Concrete Pavement Mixture Design and Analysis (MDA):

Development and Evaluation of Vibrating Kelly Ball Test (VKelly test) for the Workability of Concrete

National Concrete Pavement Technology Center

Tech Center

Final Report
March 2015

Sponsored through
Federal Highway Administration (DTFH61-06-H-00011 (Work Plan 25))
Pooled Fund Study TPF-5(205): Colorado, Iowa (lead state), Kansas, Michigan, Missouri, New York, Oklahoma, Texas, Wisconsin

IOWA STATE UNIVERSITY
Institute for Transportation

About the National CP Tech Center

The mission of the National Concrete Pavement Technology Center is to unite key transportation stakeholders around the central goal of advancing concrete pavement technology through research, tech transfer, and technology implementation.

The preparation of this report was financed in part through funds provided by the Iowa Department of Transportation through its "Second Revised Agreement for the Management of Research Conducted by Iowa State University for the Iowa Department of Transportation" and its amendments.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.	
TPF 5(205)			
4. Title and Subtitle Concrete Pavement Mixture Design and Analysis (MDA): Development and Evaluation of Vibrating Kelly Ball Test (VKelly Test) for the Workability of Concrete		**5. Report Date** March 2015 **6. Performing Organization Code**	
7. Author(s) Peter Taylor, Xuhao Wang, Xin Wang		**8. Performing Organization Report No.**	
9. Performing Organization Name and Address National Concrete Pavement Technology Center Iowa State University 2711 South Loop Drive, Suite 4700 Ames, IA 50010-8664		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.**	
12. Sponsoring Organization Name and Address Federal Highway Administration and Pooled Fund Partners U.S. Department of Transportation 1200 New Jersey Avenue SE Washington, DC 20590		**13. Type of Report and Period Covered** Technical Report **14. Sponsoring Agency Code** TPF-5(205)	
15. Supplementary Notes Visit www.cptechcenter.org for color pdfs of this and other research reports.			
17. Key Words concrete mixtures—concrete workability—Kelly ball test—vibrating Kelly ball—VKelly test		**18. Distribution Statement** No restrictions.	
19. Security Classification (of this report) Unclassified.	**20. Security Classification (of this page)** Unclassified.	**21. No. of Pages** 43	**22. Price** NA

16. Abstract

Due to the low workability of slipform concrete mixtures, the science of rheology is not strictly applicable for such concrete. However, the concept of rheological behavior may still be considered useful. A novel workability test method (Vibrating Kelly Ball or VKelly test) that would quantitatively assess the responsiveness of a dry concrete mixture to vibration, as is desired of a mixture suitable for slipform paving, was developed and evaluated. The objectives of this test method are for it to be cost-effective, portable, and repeatable while reporting the suitability of a mixture for use in slipform paving.

The work to evaluate and refine the test was conducted in three phases:
1. Assess whether the VKelly test can signal variations in laboratory mixtures with a range of materials and proportions
2. Run the VKelly test in the field at a number of construction sites
3. Validate the VKelly test results using the Box Test developed at Oklahoma State University for slipform paving concrete

The data collected to date indicate that the VKelly test appears to be suitable for assessing a mixture's response to vibration (workability) with a low multiple operator variability. A unique parameter, VKelly Index, is introduced and defined that seems to indicate that a mixture is suitable for slipform paving when it falls in the range of 0.8 to 1.2 in./√s.

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

CONCRETE PAVEMENT MIXTURE DESIGN AND ANALYSIS (MDA): DEVELOPMENT AND EVALUATION OF VIBRATING KELLY BALL TEST (VKELLY TEST) FOR THE WORKABILITY OF CONCRETE

Technical Report
March 2015

Principal Investigator
Peter Taylor, Associate Director
National Concrete Pavement Technology Center, Iowa State University

Research Assistants
Xuhao Wang and Xin Wang

Authors
Peter Taylor, Xuhao Wang, and Xin Wang

Sponsored by
FHWA Pooled Fund Study TPF-5(205): Colorado, Iowa (lead state), Kansas, Michigan, Missouri, New York, Oklahoma, Texas, Wisconsin

Preparation of this report was financed in part
through funds provided by the Iowa Department of Transportation
through its Research Management Agreement with the
Institute for Transportation
(InTrans Project 10-374)

A report from
National Concrete Pavement Technology Center
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-8103
Fax: 515-294-0467
www.cptechcenter.org

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

This research was conducted under the Federal Highway Administration (FHWA) Transportation Pooled Fund Study TPF-5(205) with support from the following state departments of transportation (DOTs):

- Colorado
- Iowa (lead state)
- Kansas
- Michigan
- Missouri
- New York
- Oklahoma
- Texas
- Wisconsin

The authors would like to express their gratitude to the Iowa DOT and the other pooled fund state partners for their financial support and technical assistance.

