Nm in the direction of the applied vibration, such that each mold containing concrete was vibrated in the exact same position. Two concrete samples per day were not subjected to revibration; these were used as a reference.

On the following day, the samples were retracted and stored in the same air-conditioned room for 27 days in water. After a total of 28 days, the cubes were tested according to DIN EN 12390-3.[35] The first specimen series was loaded in the direction of the vibration and the second transversely to it.

The total vibration duration was ~6 min and comprised three phases. At first, the vibration was applied and increased for about 30 s from zero until it reached the intended vibration level. This level was maintained for 5 min, and thereafter the vibration was decreased gradually over 10–30 s, depending on the acceleration magnitude.

During vibrations after 4 h with higher accelerations and velocities, the concrete at the edges transverse to the direction of the vibration appeared to liquefy (Figure 5, left). The only other time that this happened was for vibration of ~50 m/s^2 after 6 h. At the vibration time of 4 h with experiment series 1–5 and 2–5 (maximum applied acceleration and velocity), a plastic cover was attached to the top of the cube during the vibration to keep the re-liquefied concrete inside the mold.

This was also apparent from the external appearance of the concrete specimens. The area where the concrete was liquefied had a darker discoloration (Figure 5, right). It is also evident that the concrete structure had changed due to the different directions of vibration (the yellow arrows on the top of the cube show the direction of vibration). At maximum acceleration and a vibration time of 4 h, the entire concrete cube began to liquefy, after which no layers could be detected within the concrete.

3.5 | Results

The full results of the experiments are given in Table S1. The relative compressive strength (RCS) was calculated by dividing the individual values by the arithmetic means of the respective two reference samples:

$$\mathrm{RCS} = \frac{f_{c,i}}{\left(f_{c,R1,i} + f_{c,R2,i}\right)/2} \times 100 \tag{6}$$

As each mold was labeled with a fixed time, it could be seen over the course of the experiments that concrete cubes from specific molds were consistently of lower strength. This was verified by testing the concrete strengths of nonvibrated specimens (experimental series number 0). A possible reason was found to be the slight alteration of the mold geometry. Thus, the RCS of all vibrated specimens was additionally adjusted by the RCS of each mold with no vibration in the further analysis as follows:

$$\mathrm{RCS}_{\mathrm{adjusted}} = \mathrm{RCS} \cdot \frac{\left(f_{c,\mathrm{mold},R1} + f_{c,\mathrm{mold},R2}\right)/2}{f_{c,\mathrm{mold},i}} \tag{7}$$

Figure 6 shows all individual adjusted compressive strength values. The thresholds shown are equal to the maximum variance of the reference specimens, and the two curves represent the arithmetic means of all specimens tested in the shown direction.

Here it can be seen that a vibration generated after 4 h can raise the compressive strength of the concrete, while a vibration at a later age does not significantly affect the concrete strength. Generally, lower displacements and frequencies decrease the concrete strength, but there is no statistical correlation. The two

FIGURE 6 Compressive strength changes of all individual values.

