Effects of Induced Vibrations on Early Age Concrete

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Abstract: The purpose of this investigation was to conduct a laboratory test program on how much induced vibrations on concrete during the period between initial set and final set affect the attainable strength of concrete. To achieve this purpose, a laboratory test program was conducted. The laboratory program consisted of casting 144 76 mm by 152 mm (3×6 in.) concrete cylinders and subjecting them to one of two levels of vibration for either 1 or 2 min at five different ages ranging in time from before, during, and after the setting period for the concrete. The levels of vibration correspond to typical frequencies of vibratory soil compactors and the peak particle velocity produced by the compactors. Both compression and splitting tensile tests were performed. The results of the laboratory study indicate that vibratory soil compaction should not be considered a significant hazard to foundation strength as long as the vibrations are within the limits in this study.

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Introduction

During the setting process, fresh concrete may be exposed to vibrations from a variety of sources: earthquakes, heavy traffic, pile driving, or vibratory soil compactors. Of the various sources, vibratory soil compactors would be the most likely to cause sustained vibrations for durations on the order of minutes. During the setting process, bonds are being formed in the cement matrix; therefore, vibration might cause damage to those bonds and result in a reduction of attainable strength. The fast pace of modern construction projects increases the possibility that soil compaction takes place adjacent to freshly placed concrete foundations. However, relatively few studies have been conducted concerning the effects of soil compactors on setting foundations. The goal of this project was to determine whether vibrations from compactors before, during, and right after the setting period pose a threat to the attainable concrete compressive and splitting tensile strengths. Without understanding of the impact of these vibrations, any concrete failure in a foundation may be incorrectly attributed to the ready mix producer.

Research Significance

Previous studies on effects of vibration on curing concrete showed no substantial effects on the compressive strength attained. Few of the completed studies, however, focused on the effect of vibration when the concrete was only a few hours old, and few measured the effect on tensile strength. This study investigated the effect of vibration at five ages between 2 and 6 h from initial water–cement contact on the compressive and splitting tensile strength. Two levels of vibration for two different durations were used to simulate the effects of vibratory compactors operating near newly placed foundations.

Background

Researchers have been concerned for many years about the effects of vibration at early ages on the strength attained by concrete. Most of these studies were conducted regarding traffic loading (Manning 1981; Furr and Fouad 1982), pile driving (Wiss 1967; Bastian 1970), and/or blasting (Gamble et al. 1985; Hulshizer 1996). Many of the studies focused on predicting the amount of vibration that can be anticipated, and recommended that they stay below "standard" thresholds. "Standard" was not always defined, however. Of the studies that measured the impact on concrete strength, most concluded that vibrations have no effect on or actually improve the compressive strength. One study (Kwan et al. 2005) showed that vibrations have little effect on compressive strength, but can have a significant effect on splitting tension strength. Their study, however, did not expose concrete to vibration during the setting period; the first exposure was at 12 h. Most of their tests were performed with peak particle velocities between 300 and 750 mm/s (12–30 in./s); therefore, the observed effect on splitting tension strength was limited to very strong vibrations. Only two of the studies (Bastain 1970; Hulshizer 1996) quantified the magnitude of vibration while exposing concrete to vibrations during the setting period. Those two studies exposed concrete to vibrations from pile driving and blasting rather than the sustained vibrations that can be anticipated during soil compaction.

Cement Hydration

The setting period for concrete is loosely defined as the transition from fluid concrete to rigid concrete. Formal definitions of time of

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set are arbitrary because the conditions of initial set and final set do not denote specific changes in concrete properties (ASTM 1997). In practice, setting times are used to provide a guideline for workers to conduct different activities necessitating that the concrete have a certain level of rigidity (e.g., striking and finishing a slab). Initial set corresponds to the time when concrete is no longer workable and has relatively no slump; where final set indicates the time at which the concrete begins to harden, but no measurable strength can be observed (Mindess et al. 2003).