The researchers would also like to acknowledge the agencies and contractors that allowed them to be on their construction sites and to take samples.

EXECUTIVE SUMMARY

The aim of the work described in this report is to develop and evaluate a method that would quantitatively assess the responsiveness of a dry concrete mixture to vibration, as is desired of a mixture suitable for slipform paving. Even though a number of workability test methods have been developed, there continues to be a need to measure workability in order to achieve the following objectives:

- The test should be cost-effective
- Testing equipment should be portable
- The test should measure two parameters
- The test should simulate the paving process
- The test should be repeatable

Due to the low workability of slipform concrete mixtures, the science of rheology is not strictly applicable for such concrete. However, the concept of rheological behavior may still be considered useful. The workability test method discussed in this report, the Vibrating Kelly Ball (VKelly) Test, considers the rate of movement under vibration as well as the initial yield stress.

The work to evaluate and refine the test was conducted in three phases. The first phase was to assess whether the VKelly test can signal variations in laboratory mixtures with a range of materials and proportions. The second phase was to run the VKelly test in the field at a number of construction sites. The third phase was to validate the VKelly test results using the Box Test developed at Oklahoma State University for slipform paving concrete.

The data collected to date indicate that the VKelly test appears to be suitable for assessing a mixture's response to vibration (workability) with a low multiple operator variability. A unique defined parameter, VKelly Index, is introduced, and a mixture in the range of 0.8 to 1.2 in./√s seems to be suitable for slipform paving.

INTRODUCTION

Workability of concrete is a poorly defined property that has long been a challenge to predict and measure (Cook et al. 2013). Researchers have spent over 80 years working on test procedures to determine workability for research, mix proportioning, and field use. The majority of these test methods have never found any use beyond the initial studies (Koehler and Fowler 2003). In addition, the workability requirements of slipform paving mixtures are unique in that the ideal is a stiff mixture with no edge slump, yet one that flows readily under vibration.

The science of rheology is sometimes applied to concrete systems, but, as the study of fluids in motion, it is not strictly applicable to dry concrete mixtures. However, the concept of a two-parameter measurement may be considered useful. The testing approach reported here considers the rate of movement under vibration as well as the initial yield stress.

This document discusses work carried out in developing and evaluating a novel workability test called the Vibrating Kelly Ball (VKelly) Test.

BACKGROUND

Multiple definitions of the term "workability" are summarized by Koehler and Fowler (2003):

- American Concrete Institute (ACI 116R-00 2000): "that property of freshly mixed concrete or mortar that determines the ease with which it can be mixed, placed, consolidated, and finished to a homogenous condition"
- Japanese Association of Concrete Engineers: "that property of freshly mixed concrete or mortar that determines the ease and homogeneity with which it can be mixed, placed, and compacted due to its consistency, the homogeneity with which it can be made into concrete, and the degree with which it can resist separation of materials"
- Mindess et al. (2003): "the amount of mechanical work, or energy, required to produce full compaction of the concrete without segregation"

In the early 20th century, a simple and cost-efficient slump test was adopted because, in the mixtures at the time, workability could be tied to water-to-cement ratio (w/c) and thus potential performance (Abrams 1922). However, with the adoption of supplementary cementitious materials (SCMs) and water-reducing admixtures, this correlation has been lost. However, there continues to be a need to measure workability as a means to monitor uniformity, as well as to ensure that a mixture has the right workability for the proposed construction method. As such, the slump test is insufficient because it only measures one parameter.

If concrete is considered to be a Bingham fluid, it is characterized by two parameters (yield stress and plastic viscosity) that can be measured using a rheometer (Tattersall and Banfill 1983).

Tattersall (1991) split the assessment of workability into three broad categories, and the majority of workability test methods fall into categories II and III, as follows:

- Category I – Qualitative: workability, flowability, compactability, finishability, and pumpability; to be used only in a general descriptive way without any attempt to quantify
- Category II – Quantitative Empirical: slump, compacting factor, Vebe time, and flow table spread; to be used as a simple quantitative statement of behavior in a particular set of circumstances
- Category III – Quantitative Fundamental: viscosity, mobility, fluidity, and yield stress; to be used strictly in conformity with standard definitions

Most test methods for workability have traditionally been split between single-point tests and multi-point tests (Koehler and Fowler 2003). A single-point test measures only one point on the flow curve to provide an incomplete description of workability. For example, the slump test may provide one point on the flow curve, i.e., the yield stress. Multi-point tests, by contrast, measure additional points, such as yield stress, viscosity, or thixotropy, on the flow curve, placing these tests in Category III of Tattersall's (1991) scheme. The tradeoff between two sets of tests is that single-point tests are easier to perform, albeit less complete.

