ACCEPTABLE VIBRATIONS ON GREEN CONCRETE

FINAL REPORT

State Study 252

By

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16. Abstract Vibrations are potentially harmful to green concrete in shaft foundations, and many states, including Mississippi, cautiously established limits in terms of compressive strength, distance boundary, and wait time to protect early age concrete. But these limits could be overly conservative with respect to experimental evidence, and perhaps unnecessarily impede construction schedules and add cost to projects. The objective of this study was to quantify the effects of early age vibrations on concrete performance. Concrete cylinders were exposed to several combinations of vibration magnitudes and durations that were representative of shaft construction, and at ages coincident with the sensitive period between initial and final set. The vibrations had no consistent effect on compressive strength and electrical resistivity. There was also no discernable difference between limestone and river gravel coarse aggregates.			
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BIOGRAPHICAL SKETCH OF AUTHORS

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TERMS OF THE STUDY

The findings and recommendations expressed in this report are those of the authors and do not necessarily reflect the views of the Mississippi Department of Transportation. This report does not constitute a standard, specification, or statute.

ABSTRACT

Vibrations are potentially harmful to green concrete in shaft foundations, and many states, including Mississippi, cautiously established limits in terms of compressive strength, distance boundary, and wait time to protect early age concrete. But these limits could be overly conservative with respect to experimental evidence, and perhaps unnecessarily impede construction schedules and add cost to projects. The objective of this study was to quantify the effects of early age vibrations on concrete performance. Concrete cylinders were exposed to several combinations of vibration magnitudes and durations that were representative of shaft construction, and at ages coincident with the sensitive period between initial and final set. The vibrations had no consistent influence on compressive strength and electrical resistivity. There was also no discernable difference between limestone and river gravel coarse aggregates.

KEYWORDS

Early age, green concrete, vibration, foundation, coarse aggregate, compressive strength

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CHAPTER 1

Introduction

Vibrations are potentially harmful to green concrete, but a statement in the *Mississippi Standard Specifications for Road and Bridge Construction*[1] meant to protect early age concrete in shaft foundations could be overly restrictive. Article 803.03.2.3.1.1 states that construction of any shaft cannot commence within 30 feet (9 m) of a newly built shaft until the compressive strength there reaches 2,500 psi (17 MPa). The rule was conceived on the basis of judgment but apparently without experimental evidence of concrete performance. The resultant delay in construction between adjacent shafts is typically 48 to 72 hours. Delays become especially pronounced with construction of shaft groups, and any additional cost is ultimately assumed by the state.

The objective of this study was to quantify concrete performance when concrete is exposed to vibrations at early ages. There were two phases of the study, fieldwork to observe actual conditions followed by laboratory experiments. Compressive strength and electrical resistivity were the measures used to evaluate the effects of vibrations on concrete.

Research Significance

The objective of this study was to quantify the effects of early age vibrations on concrete performance. If the study shows green concrete can tolerate vibrations like those observed in the field, then the *Mississippi Standard Specifications for Road and Bridge Construction* and specifications in other states might be amended to allow construction of shafts in proximity to green concrete.

CHAPTER 2

Literature Search

As concrete cures, it is generally thought to be vulnerable to disturbance from extreme vibrations. Today, there is little knowledge and agreement of acceptable vibration levels on early age concrete, and construction specifications are consequently very conservative.

Spears[2] examined transitory and continuous vibrations on green concrete. Cylinders did not show any adverse effects, and vibrations actually increased compressive strength relative to control cylinders. Still, the limited evidence did not justify any broad conclusions since early age concrete could experience loss of structural properties if exposed to vibrations of great enough intensity. Conservative guidelines were recommended of 0.1 in/s (3 mm/s) within 10 hours of concrete batch, then 4 in/s (100 mm/s) up to 24 hours, and 7 in/s (180 mm/s) beyond 24 hours.

Krell[3] performed a study of concrete that was exposed to nearly continuous vibration of low level from concrete placement through 28 days. The disturbance was not detrimental to the concrete and actually produced beneficial effects and increased compressive strength 7% above control cylinders that were free from vibration. Also, there was no sign of segregation and no evidence of bond failure of steel bars. The

concrete in this study had slump of 5 in (130 mm) and compressive strength of 6,000 psi (41 MPa) at 28 days.