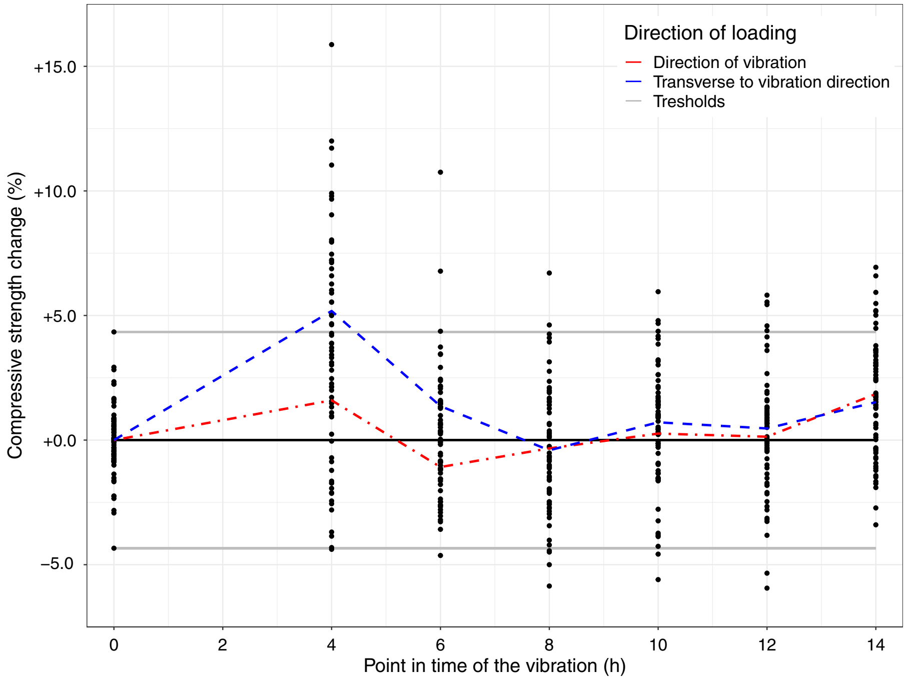

TABLE 5 The p-values of different combinations.

Variables	4 h, loading transverse to the direction of vibration	4 h, loading in direction of vibration	4 h, all values
Frequency (f)	1.1×10^{-6}	6.7×10^{-4}	1.8×10^{-4}
Amplitude (U)	0.27	0.09	0.21
Velocity (v)	6.1×10^{-8}	1.6×10^{-3}	1.1×10^{-4}
Acceleration (a)	$\mathbf{2.2 \times 10^{-16}}$	1.3×10^{-3}	8.4×10^{-7}
$f + U$	4.4×10^{-13}	$\mathbf{1.3 \times 10^{-8}}$	$\mathbf{2.1 \times 10^{-8}}$
$f + v$	$\mathbf{2.2 \times 10^{-16}}$	3.8×10^{-6}	2.4×10^{-8}
$f + a$	4.6×10^{-16}	1.0×10^{-3}	3.0×10^{-6}

Note: The bold values indicate the lowest p-values of each data set.

measurements above the threshold after 6 h were generated by the maximum acceleration (ca. 50 m/s^2), with loading transverse to the direction of the applied vibration.

The direction of vibration after 4 h generally affects the increase in compressive strength. In Table 5, the results of a statistical analysis are shown. Due to the interdependence between the displacement, velocity, and acceleration no further combination of variables was considered here.

The p-value is defined as the probability—under the condition that the null hypothesis (H_0: there are no strength changes) is true—of obtaining the observed value of the test variable. Since the p-value is an auxiliary variable from a hypothetical statistical model, it cannot be directly related to the real values. However, the smaller the p-value, the greater the incompatibility between the measured values and the null hypothesis, so that the null hypothesis must be rejected.

In summary, there is a significant impact of all variables except the displacement alone. This indicates that the intensity of the vibration—including each vibration parameter—influences the strength increases and it cannot be reduced to one single parameter. Furthermore, it was verified that the compressive strength of the concrete increases with rising vibration parameters.

For all values of specimens vibrated after 4 h and the values of specimens, which were loaded in the direction of the vibration, the lowest p-value exists for the characterization by frequency and displacement. For compressive strength of specimens vibrated after 4 h and loaded transversely to the direction of the vibration the lowest p-values exist for acceleration only as well as the combination of frequency and velocity. The best statistical fit is