Workability test methods have also been classified by the National Institute of Standards and Technology (NIST) in terms of flow produced during the test (Hackley and Ferraris 2001):

- Confined flow tests: the material flows under its own weight or under an applied pressure through a narrow orifice.
- Free flow tests: the material either flows under its own weight, without any confinement, or an object penetrates the material by gravitational settling.
- Vibration tests: the material flows under the influence of applied vibration. The vibration is applied by using a vibrating table, dropping the base supporting the material, using an external vibrator, or using an internal vibrator.
- Rotational rheometers: the material is sheared between two parallel surfaces, one or both of which are rotating.

This classification scheme may be considered to be the most consistent with the current understanding of concrete rheology and workability. Koehler and Fowler (2003) summarized comprehensive workability test methods in accordance with the NIST flow-type classification scheme, as shown in Table 1.

Table 2 (Part 1 and Part 2) summarizes the findings of Koehler and Fowler (2003) for each of the above mentioned methods, including their advantages, disadvantages, and performance criteria.

The aim of the work described in this report was to develop and evaluate a method that would quantitatively assess the responsiveness of a dry mixture to vibration, as is desired of a mixture suitable for slipform concrete.

Table 1. Categorization of concrete workability test methods (Koehler and Fowler 2003)

Tests for Conventional Concrete			
Confined Flow Tests		**Vibration Tests**	
1	Compaction factor test	1	Angles flow box test
2	Orimet test	2	Compaction test
3	K-slump tester	3	Flow table test
		4	Inverted slump cone test
Free Flow Tests		5	LCL flow test
1	Cone penetration test	6	Powers remolding test
2	Delivery-Chute depth meter	7	Column test
3	Delivery-Chute torque meter	8	Thaulow tester
4	Flow trough test	9	Vebe consistometer
5	Kelly ball test	10	Vertical pipe apparatus
6	Modified slump test	11	Vibration slope test
7	Moving sphere viscometer	12	Vibropenetrator
8	Ring penetration test	13	Wigmore cosistometer
9	Slump rate machine	14	Vibratory flow meter
10	Slump test		
11	Surface settlement test	**Other Test Methods**	
		1	Multiple single-point test
Low Workability Concrete		2	Soil triaxial test
1	Intensive compaction test	3	Trowel test
2	Kango hammer test		
3	Proctor test		
Tests for SCC		**Tests for Paste and Mortar**	
Confined Flow Test		1	Flow cone test
1	Fill-box test	2	Miniflow test
2	L-box test	3	Minislump test
3	U-box test	4	Turning tube viscometer
4	V-funnel test	5	Vicat Needle test
		6	VisoCorder
Free Flow Tests		7	Wuerpel device
1	J-ring test		
2	Slump flow test		
Stability Tests			
1	Penetration test		
2	Wet sieving test		

Table 2. Summary of features of existing workability test methods (Part 1)

Category	Test Methods	Parameters Measured	Ruggedness	Workability Range	Aggregate Size Restrictions	Cost	Sample Size	Test Speed	Complexity
Confined Flow Test Methods	Compaction Factor Test	Compactability, non-linear relationship to slump	Good, commercially available	0-7 in.	Larger apparatus up to 1.5 in.	Expansive	Moderate	Moderate	Moderate
	Orimet Test (Free Orifice Test)	The time of concrete flow out of the tube	Stable	High slump concrete	Up to 1 in.	Cheap	Moderate	Fast	Simple
	K-slump Tester (Nasser probe)	Workability by graduated scale, K and W terms	Commercially available, good	Medium and high workability concretes	Greater than 3/8 in. cannot fit	Fair	Moderate	One minute	Simple
Free Flow Test Methods	Slump Test	Yield stress	Stable	0.5 to 9 in.	Up to 1.5 in.	Cheap	Small	Fast	Simple
	Modified Slump Test	Viscosity and yield stress	Stable	Similar to slump test	Similar to slump test	Similar to slump test	Similar to slump test	Similar to slump test	Similar to slump test
	Slump Rate Machine (SLRM)	Slump, slump flow, and slump time	Complicated in the field condition	Similar to slump test	Similar to slump test	Similar to slump test	Similar to slump test	Similar to slump test	Similar to slump test
	Kelly Ball Test	Penetration correlated to the slump	Stable	Similar to slump test	Up to 1.5 in.	Cheap	Small	Fast	Simple
	Ring Penetration Test	Penetration correlated to yield stress	Need a level concrete surface	Good for grounts and high-workability concretes	Not for large aggregate	Cheap	Small	Fast	Simple
	Cone Penetration Test	Penetration, correlate to slump and Vebe time	Stable	Low slump and fiber-reinforced mixtures	Not specified	Cheap	Small	Fast	Simple
	Flow Trough Test	The time to flow a certain distance	Stable	Highly flowable concretes	Not specified	Cheap	6 liters	Long duration	Simple
	Delivery-Chute Torque Meter	Torque measured from concrete mixing truck	Stable	Wide range	Not specified	Little expensive	Concrete in the truck	Fast	Simple
	Surface Settlement Test	Surface settlement versus initial concrete height	Stable	Better for high slump concrete	Not specified	Little expensive	Small	Long until concrete hardens	Fair, use LVDT