Similarly, Soutsos[4] discovered a positive relationship between vibration and compressive strength as increasingly lengthy vibration times allowed concrete to achieve full potential.

Hulshizer and Desai[5] subjected concrete cylinders to vibrations of various magnitudes at various ages. Control cylinders were cast from the same concrete batches, and the compressive strength at 28 days was typically 3,000 psi (21 MPa). No experimental evidence of deleterious effects was found in terms of compressive strength and bond capacity of steel bars. Still, a maximum intensity of 2 in/s (50 mm/s) was conservatively recommended within the critical period between initial and final set.

A second study by Hulshizer [6] built on the previous work. Comparative compressive strength values between concrete cylinders exposed to vibration and control duplicates were within plus or minus 6%, but no trend was apparent. It was concluded that concrete easily tolerates 2 in/s (50 mm/s) of continuous vibration, and even as high as 5 in/s (130 mm/s) without definitive adverse effects. The historical limit of 2 in/s (50 mm/s) was thought to be more reactive to potential public annoyance and consequent legal hassles than to concrete structural properties.

Ansell and Silfwerbrand[7] determined the slump of concrete influences the risk of vibration damage. In this study, high slump mixtures experienced 10% decrease of compressive strength and bond to reinforcement, while no detrimental effects were observed with low slump mixtures. Concrete was found to be particularly susceptible to vibration between the ages of 3 to 12 hours, and the maximum intensity in this critical period was recommended to be 1.5 in/s (38 mm/s). Before an age of 3 hours and typically before concrete has set, a limit of 4 in/s (100 mm/s) was thought reasonable, with 2 in/s (50 mm/s) allowable between 12 to 24 hours. Eventually concrete appears invulnerable to magnitudes as high as 12 in/s (300 mm/s).

Tawfiq[8] worked with concrete that initial set in about 15 hours and needed an additional 5 hours to reach final set. Compressive strength at 28 days increased by 10% when cylinders were subject to vibration of 2 in/s (50 mm/s) continuously between batch and final set time, 20 hours in all. Conversely, compressive strength decreased by 10% when cylinders were subject to continuous vibration only between initial and final set. This concrete had a water/cement (w/c) ratio of 0.41, slump of 8 in (200 mm), and compressive strength of approximately 8,700 psi (60 MPa). A minimum distance of two shaft diameters from a source of vibration of this intensity was recommended to protect green concrete.

Tawfiq[8] also determined the most significant source of shaft construction vibrations arises when casings are installed and removed from excavations. Vibrations from shaft

drilling were less intense. The disturbance at the ground surface caused by driving casings into shaft excavations was 0.79 in/s (20 mm/s) at distance of 5 ft (1.5 m). The intensity decayed quickly to 0.28 in/s (7 mm/s) at 10 ft (3.0 m), evidence of attenuation with distance from the vibration source.

A study by Safawi[9] determined that segregation tendency depends on the viscosity of the concrete. High viscosity mixtures can suspend aggregates despite vigorous vibration, while low viscosity mixtures lack resistance against segregation and aggregates settle downward.

Bergstrom[10] determined that vibration can increase concrete compressive strength, but some concrete mixtures are more susceptible to segregation. Increases of the w/c ratio, cement paste content, and quantity of coarse aggregate relative to fine aggregate were found to elevate the risk of segregation.

ACI Committee 309[11] recognized that vibration can improve concrete properties by removal of excess water and voids, but concrete of low viscosity is highly susceptible to segregation.

Requirements by State

The Mississippi Department of Transportation (MDOT) sent a brief survey to associates nationwide to determine shaft construction requirements. In all, officials from 25 states responded to the survey. As concerns shafts adjacent to green concrete, most of these states use combinations of concrete set or minimum compressive strength, minimum distance and wait time, and maximum vibration magnitude, with a statement about which of the criteria governs. Only four states that responded to the survey do not address this issue due to the infrequency of shaft groups.