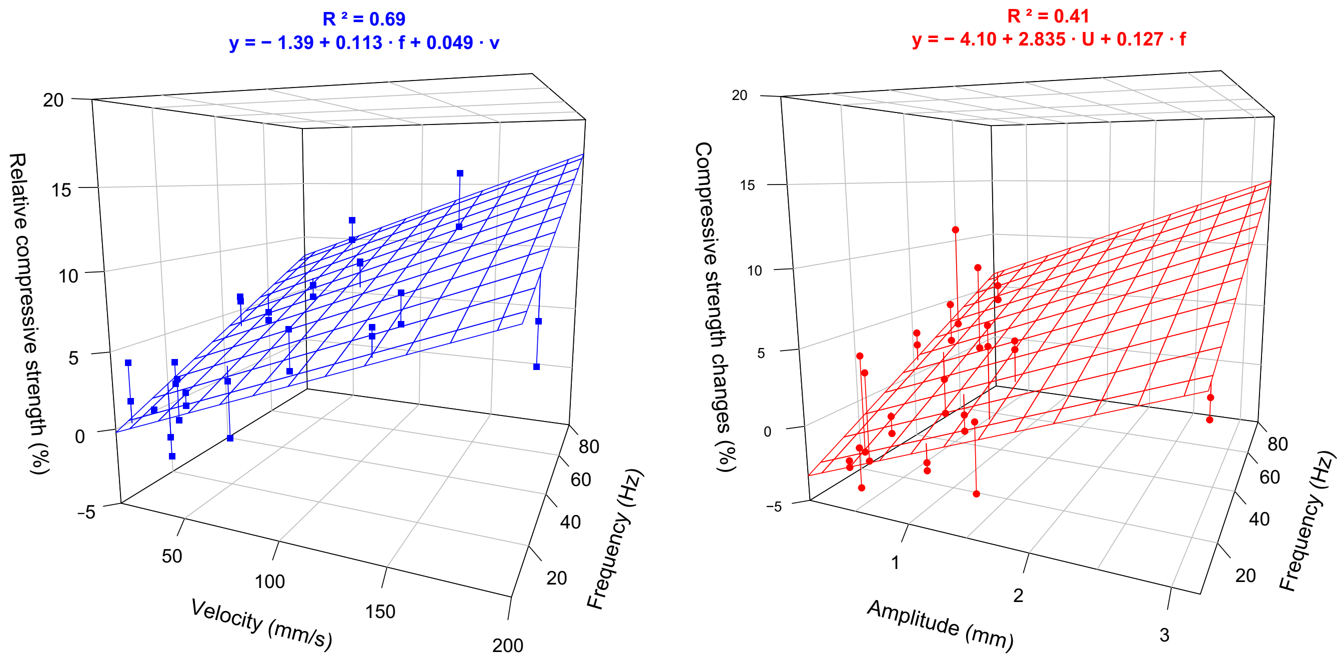

FIGURE 7 Compressive strength changes of specimens vibrated after 4 h: Loaded transversely to the direction of vibration (left) and loaded in direction of vibration (right).

the latter due to a higher R^2 (for a: $R^2 = 0.66$; for $f + v$: $R^2 = 0.69$). The best fit for each vibration direction with a mathematical expression of the regression plane is presented in Figure 7.

3.6 | Further examinations

3.6.1 | Preface

The reasons for the increase in compressive strength could be either mechanical or chemical or a combination of both. The concrete structure can be mechanically strengthened by postdensification, which results in less pore structure. This increase can also be explained chemically as the result of a higher degree of hydration or the formation of longer and more stable C—S—H phases. The following possible explanations are dependent on the end of the induction period of the cement, which has not yet been fully clarified[36]:

- Cement clinker grains could be rubbing against each other or cracking, resulting in an enlarged cement surface and the activation of otherwise nonhydrated cement clinker.
- The first hydration products, which may disturb the further reaction of the C_3S, become separated, allowing the hydration of tricalcium silicate to progress faster. The dissolved hydration products may also serve as a crystallization nucleus—similar to the seeding effect of additional C—S—H in hydrating cement[37]—and thus quicken the chemical reaction.
- More ions might be dissolved into the solution enabling the hydration to progress faster. This might be explained by two effects:
  - mixing—comparable with stirring sugar in a hot drink
  - destruction of the electronic double layer and dissolution of more ions