Category	Test Methods	Parameters Measured	Ruggedness	Workability Range	Aggregate Size Restrictions	Cost	Sample Size	Test Speed	Complexity
Vibration Test Methods	Compaction Test	Degree of compaction - compactability	Stable	Low to moderate slump concrete	Not specified	Cheap	Small	Fast	Simple
	Vebe Consistometer	Remolding ability of concrete under vibration	Inappropriate for field use	Commonly used for low slump mixtures	Up to 2 in.	Expensive	Minimum 50 lbs	Fair	Simple
	Powers Remolding Test	Similar to Vebe test, different apparatus	Inappropriate for field use	Commonly used for low slump mixtures	Not specified	Fair	Similar to Vebe test	Fair	Simple
	Thaulow Tester	Similar to the Powers remolding test, but modified to allow for the measurement of concretes with higher workability							
	Flow Table Test	Horizontal spread of a cone specimen subjected to jolting	Stable, but place on firm level ground	Wide range of concrete	Not specified	Fair	As slump cone test, 0.25 cf	Fast	Simple
	Angles Flow Box Test	The time of concrete to flow under vibration and pass obstructions	Inappropriate for field use	Moderate slump mixtures	Not specified	Fair	Fair	Fast	Simple
	LCL Flow Test	Similar to Angles flow test, not suitable for very low or very high workability							
	Wigmore Consistometer	Penetration resistance by adding energy	Stable	Wide range of concrete	Not specified	Fair	Fair	Fast	Simple
	Inverted Slump Cone Test	Elapsed time from the insertion of the vibrator until all concrete discharged	Stable	Specially for fiber-reinforced concrete	Up to 1.5 in.	Cheap	As slump cone test, 0.25 cf	Fast	Difficult to perform
	Vertical Pipe Apparatus	Penetration depth versus time	Stable for lab use	Low to moderate slump concrete	Cannot be too large due to the apparatus	Expensive	Fair	Fair	Fair, use displacement transducer
	Vibrating Slope Apparatus (VSA)	Discharge rate of concrete falling from the chute to bucket with vibration	Stable	Low slump concrete	Not specified	Expensive	Large	Fair	Fair
	Vibratory Flow Meter	Similar to the LCL flow test, Angles flow box, and the vibrating slope apparatus							
	Box Test	Visual rates, surface voids and edge slumping	Stable	Slipform paving concrete	May up to 2 in.	Cheap	About 1 cf	Fast	Simple

Category	Test Methods	Parameters Measured	Ruggedness	Workability Range	Aggregate Size Restrictions	Cost	Sample Size	Test Speed	Complexity
Methods for Very Low Slump Concrete	Proctor Test	Dry unit weight and corresponding moisture content	Stable	Lean, dry concrete	Not specified	Cheap	Small	Very time consuming	Simple
	Kango Hammer Test	Density of compacted concrete	Stable	Low-slump concretes	Not specified	Fair	Cubic, small	Fair	Simple
	Intensive Compaction Test	Density of compacted concrete	Stable	Slump less than about 1 cm	Up to 1.25 in.	Expensive	Small cylindrical sample	3-5 mins	Simple

Table 2. Summary of features of existing workability test methods (Part 2)

Category	Test Methods	Data Processing	Size and Weight	Number of People Required	Remarks	Advantages	Disadvantages	References
Confined Flow Test Methods	Compaction Factor Test	Moderate	Heavy (over 80 lbs)	More than one	Widely used in Europe	Give more information than the slump test Dynamic test is more appropriate than static tests for highly thixotropic mixtures	Large and bulky nature Require a balance to measure the mass of concrete May not reflect the filed situation Do not use vibration	Powers 1968 Wilby 1991 Bartos 1992 Bartos et al. 2002
	Orimet Test (Free Orifice Test)	Quick and direct result	Light	One person	Need modification for low slump mixtures	Inexpensive and simple to use Quickly and provides a direct result Good simulation of actual placing conditions Sensitive to changes in fine aggregate content	Only appropriate for highly flowable and self-compacting concrete Results are not expressed in terms of fundamental units	Bartos 1992 Bartos 1994 Wong et al. 2000
	K-slump Tester (Nasser probe)	Direct reading on workability and compatiabilit y	Portable	One person	US Patent 3,863,494 (1975)	Direct result, simple and easier than slump test Can be performed on in-situ concrete K and W terms provide more information than slump	Does not consider the effects of coarse aggregate Static test and not appropriate for low slump mixtures	Ferraris 1999 Bartos et al. 2002
Free Flow Test Methods	Slump Test	Quick and direct result	Small and portable	One person	ASTM C143 and EN 12350-2 in Europe	Well known and widely used device worldwide Specifications are typically written in terms of slump Results can be converted to yield stress based on various analytical treatments and experimental study	Does not give an indication of viscosity Static, not dynamic test, results are influenced by concrete thixotropy Less relevant for higher slump mixtures	ASTM C143 EN 12350-2
	Modified Slump Test	Similar to slump test	Similar to slump test	Similar to slump test	Add the parameter of time to the slump test	Simple to perform and only requires slightly more equipment than the slum test The test gives an indication of both yield stress and plastic viscosity	Static test, not a dynamic test, does not account for the thixotropy of concrete or the ability of concrete to flow under vibration Need to verify the validity of the test	Ferraris and de Larrard 1998 Ferraris 1999