According to Mindess et al. (2003), the time of set is primarily controlled by the hydration of tricalcium silicate (C_3S) in the cement, but may also be controlled by the rapid formation of ettringite from the hydration of tricalcium aluminate (C_3A) in the case of a rapid setting concrete or a false/flash set. Initial set approximately denotes the beginning of the hydration of C_3S and final set approximately denotes the fastest rate of hydration for C_3S (Mindess et al. 2003). At final set, the C_3S is rapidly hydrating to form calcium silicate hydrate (C–S–H). Although the chemical composition of this product is highly variable, depending upon the water-to-cement ratio, the physical properties remain fairly consistent. Because concrete gains most of its strength from the hydration of C_3S, the rate at which it reacts and the quantity that reacts become important. Concrete also gains some of its final strength from C_2S, but that reaction is much slower and does not contribute nearly as much to the overall strength as the C_3S (Mindess et al. 2003). Therefore, the authors hypothesize that concrete is most vulnerable to vibrations during the setting period when vibrations might disrupt the formation of hydrated bonds.

Previous Studies

Bastian (1970) identified several studies on revibration of concrete. He defined revibration as vibration occurring some time after initial consolidation of the concrete. Based on his literature review, he concluded that strength gain due to early age vibration is likely due to the release of free water as bleed water. However, none of the studies provided quantification of the level of vibration. In his paper, Bastian did provide data on vibrations due to pile driving adjacent to concrete piles that were being cast. The pile driving caused peak particle velocities (PPVs) of approximately 10 mm/s (0.4 in./s) for the first 7 h of curing for the cast piles. PPV is a measure of the intensity of ground vibration. More specifically, it is the time rate of change of the amplitude of ground vibration. By comparing cores with control cylinders, he found that the vibrations had resulted in a 4% increase in compressive strength. The study did not, however, explore the effect on tensile strength.

Another study provides the starting point for the research presented in this paper. Hulshizer (1996) combined field experiments with laboratory work in his Seabrook Blast Test Program. He tested the effects of blast vibrations through soils upon fresh and maturing concrete. His testing consisted of cylinder compression tests at 7 and 28 days, shear and bond beam tests, and bond pull-out tests. He tested a wide range of peak particle velocities from less than 25 mm/s (1 in./s) to more than 400 mm/s (16 in./s), the latter signifying a large explosion. The study consisted of specimens exposed to blast vibrations at 3, 6, 8, 14, or 24 h. He found that the average effect on shear strength for all of the combinations of exposure was a drop of 4%. He also found that the average effect on bond strength was a drop of 3%. Most of the compression specimens exposed to the blast vibrations experienced an increase in strength. Of all the compression test results, the specimens that experienced the greatest decrease of 28-day strength were those exposed at 3 h after casting, which is the only time that corresponds to the setting period. Those specimens exhibited a 7% loss of strength. Since most of the test results were within the coefficient of variation of the control group, Hulshizer concluded that blast vibrations did not affect concrete strength enough to be concerned about these or any other vibrations (Hulshizer 1996). However, the study did not explore the possibility that the 7% loss might be a lower bound of what could be expected for concrete exposed to vibrations during the setting period.

Experimental Investigation

The purpose of this investigation was to conduct a laboratory test program on the effects of induced vibrations on concrete before, during, or after the setting period. Specifically, the authors explored the effects on the attainable compressive and splitting tensile strength of concrete. To achieve this purpose, a laboratory program was conducted. The laboratory program consisted of casting 144 76 mm by 152 mm (3×6 in.) concrete cylinders from a single batch of ready-mix concrete. Nasser and Kenyon (1984) showed that specimens of this size produce compressive strength values comparable to 152 mm by 305 mm (6×12 in.) as long as the maximum aggregate size does not exceed 25 mm (1 in.).

A team of ten people cast the cylinders over a period of 2 h. To minimize any systematic variation in test results due to who cast a group of cylinders and when a group of cylinders was cast, each cylinder was given a serial number. A random number generator was used to assign cylinders to test groups.

The cylinders were used to obtain compressive strength at 7 and 28 days, and to obtain splitting tensile strength at 29 days. Three variables were considered to be of greatest interest for the experimental program: age when vibrated, PPV, and duration of vibration.

The first variable, age or time when vibrated, was selected to determine the effects of vibration on concrete at different ages throughout the setting period. The ages at which groups of cylinders were vibrated were 2, 3.5, 4.5, 5, and 6 h after water–cement contact. These ages ensured that at least one group would be exposed to vibration in each of the following age ranges: before initial set, during the setting process, and after final set.