A summary of requirements by state is presented in Table 1. Little consensus was found. Among the respondents, ten states have concrete compressive strength requirements before construction can start on an adjacent shaft, while Florida and New York specify final set instead. Eighteen states impose boundaries, typically three shaft diameters. Georgia alone distinguishes between excavation of a shaft and installation and removal of a casing. Wait times established by twelve states range from 12 to 72 hours. Only five states have maximum vibration allowances, and two of these states, New Hampshire and South Dakota, disallow any disturbance. Idaho accepts up to 0.25 in/s (6 mm/s) from 6 to 72 hours, and then 2 in/s (50 mm/s) through 7 days. States may add special provisions to a project with unusual soil conditions, and shafts of unusual size. Many states perform tests to determine the concrete properties in place. Several

states require a construction sequence plan when multiple shafts are made on the same day.

The Federal Highway Administration (FHWA)[12] recommends a minimum distance of three shaft diameters until concrete reaches initial set. The concern is less that vibration could be harmful to the concrete as the concrete could breach into a nearby excavation. Management of a construction sequence, the FHWA contends, should alleviate significant delay.

Table 1. Summary of Requirements by State

State	Concrete Set or Minimum Compressive Strength	Minimum Distance	Minimum Time	Maximum Vibration Magnitude
Alabama	80% of design			
Arizona		Three shaft diameters	48 hours	
Arkansas		Three shaft diameters	24 hours	
Florida	Final set	Three shaft diameters or 30 feet		1.5 in/s
Georgia		Excavation, 15 feet; installation or extraction of casing, 50 ft	24 hours	
Idaho	3,000 psi	Four shaft diameters or 30 feet		0.25 in/s from 6 to 72 hours, then 2 in/s through one week
Kansas	2,800 psi	Three shaft diameters	72 hours	
Michigan		Three shaft diameters		
Mississippi	2,500 psi	30 feet		
Missouri		Three shaft diameters	24 hours	
New Hampshire	80% of design	20 feet		No vibrations
New Jersey	80% of design	Three shaft diameters		0.25 in/s
New York	Final set	5 feet	24 hours	
North Carolina	80% of design	Three shaft diameters or 10 feet		
South Carolina	75% of design	20 feet	12 hours	
South Dakota	1,600 psi		72 hours	No vibrations
Tennessee		Three shaft diameters	24 hours	
Texas		Two shaft diameters	24 hours	
Utah		Three shaft diameters	48 hours	
Virginia		Three shaft diameters	72 hours	
Washington	2,000 psi			

Representatives from Delaware, Montana, Ohio, and Oklahoma also responded to the survey, but those states do not have specific requirements

Unit conversions

1 MPa = 145 psi

1 m = 3.28 ft

25.4 mm/s = 1 in/s

CHAPTER 3

Field Observations

Locations to observe construction of shafts and record vibrations were recommended by MDOT. In Mississippi approximately three of every ten deep foundations are made with shafts and, at the time of this study, several shaft construction projects were in progress throughout the state. On 7/5/2012, the research team observed shaft construction around Jackson, the state capital. Here shafts were excavated into clay in a dry construction method that does not use casings. Since installation and removal of casings generally produce more significant vibrations than shaft drilling, the scenario of interest was found elsewhere. In DeSoto County, close to Memphis, Tennessee, nearly 200 shaft foundations were necessary to support a new bridge on Interstate Highway 269. Three visits were made to this construction location on 10/18/2012, 10/25/2012, and 12/7/2012. Shaft depths and diameters were as great as 70 feet (21 m) and 66 in (1.7 m), respectively. Casings did not extend the full depth of excavations and were typically 40 feet (12 m) in length.

An Instantel Minimate Plus was used to measure vibration magnitudes. The instrument was set at various distances from new shafts, the sources of vibrations, and measurements were recorded throughout the approximately 20 minutes of the process to insert casings, and again to remove casings. The instrument was kept steady on firm

ground, though heavy rains frequently delayed construction and conditions were generally muddy.