Category	Test Methods	Data Processing	Size and Weight	Number of People Required	Remarks	Advantages	Disadvantages	References
	Slump Rate Machine (SLRM)	Similar to slump test	Similar to slump test	Similar to slump test	A computer-controlled device	Give an indication of both yield stress and viscosity A simplified traditional rheometer and less expensive	Static test, not a dynamic test, does not account for the thixotropy of concrete or the ability of concrete to flow under vibration Requires computer to log data and calculate	Chidiac et al. 2000
	Kelly Ball Test	Quick and direct result	Little heavier than slump test	One person	Developed in 1950s in US, alternative to the slump test	Faster than the slump test and more accurate in determining consistency than the slump test Provides an indication of yield stress	Static test Must be performed on a level concrete surface The test is no longer widely used Large aggregate can influence the results	Powers 1968 Bartos 1992 Scanlon 1994 Ferraris 1999
	Ring Penetration Test	Quick and direct result	Portable	One person	Not a well known test	Easy and simple to perform Can be performed on in-situ concrete	Static test, perform on a level concrete surface Large aggregate can influence the results Test is not widely used and the interpretation of the results is not well known	Wong et al. 2000
	Cone Penetration Test	Quick and direct result	4 kg metal cone	One person	Not a well known test	Provide a direct result and easy to perform Can be performed on in-situ concrete	Static test, not particularly appropriate for fiber-reinforced concrete Not recorded in fundamental units	Sachan and Kamesawara 1998
	Flow Trough Test	Quick and direct result	1 m long and .23 m wide	One to two persons	Not widely used	Simple and inexpensive Test results are a function of the time required for the concrete to flow both out of the cone and down the trough	Only appropriate for highly flowable concrete Not standardized and not widely used	Bartos et al. 2002

Category	Test Methods	Data Processing	Size and Weight	Number of People Required	Remarks	Advantages	Disadvantages	References
	Delivery-Chute Torque Meter	Quick and direct result	Portable	One person	US Patent 4,332,158 (1982)	Measure the workability of the concrete as it exists the mixer before it is placed Directly read the torque from device No need computer or other sensors	It gives no indication of plastic viscosity Readings are made at only one shear rate Device need calibration for each mixture	Wong et al. 2000
	Surface Settlement Test	Do not give a direct result	Fair	One person	Can be used for moderate slump mixtures	Inexpensive and simple to perform Appropriate for a wide range of concrete mixtures	It does not give a direct result Time required to perform the test is longer than other test methods due to the settlement distance must be recorded until concrete hardens	Bartos et al. 2002
Vibration Test Methods	Compaction Test	Quick and direct result	200 by 400 mm rigid metal containe r	One	EN12350-4, similar test (Fritsch test)	Provide an indication of the compactability Simple and inexpensive Can give an indirect indication of plastic viscosity when the variable of time is added	Difficult to empty for low slump concrete Different compaction methods cannot be compared directly May need a computer to facilitate the readings	Bartos et al. 2002 Ferraris 1999
	Vebe Consistometer	Direct results	Heavy	At least one	ASTM C1170 (1998)	Dynamic test, can be used on very dry concrete Standardized in ASTM and identified by ACI 211 in its guide for proportioning low slump concrete Test results are directly obtained	Size of the device generally unsuitable for field Only works for low slump concretes No analytical treatment of the test method has been developed, shear rate declines during vibration	Bartos 1992 Bartos et al. 2002 Scanlon 1994
	Powers Remolding Test	Direct results	Heavy	At least one	ASTM C124 (Withdrawn in 1973)	Dynmaic test and suitable for low slump concretes Test results are directly obtained	Only works for low slump concretes Size of the device generally unsuitable for field No analytical treatment of the test method has been developed, shear rate declines during vibration	Powers 1968 Scanlon 1994 Wong et al. 2000