The second variable, peak particle velocity, was selected to determine the effect that different magnitudes of vibration have on concrete strength. The amplitude and frequency of the vibrations were chosen to match those produced by vibratory soil compactors. The frequency range of these machines is normally in the range of 25–60 Hz (Caterpillar 2004). The frequency of the shake table used in the experiment was 60 Hz. Most compactors have variable amplitude control ranging from 25 to 275 mm/s (1–11 in./s) PPV of induced vibrations. The lower level (L) of vibration used in this study corresponds to particle velocities of approximately 50–100 mm/s (2–4 in./s) and the higher level (H) corresponds to particle velocities of approximately 200–300 mm/s (8–12 in./s). In order to quantify the PPV for each level, vertical accelerations were measured at various locations on the shake table. By assuming that the shake table produces harmonic vibrations, the authors were able to use relationships provided by Hulshizer (1996) to convert measured accelerations to peak particle velocities.

Table 1. Concrete Mix Proportions (by Weight)

Water	Cement	Fly ash	Fine agg	Coarse agg
0.060	0.101	0.018	0.346	0.476

The final variable, duration of vibration, explored whether the length of vibration affects the compressive or splitting tensile strength of the concrete. Durations of 1 and 2 min were used to represent a range of possible times that a vibratory compactor would be operating immediately adjacent to a concrete foundation.

The authors followed the American Society for Testing and Materials standard for making and curing concrete test specimens in the laboratory (ASTM 2002), and all specimens were placed in a lime water bath after 24 h and maintained in the bath until testing. The concrete was batched by a local ready-mixed concrete company. The mix proportions are shown in Table 1. The mix had a water/cementitious material ratio of 0.50. Water reducer was used at the rate of 195 mL per 100 kg (3 oz./100 lb) of cementitious material. An admixture was also used to provide 5% air entrainment; however, the air content was not measured. The coarse aggregate had a maximum size of 20 mm (3/4 in.). A more detailed description of the procedures followed is available in Dunham and Rush (2004).

All of the specimens with a particular combination of vibration duration and intensity were vibrated simultaneously (Fig. 1) on a Syntron Vibrating Table, model number VP5101, by Soiltest, Inc. Finally, ASTM C39/C39M-01 (ASTM 2001) and C496-96 (ASTM 1996) were followed to perform 7- and 28-day compression strength and 29-day splitting tensile strength tests, respectively.

The ages when the specimens would be vibrated were predetermined. To correlate the age when vibrated with the setting period, a penetrometer test was conducted on two mortar samples extracted from the concrete batch (ASTM 1997). Initial and final set are defined by the standard test method as when the penetration resistance reaches 3.45 MPa (500 psi) and 27.6 MPa (4,000 psi), respectively. The observed initial and final set times were 3.4 and 4.3 h, respectively (Fig. 2). Based on those results, some specimens were vibrated before initial set (2 h), during the setting period (3.5 h), and after final set (4.5, 5, and 6 h).

Fig. 1. Arrangement of specimens on shake table

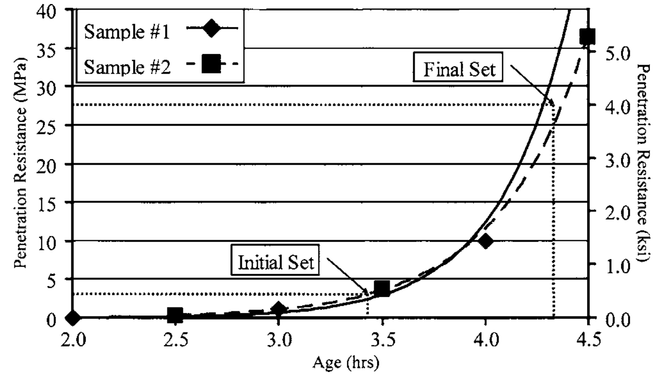

Fig. 2. Results from penetration tests showing time of initial and final set. Each curve represents the exponential function that best fits the data from the particular mortar sample.