To discover the cause of these increases further chemical and physical analysis was conducted. For this purpose, two concrete cubes were made, one was used as a reference sample and the other was subjected to the maximum acceleration of ~ 50 m/s^2 after 4 h (due to maximum strength increases). These additional specimens were manufactured and stored under the same conditions as the other concrete cubes. After 28 days, one sample each was taken from the upper (4 h, top) and lower third (4 h, bottom) of the vibrated concrete cube, and one reference sample was extracted from the middle of the reference cube. These specimens were then dried in a vacuum dryer at 40°C and 70 mbar for 7 days to prevent further hydration. They were transported under vacuum from Münster to Munich for subsequent examinations. The aim of this procedure was to reduce the affectation of these specimens by humidity (and consequential further hydration) or CO_2 (and the altering of hydration

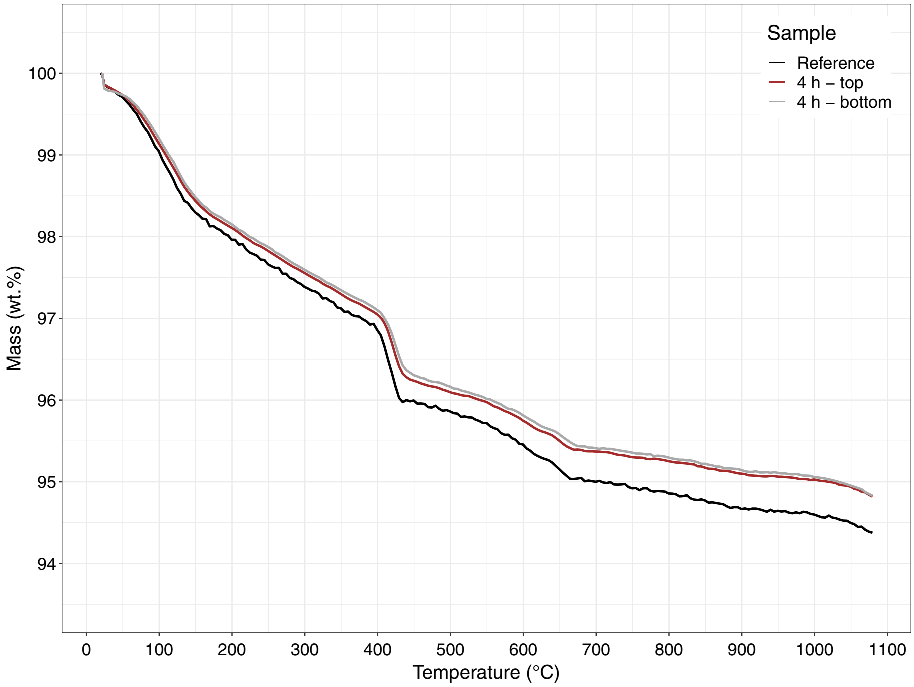

FIGURE 8 Thermogravimetric analysis results

products) to an absolute minimum. In Munich, these specimens were ground and stored airtight until the examinations. The following three investigations were carried out once on each sample.

3.6.2 | Thermogravimetric analysis

Figure 8 shows the results of the thermogravimetric analysis (TGA). It is evident that the reference sample loses more weight (in total 0.5 wt.% at 1100°C). This difference in mass loss is due to the partial decomposition of C—S—H, ettringite and gypsum at 50°C–150°C as well as a slightly higher amount of decomposed $Ca(OH)_2$ at ~400°C–450°C. At other temperatures, the graphical progressions are very similar. This indicates that there are no major differences between the hydration products of the samples and the reference might even have a higher degree of hydration.

3.6.3 | X-ray diffraction

In addition to TGA, X-ray diffraction (XRD) was also performed. The results of the Rietveld refinement are given in Table 6. They show that the amount of nonhydrated clinker phases is almost comparable. There is a larger amount of $Ca(OH)_2$ and calcite (reaction product of CH and CO_2) in the reference sample, which fits to the result of the TGA. The amount of ettringite is always <0.2 wt.% due to the sample preparation with the vacuum dryer. Furthermore, there is comparable amount of aggregate (quartz and microcline) in all samples.