Category	Test Methods	Data Processing	Size and Weight	Number of People Required	Remarks	Advantages	Disadvantages	References
	Thaulow Tester	Similar to the Powers remolding test, but modified to allow for the measurement of concretes with higher workability				Measure higher workability than that measured with the Vebe and the Powers remolding test	Size of the device generally unsuitable for field No analytical data are available	ACI 211.3R-02 (2002)
	Flow Table Test	Direct results	Fair	One person	DIN 1048 and EN12350-5	Simple and can be used in the field Direct result Appropriate for highly thixotropic concrete	Does not represent actual placement conditions Results tend to converge as the number of drops is increased An analytical treatment of the test is difficult	Tattersall 1991 Wong et al. 2000 Bartos et al. 2002
	Angles Flow Box Test	Direct results	Fair	One person	Similar concept for SCC mixtures	Represent actual field conditions Dynamic test that subjects concrete to vibration The ability of concrete to pass obstructions and resist segregation is assessed	Not be appropriate for field use Results are likely a function of yield stress and viscosity, but the values are not directly recorded	Scanlon 1994 Wong et al. 2000
	LCL Flow Test	Similar to Angles flow test, not suitable for very low or very high workability				Similar to Angles flow box test	More expensive, requires electricity, not precise	Bartos 1992
	Wigmore Consistometer	Direct results	Large	One person	-	Dynamic test Wide range of concrete workability	The drop ball need to be larger than the maximum coarse aggregate size Device is too large and bulky for field use	Scanlon 1994
	Inverted Slump Cone Test	Direct	Small and portable	One person	ACI Committee 544 recommended	Dynamic test considering the high thixotropy of fiber-reinforced concrete Simple and direct results Readily available apparatus	Appropriate for less than 2 in. slump mixtures Operation is tricky to maintain consistency Long fibers may wrap around the vibrator Important test parameters are not standardized	Tattersall and Banfill 1983 ASTM C995-01 (n.d.) Bartos et al. 2002
	Vertical Pipe Apparatus	Direct results	Fair	More than one person	Behaves as a Newtonian fluid subjected to vibration	Dynamic and provide valuable information By changing the vibration parameters, the test can be used to determine values related to yield stress and viscosity	Expensive and may not be suitable for field use Pipe has 60 mm opening may too small for sizes	Tattersall and Baker 1989 Banfill et al. 1999

Category	Test Methods	Data Processing	Size and Weight	Number of People Required	Remarks	Advantages	Disadvantages	References
	Vibrating Slope Apparatus (VSA)	Direct results	Very heavy	More than two people	Developed in the 1960s, modified by FHWA	Measure low slump concrete Results can be correlated to yield stress and viscosity It is designed to be rugged for field use	Very large, bulky, and heavy device Results have not been verified analytically Need a notebook computer to record data Vibration is limited and shear rate is non-uniform	Wong et al. 2000
	Vibratory Flow Meter	Similar to the LCL flow test, Angles flow box, and the vibrating slope apparatus				Simple and direct results Readily available equipment and materials	Not effective in distinguishing changes of mixtures Different vibrators result in varied results	Szescy 1997
	Box Test	Direct results	Fair	One person	Developed from Okalahoma State University	Simulate actual placement conditions Simple and does not require expensive equipment Suitable for slip-form paving concrete Repeatability is good for single and muti-operators	More work is needed to verify the rating scale No field data is available No specifications for evaluating the edge slumping	Cook et al. 2013
Methods for Very Low Slump Concrete	Proctor Test	Direct results	Small and portable	One person	Designed for soil test	Can be used for low slump mixtures The test is simple and well known	Does not incorporate vibration and can be only used for low slump concretes Very time consuming, need preparation	ASTM D698 ASTM D1557
	Kango Hammer Test	Direct results	Larger than proctor test	One person	Designed for soil test	With vibration and pressure, the test accurately simulates field placmeent conditions Simple and easy to perform	Hammer is not specified, making comparisons of the test results difficult The apparatus is large and requires electricity	Juvas 1994 Bartos, et al. 2002
	Intensive Compaction Test	Direct results	About 120 lbs	One person	Nordtest-Build 427, US patent 4,794,799 (1989) and 4,930,346 (1990)	Accurately measure small changes in proportions Simulate low slump roller-compacted concretes Fast and computer controlled Smaller model is feasible for field use	Equipement is expensive compared to proctor test, 150 mm model is too heavy for field use The test does't incorporate vibration, which is commonly used in placing of low slump concrete	Juvas 1990 Tattersall 1991 Juvas 1994

VKELLY TEST METHOD

Background

The Kelly ball test—the basis of the VKelly test described in this report—was developed in the 1950s in the United States as a fast alternative method to the slump test (Powers 1968, Ferraris 1999, Bartos et al. 2002). It is not an expensive test and can be quickly performed in situ. Typically, the value of slump is 1.10 to 2.00 times the Kelly ball test reading. Scanlon (1994) claimed that the Kelly ball test is more accurate in determining consistency than the slump test. The Kelly ball test is applicable to a similar range of concrete consistencies as the slump test and is also appropriate for special concrete, such as lightweight and heavyweight concrete. Bartos (1992) stated that the precision of the test declines with the increasing size of coarse aggregate.