Experimental Results and Discussion

Compressive Strength

Each test group, vibrated or control, typically consisted of three specimens. Figs. 3 and 4 present the average strength of each test group as a percentage increase or decrease compared to the average strength of the control specimens for 7- and 28-day strength, respectively. Only a subset of combinations of PPV, duration of vibration, and age when vibrated was tested at 7 days. A summary of all individual compression test results can be found in Table 2. From these results, the induced vibrations appear to increase the compressive strength of the concrete compared to the control specimens in both the 7- and 28-day compression tests. As can be seen in the data of Table 2, only two of the 21 specimens tested at 7 days were weaker than the average of the control group, and of those only one was more than the coefficient of variation weaker than the average. Only five of the 56 specimens tested at 28 days were weaker than the average of the control group, and of those only one was more than the coefficient of variation weaker than the average.

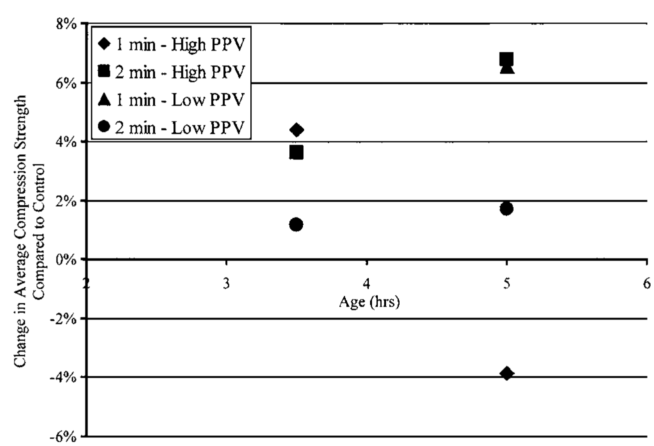

Fig. 3. Impact on average compression strength at 7 days for four combinations of PPV and duration of induced vibration. Percentages based on average of control cylinders, which were not vibrated.

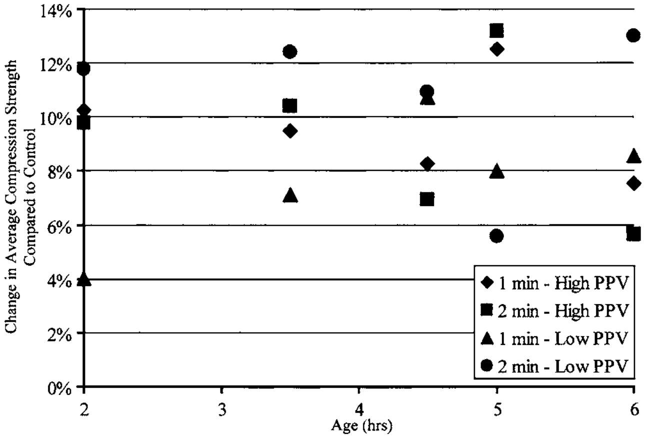

Fig. 4. Impact on average compression strength at 28 days for four combinations of PPV and duration of induced vibration. Percentages based on average of control cylinders, which were not vibrated.

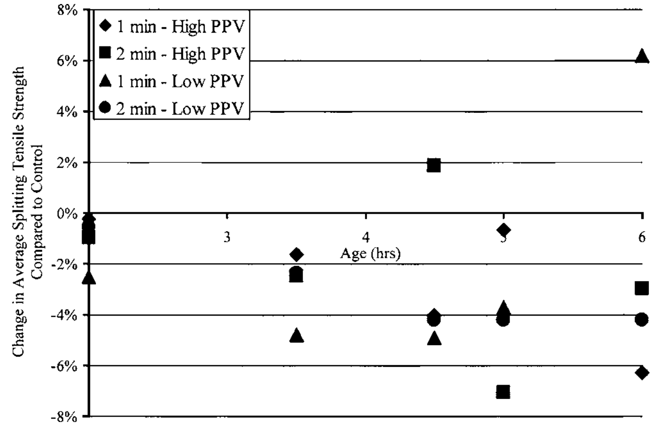

Fig. 5. Impact on average splitting tensile strength at 29 days for four combinations of PPV and duration of induced vibration. Percentages based on average of control cylinders, which were not vibrated.