Typical vibration levels observed in this study are presented in Table 2. Vibrations caused by casing installations were strongest. At the closest distance possible, the mean vibration intensity was 0.91 in/s (23 mm/s), and the maximum value recorded was 1.42 in/s (36 mm/s). Once the characteristic vibrations were captured in the field, then the range of those vibrations were reproduced in the laboratory on concrete cylinders.

Table 2. Typical Vibration Levels Observed in the Field

	Casing In	Casing In	Casing Out
Distance Away from Source, ft	7	15	15
Mean Vibration, in/s	0.91	0.54	0.32
Maximum Vibration, in/s	1.42	0.76	0.52

Unit conversions
1 m = 3.28 ft
25.4 mm/s = 1 in/s

CHAPTER 4

Experimental Program

The objective was to determine how vibrations impact the structural performance of concrete. On a laboratory shake table, standard concrete cylinders were exposed to various vibration intensities and durations at various ages. The magnitudes and lengths of vibrations included the range of values observed in the field. Vibration magnitudes were 0.5 in/s (13 mm/s), 1.0 in/s (25 mm/s), 1.5 in/s (38 mm/s), and 2.0 in/s (50 mm/s). Vibration durations were 10, 20, and 30 minutes. This study did not address blasts, which can produce vibrations in excess of 30 in/s (760 mm/s).

Concrete is thought to be most sensitive to vibrations in the period between initial and final set. With initial and final set times between 3 and 5 hours, vibrations commenced at ages of 2, 4, and 6 hours to encompass the sensitive period.

The study involved only one concrete mixture design that nearly matches what MDOT normally uses in shaft foundations. All materials were locally available and approved by MDOT. With a w/c ratio of 0.44, compressive strength at 28 days usually exceeded 5,000 psi (34 MPa).

A total of 24 batches were made, twelve batches with each of two different coarse aggregates commonly found in Mississippi. As methodical approach, both cylinders to be vibrated and control (nonvibrated) cylinders were cast from the same concrete batches. Compressive strength and electrical resistivity were tested at an age of 28 days.

All experimental work was performed at Mississippi State University and followed the applicable ASTM standards.[13,14] In the interest of uniformity and productivity, an adequate supply of materials was gathered to complete all the concrete batches.

Material Properties and Concrete Mixture

Only one concrete mixture was used in this study and contained straight cement exclusive of supplementary cementitious materials. The content of the ASTM C150 Type I/II cement was 610 lb/yd^3 (360 kg/m^3). Though shaft concrete normally contains supplementary cementitious materials, there was thought that pozzolanic activity could enhance restorative effects and mask any damage caused by vibrations, which would obscure the purpose of this study. Recovery of structural properties is possible as previously unhydrated cement seals cracks with new compounds.[15]

Two coarse aggregates were used in this study, limestone and river gravel, to compare extremes of absorption and surface roughness. Limestone had rough surface texture

that improves bond with cement paste, while the river gravel was very smooth.[16] The absorption of limestone was 0.4%, and the absorption of river gravel was 2.4%. The relative density of the limestone and river gravel was nearly identical, and both coarse aggregates had comparable gradations with a maximum particle size of $^{3}/_{4}$ in (19 mm). Coarse aggregate content was 1,850 lb/yd^3 (1,100 kg/m^3). The content of fine aggregate, which was natural sand, was 1,400 lb/yd^3 (830 kg/m^3).

An ASTM C494 Type A/F chemical admixture was used to aid workability and achieve target slump, which was 6 in (150 mm). Actual shaft concrete typically contains a second chemical admixture that extends set time to approximately 12 hours to prevent cold joints between successive lifts. The initial and final set times in this study were between 3 and 5 hours.

Experimental Procedures

Concrete was batched in the laboratory in accordance with ASTM C192. Individual batch amounts were adjusted due to aggregate moisture conditions to keep a constant w/c ratio. As quality assurance, fresh concrete properties were measured regularly, namely temperature, slump, and unit weight. Concrete set time tests followed ASTM C403. Concrete cylinders where cast in 4 by 8 in (100 by 200 mm) molds, and caps were used to prevent evaporation and maintain shape.