The Kelly ball test apparatus consists of a 6 in. diameter, 30 lb. steel ball attached to a stem, as shown in Figure 1. The penetrator is attached to a shaft graduated to measure penetration to the nearest ¼ in. About 3 $ft.^2$ of the concrete surface is struck off level, the ball is placed on the surface, released, and the depth of penetration is recorded. Three measurements should be made for each sample.

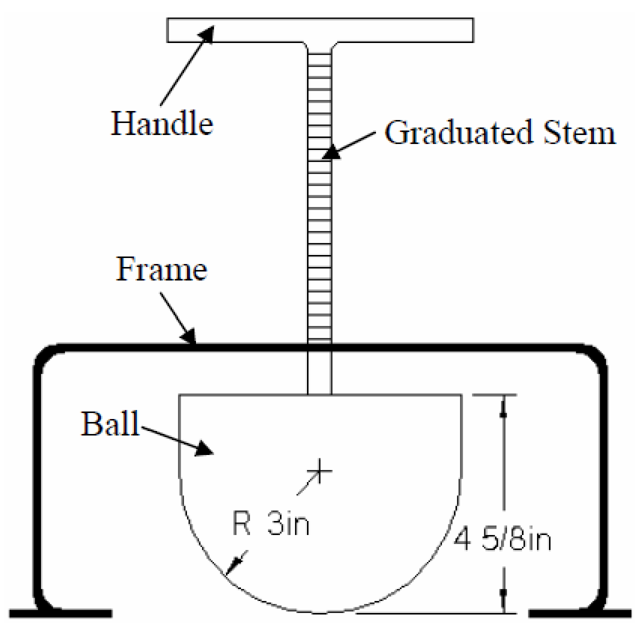


Figure 1. Kelly ball test apparatus (Koehler and Fowler 2003)

The test was formerly standardized in ASTM C360-92, Standard Test Method for Ball Penetration in Freshly Mixed Hydraulic Cement Concrete (1992). However, it was discontinued in 1999 due to lack of use and never been widely used outside the United States. In 2014, California Test 533 brought it back again as a modification of ASTM C360.

Ferraris (1999) stated that the Kelly ball test provides an indication of yield stress, because the test essentially measures whether the stress applied by the weight of the ball is greater than the yield stress of the concrete. However, this test may not be able to give valuable information when testing on very low-slump concrete or highly thixotropic concretes where energy is required to overcome the initially high-yield stress at rest.

Overview of VKelly Test

As shown in Figure 2, a VKelly test apparatus consists of a Kelly ball with a vibrator attached. The ball is trimmed to maintain the original weight of 30 lbs. This means that the VKelly test apparatus can still be used to measure slump statically.

Figure 2. VKelly test apparatus

Initial tests indicated that the vibrator selected was providing too much energy to the system. Smaller devices were considered, but none were capable of delivering the desired frequency discussed below. Instead, the eccentric weight within the vibrator was drilled out reduce its mass. 5 holes were drilled, each $^{3}/_{8}$ in. diameter (as shown in Figure 3). The characteristics of the vibrator were determined to be 58% of the original 0.077 in.-lbs.

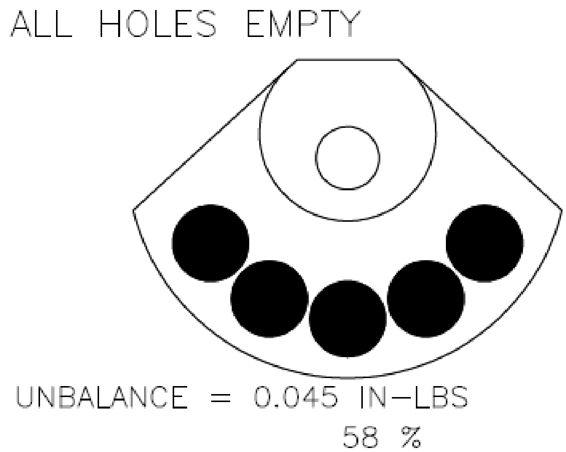


Image source: VIBCO

Figure 3. Modified eccentric weight in vibrator

Tymkowicz and Steffes (1996) concluded that the Iowa Department of Transportation specification of 5,000 to 8,000 vibrations per minute (vpm) for slipform pavers is effective for normal paver speeds while maintaining a good air-void structure. In order to simulate the vibrator frequency recommended for slipform paving, the vibrator speed is set at 6,000 vpm using a variable transformer, as shown in Figure 4.