Table 2. Results of Compression Tests at 7 and 28 Days

Age when vibrated (h)	Peak particle velocity (L/H)[a]	Duration of vibration min)	Age when tested days)	Specimen Number 1 [MPa (ksi)]	Specimen Number 2 [MPa (ksi)]	Specimen Number 3 [MPa (ksi)]	Average [MPa (ksi)]	Change over control average (%)	Coefficient of variation (%)
Control		—	7	20.4 (3.0)	19.8 (2.9)	21.7 (3.1)	20.6 (3.0)	—	5
3.5	*H*	1	7	21.2 (3.1)	22.8 (3.3)	20.6 (3.0)	21.5 (3.1)	4	5
3.5	*H*	2	7	22.0 (3.2)	21.4 (3.1)	20.7 (3.0)	21.4 (3.1)	4	3
3.5	*L*	2	7	20.7 (3.0)	20.3 (2.9)	21.6 (3.1)	20.9 (3.0)	1	3
5	*H*	1	7	20.8 (3.0)	17.9 (2.6)	20.8 (3.0)	19.8 (2.9)	−4	8
5	*H*	2	7	21.4 (3.1)	23.5 (3.4)	21.2 (3.1)	22.0 (3.2)	7	6
5	*L*	1	7	22.4 (3.3)	21.6 (3.1)	21.9 (3.2)	22.0 (3.2)	7	2
5	*L*	2	7	21.2 (3.1)	20.0 (2.9)	21.8 (3.2)	21.0 (3.0)	2	4
Control		—	28	29.8 (4.3)	24.6 (3.6)	25.8 (3.7)	26.7 (3.9)	—	10
2	*H*	1	28	31.0 (4.5)	29.3 (4.2)	28.2 (4.1)	29.5 (4.3)	10	5
2	*H*	2	28	29.5 (4.3)	28.7 (4.2)	29.8 (4.3)	29.3 (4.3)	10	2
2	*L*	1	28	23.7 (3.4)	28.5 (4.1)	31.2 (4.5)	27.8 (4.0)	4	14
2	*L*	2	28	30.8 (4.5)	27.8 (4.0)	31.0 (4.5)	29.9 (4.3)	12	6
3.5	*H*	1	28	29.3 (4.2)	30.2 (4.4)	28.3 (4.1)	29.3 (4.2)	9	3
3.5	*H*	2	28	29.5 (4.3)	30.6 (4.4)	28.4 (4.1)	29.5 (4.3)	10	4
3.5	*L*	1	28	29.9 (4.3)	27.3 (4.0)	— —	28.6 (4.2)	7	7
3.5	*L*	2	28	30.0 (4.4)	— —	— —	30.0 (4.4)	12	—
4.5	*H*	1	28	28.2 (4.1)	28.4 (4.1)	30.2 (4.4)	28.9 (4.2)	8	4
4.5	*H*	2	28	28.9 (4.2)	29.1 (4.2)	27.8 (4.0)	28.6 (4.1)	7	2
4.5	*L*	1	28	28.6 (4.1)	29.4 (4.3)	30.9 (4.5)	29.6 (4.3)	11	4
4.5	*L*	2	28	29.7 (4.3)	29.6 (4.3)	— —	29.7 (4.3)	11	0
5	*H*	1	28	33.5 (4.9)	29.3 (4.2)	27.5 (4.0)	30.1 (4.4)	13	10
5	*H*	2	28	26.2 (3.8)	32.5 (4.7)	32.1 (4.7)	30.3 (4.4)	13	12
5	*L*	1	28	32.4 (4.7)	29.5 (4.3)	24.8 (3.6)	28.9 (4.2)	8	13
5	*L*	2	28	29.6 (4.3)	28.6 (4.2)	26.5 (3.8)	28.2 (4.1)	6	6
6	*H*	1	28	26.1 (3.8)	28.9 (4.2)	31.2 (4.5)	28.7 (4.2)	8	9
6	*H*	2	28	27.5 (4.0)	29.3 (4.2)	28.0 (4.1)	28.2 (4.1)	6	3
6	*L*	1	28	27.2 (3.9)	29.2 (4.2)	30.6 (4.4)	29.0 (4.2)	9	6
6	*L*	2	28	30.7 (4.5)	32.1 (4.7)	27.8 (4.0)	30.2 (4.4)	13	7

[a] L=low PPV and H=high PPV.