Concrete cylinders from each batch were divided into two sets, one set to be subjected to vibration and one set to serve as the control. Concrete cylinders still in molds were placed on a shake table at various times and subjected to vibrations of various intensities and durations. The vibration characteristics examined on a shake table encompassed the range of values observed in the field. All concrete cylinders were removed from molds at an age of 24 hours and placed into a bath to wet cure until the time of test.

Three vibrated cylinders and three control cylinders were tested from each batch at 28 days, and mean values were used to compare. Compressive strength tests followed ASTM C39, and concrete cylinders were seated on pads set within steel rings.

The Resipod instrument made by Proceq was used to measure the electrical resistivity of concrete. Resistivity provides an assessment of concrete quality, mainly permeability and durability. There is a correlation between resistivity and the presence of cracks within concrete cylinders where high resistivity indicates there are few cracks, and low resistivity indicates there is extensive damage. The completely nondestructive test is rapid to perform and repeatable, and now complies with a provisional ASTM standard.[17] The surface of the concrete cylinders was clean and wet at the time of test, and the contact points of the instrument were pressed firmly against the concrete. The temperature of the sample was kept within a narrow range to not influence the resistivity response. A standard sample was used each day to confirm the Resipod worked properly.

CHAPTER 5

Results And Discussion

Concrete compressive strength results with limestone and river gravel coarse aggregates are presented in Tables 3 and 4, respectively. The results represent the compressive strength measured on vibrated cylinders relative to control cylinders and are calculated as a percent. Positive values mean the vibrations improved compressive strength while negative values, designated with parenthesis, mean the vibrations were harmful.

Concrete resistivity results with limestone and river gravel coarse aggregates are presented in Tables 5 and 6, respectively. Likewise, the results represent the resistivity measured on vibrated cylinders relative to control cylinders. Negative values, which mean the vibrations were harmful, are designated with parenthesis.

Variables that were central to the scope of interest were an age of 4 hours, which was in the middle of the sensitive period between initial and final set, and vibration duration of 20 minutes, which was the work time observed in the field, so the full range of vibration intensities were examined only here.

Table 3. Concrete Compressive Strength Results with Limestone

Vibration Duration	Vibration Intensity	Time after Batch at Start of Vibrations		
		2 hours	4 hours	6 hours
10 min	1.0 in/s	4.7%	2.6%	(1.9%)
20 min	0.5 in/s		3.8%	
	1.0 in/s	(5.8%)#	0.9%	0.7%
	1.5 in/s		(0.7%)	
	2.0 in/s		3.6%	
30 min	1.0 in/s	0.0%	3.9%	1.7%

The values represent the compressive strength measured on vibrated cylinders relative to control cylinders, and negative values, which mean the vibrations were harmful, are designated with parenthesis
#Statistically significant at the 95% confidence level
Unit conversions
25.4 mm/s = 1 in/s

Table 4. Concrete Compressive Strength Results with River Gravel

Vibration Duration	Vibration Intensity	Time after Batch at Start of Vibrations		
		2 hours	4 hours	6 hours
10 min	1.0 in/s	0.0%	2.7%	2.2%
20 min	0.5 in/s		1.9%	
	1.0 in/s	(1.5%)	4.9%	(1.1%)
	1.5 in/s		3.1%#	
	2.0 in/s		0.0%	
30 min	1.0 in/s	(2.5%)	(2.0%)	(3.8%)

The values represent the compressive strength measured on vibrated cylinders relative to control cylinders, and negative values, which mean the vibrations were harmful, are designated with parenthesis
#Statistically significant at the 95% confidence level
Unit conversions
25.4 mm/s = 1 in/s

Table 5. Concrete Resistivity Results with Limestone

Vibration Duration	Vibration Intensity	Time after Batch at Start of Vibrations		
		2 hours	4 hours	6 hours
10 min	1.0 in/s	(7.5%)#	(8.1%)	5.0%
20 min	0.5 in/s		1.4%	
	1.0 in/s	4.7%	(3.0%)	(4.9%)#
	1.5 in/s		(1.7%)	
	2.0 in/s		(7.9%)#	
30 min	1.0 in/s	2.3%	(9.7%)	4.3%