In conclusion, there are minor differences between the samples, but no clear trend can be identified. This indicates that there is no evidence of further hydration of the vibrated samples. This result is in line with the findings of the TGA. Moreover, examination of a comparable quantity of aggregate shows that no segregation occurred as a result of the vibration treatment.

3.6.4 | Nuclear magnetic resonance

^{29}Si magic angle spinning nuclear magnetic resonance (^{29}Si MAS NMR) was performed to obtain further insights into the amorphous silicate phases. The NMR spectra (Figure 9) show largely similar trends for all specimens. This means that there is a comparable amount of nonhydrated clinker (Q^0 from −68 to −73 ppm), although there may also be longer C—S—H phases in the vibrated concrete, shown by a slightly different ratio between dimers (Q^1 at −79 ppm) and trimers (Q^2 at −82 and − 85 ppm). Furthermore, analysis of the NMR shows that slightly more C_3S was hydrated in the reference sample, which contradicts the XRD results. This indicates that the differences between the specimens are marginal that it can be assumed that the proportion is roughly identical. So, here there is no evidence of a further hydration of vibrated specimens, but the C—S—H phases formed might be longer in vibrated samples.

One conspicuous feature of the NMR spectrum of the vibrated sample extracted from the lower part of the concrete is the higher resonance of the quartz (Q^4 at −107 ppm), indicating a segregation of the aggregate. As the measurement parameters were optimized for the C—S—H phases, the long relaxation time of quartz was not considered, which resulted in saturation effects and the absence of any quantitative information from the quartz. In this case, XRD is more reliable.

4 | DISCUSSION OF THE TEST RESULTS

Investigations by Hong and Park[16] showed that at the frequency of 5 Hz higher velocities (especially the maximum velocity of 10 mm/s) lead to a decrease in strength. In contrast, the present study found no significant strength reduction at a frequency of 5 Hz, although the velocity was considerably higher (50 mm/s). This might be due to the early application of vibration by Hong and Park and subsequent segregation and/or the interaction with concrete additives.

The strength increases due to vibration after 4 h (before the initial setting time) are in line with studies of concrete revibration in Refs. 1–3 and the work of Dunham et al.[24] This is also in line with strength increases caused by the regular vibratory consolidation of concrete, where higher accelerations increase the strength up to a limit depending on the consistency of the fresh concrete.[38] During vibration, the yield value of fresh concrete decreases with increasing peak particle velocities,[39] and at low shear rates, the concrete behaves like a Newtonian fluid.[40,41] Inertia then constitutes the main resistance and Newton's second law of motion can be applied[38]:

$$F = m \cdot a \tag{8}$$

This indicates that acceleration plays an important role in (re-)consolidation. However, the question of whether acceleration[38] or peak particle velocity[39,40] is the main parameter influencing the effectivity of consolidation is still disputed. The present investigation shows that the direction of vibration also appears to influence the strength increases. So, in one direction, the acceleration as well as the combination of frequency and velocity are dominant, while in the other direction, the influence of velocity and acceleration are roughly equivalent, and the total intensity of the vibration (expressed by amplitude and frequency) is decisive (cf. Table 5). This is also evidenced by the external appearance of the concrete specimens, in which a more distinct structural change takes place in the direction of the vibration. However, the results of this study demonstrate that the effect of post-compaction cannot be reduced to just one parameter.