Table 3. Results of Splitting Tensile Strength Tests at 29 Days

Age when vibrated (h)	Peak particle velocity $(L/H)^a$	Duration of vibration (min)	Age when tested (days)	Specimen Number 1 [MPa (psi)]		Specimen Number 2 [MPa (psi)]		Specimen Number 3 [MPa (psi)]		Average [MPa (psi)]		Change over control average (%)	Coefficient of variation (%)
Control		—	29	3.19	(462)	3.52	(510)	3.55	(514)	3.42	(495)	—	6
2	*H*	1	29	3.31	(480)	3.10	(450)	3.81	(553)	3.41	(494)	0	11
2	*H*	2	29	3.18	(460)	3.73	(541)	3.24	(470)	3.38	(491)	−1	9
2	*L*	1	29	3.56	(516)	3.48	(504)	2.96	(429)	3.33	(483)	−2	10
2	*L*	2	29	3.41	(495)	3.29	(477)	3.49	(507)	3.40	(493)	−1	3
3.5	*H*	1	29	3.64	(528)	3.60	(522)	2.85	(413)	3.36	(487)	−2	13
3.5	*H*	2	29	3.04	(440)	3.39	(491)	3.57	(518)	3.33	(483)	−2	8
3.5	*L*	1	29	3.25	(472)	—	—	—	—	3.25	(472)	−5	—
3.5	*L*	2	29	3.50	(508)	3.17	(460)	—	—	3.34	(484)	−2	7
4.5	*H*	1	29	2.91	(422)	3.49	(506)	3.44	(499)	3.28	(476)	−4	10
4.5	*H*	2	29	3.87	(561)	3.33	(482)	3.25	(471)	3.48	(505)	2	10
4.5	*L*	1	29	3.07	(445)	3.73	(541)	2.95	(428)	3.25	(471)	−5	13
4.5	*L*	2	29	2.97	(431)	3.28	(476)	3.56	(516)	3.27	(475)	−4	9
5	*H*	1	29	3.64	(529)	2.98	(432)	3.56	(516)	3.39	(492)	−1	11
5	*H*	2	29	3.14	(455)	3.18	(461)	3.21	(465)	3.18	(461)	−7	1
5	*L*	1	29	3.55	(515)	3.12	(453)	3.20	(464)	3.29	(477)	−4	7
5	*L*	2	29	3.11	(452)	3.13	(454)	3.58	(519)	3.27	(475)	−4	8
6	*H*	1	29	2.57	(372)	3.12	(452)	3.92	(569)	3.20	(464)	−6	21
6	*H*	2	29	3.13	(454)	3.36	(488)	3.45	(500)	3.32	(481)	−3	5
6	*L*	1	29	3.46	(501)	3.69	(536)	3.73	(541)	3.63	(526)	6	4
6	*L*	2	29	3.03	(440)	3.63	(527)	3.15	(457)	3.27	(475)	−4	10

[a] *L*=low PPV and *H*=high PPV.

Splitting Tensile Strength

A different trend was found in the results of the splitting tensile tests. The average strength of the control group was stronger than the average strength of all but two of the other groups (Fig. 5). Table 3 presents a summary of all individual splitting tensile test results. Of the 57 specimens tested, 34 were weaker than the average of the control group. However, the average strength of only two of the 20 groups was statistically weaker than the average of the control group. The lowest average was only 7% weaker than the control group which was within the coefficient of variation for many of the groups. Therefore, the apparent reduction in splitting tensile strength was not significant enough to cause concern.

Closer review of the averages in Fig. 5 revealed that no particular combination of duration and PPV resulted in systematically low or high splitting tensile strength values when varying the age when vibrated. Three different combinations out of the four resulted in the lowest average strengths for the five ages, and three different combinations resulted in the highest average strengths for the five ages. Therefore, there is nothing to indicate that further investigation of the effect on splitting tensile strength is warranted.

Conclusions and Recommendations

The results of this study have shown that vibratory soil compaction does not negatively affect the attainable compressive strength of concrete. Although it may have a slight negative effect on the tensile capacity, the effect can be reasonably assumed to be less than 8%. Therefore, there does not appear to be sufficient reason to prohibit soil compaction adjacent to setting foundations. These results are consistent with other studies about the effects of vibration at early ages on the compressive and tensile strengths achieved.

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