The values represent the resistivity measured on vibrated cylinders relative to control cylinders, and negative values, which mean the vibrations were harmful, are designated with parenthesis
#Statistically significant at the 95% confidence level
Unit conversions
25.4 mm/s = 1 in/s

Table 6. Concrete Resistivity Results with River Gravel

Vibration Duration	Vibration Intensity	Time after Batch at Start of Vibrations		
		2 hours	4 hours	6 hours
10 min	1.0 in/s	14.6%	8.7%#	5.8%
20 min	0.5 in/s		3.0%	
	1.0 in/s	(1.3%)	10.8%#	15.3%
	1.5 in/s		(0.7%)	
	2.0 in/s		(3.8%)	
30 min	1.0 in/s	1.9%	(2.7%)	(2.6%)

The values represent the resistivity measured on vibrated cylinders relative to control cylinders, and negative values, which mean the vibrations were harmful, are designated with parenthesis
#Statistically significant at the 95% confidence level
Unit conversions
25.4 mm/s = 1 in/s

The vibrations within the limits of this study did not produce a conclusive outcome, and these findings are generally in agreement with others. There were as many positive effects as negative effects, though no discernable trend exists in the data.

Low values indicate the vibrations had little influence. With the compressive strength results, only three values exceeded 4%, with two being positive. The resistivity results were more erratic and three values exceeded 10%, with all three being positive.

Only a few of the values in Tables 3, 4, 5, and 6 were statistically significant at the 95% confidence level (alpha of 0.05). With the compressive strength results, there was one negative value that was statistically significant, and one positive value. With the resistivity results, there were three negative values that were statistically significant, and two positive values. Again, no trend was noticeable.

Use of two coarse aggregates presented two vastly different scenarios in terms of bond potential with cement paste, but this study did not reveal meaningful differences between the coarse aggregates. There was no evidence of segregation.

One obvious discrepancy between cylinders and shafts is the mass of concrete. Cylinders and shafts are vastly different in size and may respond differently to vibration. It is unknown how concrete mass absorbs vibration. Shaft concrete is likely less

susceptible to damage from vibration than concrete cylinders, thought the confinement provided by the cylinders may help prevent segregation.

A thesis by one of the authors is the basis of this article, and additional information is available there.[18]

CHAPTER 6

Summary and Conclusions

There is consensus of thought that green concrete in shaft foundations could be susceptible to damage from extreme vibration, and many states guardedly established limits in terms of compressive strength, distance boundary, and wait time to protect early age concrete. But these limits could be overly conservative with respect to experimental evidence, and perhaps unnecessarily delay construction schedules and add cost to projects.

The objective of this study was to quantify the effects of early age vibrations on concrete performance. Concrete cylinders were exposed to several combinations of vibration magnitudes between 0.5 in/s (13 mm/s) and 2.0 in/s (50 mm/s) and durations between 10 and 30 minutes that were representative of shaft construction. Vibrations commenced at ages of 2, 4, and 6 hours to encompass the sensitive period between initial and final set which was reached between 3 and 5 hours.

The vibrations had no consistent effect on compressive strength and electrical resistivity at 28 days. Of the comparative values, there were as many positive as negative, and only a few were statistically significant, with no trend apparent. There was also no

obvious difference between limestone and river gravel even though these coarse aggregates had distinctive absorption and surface texture characteristics.

As these vibrations were not found to influence concrete structural properties in any systematic way, MDOT and other departments of transportation might reasonably amend specifications to allow construction of additional shafts in proximity to green concrete. Such a change could diminish occasional shaft construction delays, as well as costs. Still, the first and best plan should always be a pragmatic shaft construction sequence that eliminates any potential risk to early age concrete. Concrete with low viscosity demands special concern.

This study could be applicable to concrete placements anywhere vibrations exist, beyond just shaft foundations. With maintenance and upgrades to the transportation infrastructure frequently accomplished in the midst of heavy vehicle traffic, early age concrete often experiences random vibrations.

This study did not determine the magnitude and duration of vibrations on green concrete that clearly causes adverse effects. Additional research is also necessary to examine if vibrations impact shaft concrete made with supplementary cementitious materials and a complexity of chemical admixtures, increasingly the norm today.

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