TABLE 6 X-ray diffraction results (wt.%)

	Amorphous content	C_3S	β-C_2S	C_3A	C_4AF	$CaCO_3$	$CaSO_4$	CH	Monocarbonate	Quartz	Microcline intermediate	Ettringite
Reference	11.99	2.22	0.28	0.51	0.72	0.73	0,32	3.06	1.72	74.02	4,28	<0.2
4 h, top	11.42	2.01	0.45	0.54	0.76	0.56	0.44	2.66	1.66	75.79	3.63	<0.2
4 h, bottom	12.95	1.81	0.61	0.58	0.51	0.60	0.49	2.56	1.66	74.59	3.63	<0.2

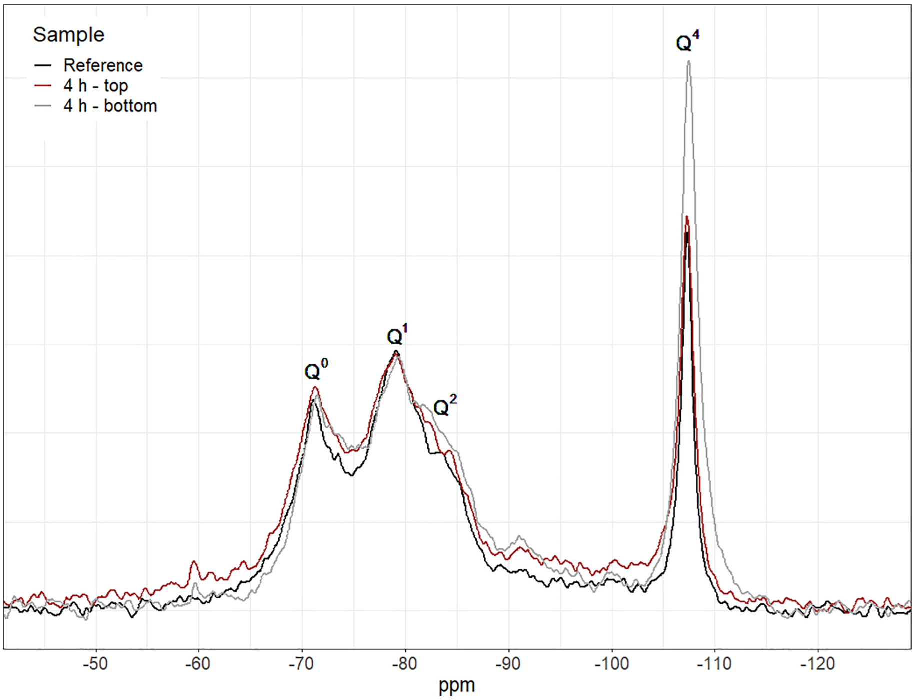

FIGURE 9 ^{29}Si magic angle spinning nuclear magnetic resonance spectra

Since further investigations found no clear trend towards a higher degree of hydration of vibrated samples, the strength increase is probably due to mechanical postcompaction. The slight tendency towards longer C—S—H chains may also contribute to a strength increase. Due to the large amount of aggregate in the samples (about 80 wt.%), no significant changes in the cement paste could be determined with the applied analytical methods to prove the effect of vibration on the hydration reaction. Further investigation will necessitate developing a special sample preparation to enrich the binder content.

5 | CONCLUSIONS

These investigations show that vibration may have a positive effect on the compressive strength of concrete generated by applying higher vibration parameters to young concrete before the initial set. These strength increases are probably due to a mechanical postdensification. Reduced compressive strengths were largely generated at lower frequencies and displacements but its magnitude is negligible.

It should be mentioned that only one concrete mixture was tested in the experiments, which means that the results are not directly applicable to other concrete mixtures—especially in the case of cement being used with different reacting components (e.g., fly ash or blast-furnace slag). Furthermore, tensile strength may be affected more by vibrations due to its sensibility of cracks which may arise through vibrations. This is also acknowledged in other publications, in which the compressive strength was not or was only slightly negatively affected, but the tensile strength was significantly reduced.[42–44] A similar result was found by Dunham et al.,[24] in which the compressive strength of the concrete increased although the tensile splitting strength decreased slightly. Therefore, there are several research questions which still require clarification.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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