Figure 4. Variable transformer

An adjustable steel frame was constructed to stabilize the VKelly test apparatus while operating, as shown in Figure 5. The graduated stem was retained to allow easy measurement of the rate at which the ball sinks into the mixture under vibration.

Figure 5. Adjustable steel frame to stabilize the VKelly apparatus

VKelly Test Procedure

The following test procedures are conducted, as shown in Figure 6:

Figure 6. Completed VKelly test

- Similar to the Kelly ball test, fresh concrete should be discharged into a wheelbarrow, buggy, or other container. The depth of concrete above the bottom of the container or reinforcement should be at least 6 in. for 1 in. aggregate or smaller and 8 in. for larger aggregate.
- The tested concrete surface should be struck off level over an area of about 3 $ft.^2$. Do not tamp, vibrate, or consolidate the concrete manually. Screed the minimum amount required to obtain a reasonable level surface. Do not overwork the surface because it may flush excess mortar to the surface, causing erroneously high penetration readings (California Test 533 2014).
- Slowly lower the ball until the ball touches the surface of the concrete. Adjust the frame to make sure the shaft is in a vertical position and free to slide through the yoke. Record the reading on the graduated stem to the nearest 0.1 in. as an initial reading. Gradually lower the ball penetrator into the concrete, maintaining enough restraint on the frame so that

penetration is due to the dead load of the ball only and is not affected by any force generated by the acceleration of the mass. Record the second reading to the nearest 0.1 in. when the ball comes to rest.

- Turn on the vibrator, which has been pre-set to run at 6,000 vpm, and simultaneously start the timer. Record the readings on the graduated stem at 6 second intervals up to 36 seconds. A video recorder can be used to record the test, and the data can be collected later using the timer in the camera and by observing the graduated stem.
- Remove the VKelly apparatus and dump the tested concrete back into a mixer to remix for 30 seconds. Repeat twice. The reported penetration is the average of the three readings, which should agree within ½ in. of penetration at any given time.
- Plot the average readings in inches (vertical scale) against the square root of the time in seconds (horizontal scale) (see Figure 7), and determine the slope of the best fit line through the data (Equation 1).
- Report the initial penetration (c) in inches and the slope (V) in in./√s.

$$D_{pene} = V_{index} \times \sqrt{t} + c \quad \textbf{(1)}$$

where,

D_{pene} = penetration depth at time t
t = elapsed time of vibration
c = initial penetration
V = VKelly Index

The static part of the test should agree well with the slump, allowing for a multiplication factor of 2. Incremental depth data do not include the multiplication factor.

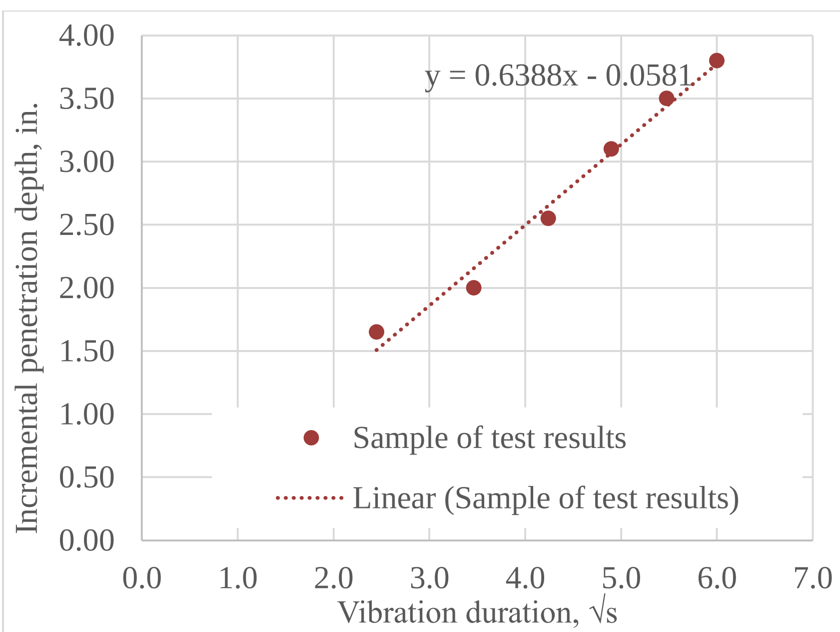


Figure 7. Sample plot of VKelly test results

WORK CONDUCTED

The work to evaluate and refine the test was conducted in three phases. The first phase was to assess whether the VKelly test can signal variations in laboratory mixtures with a range of materials and proportions. A series of mixtures was prepared and tested using the following process:

- Make a control mixture
- Incrementally adjust a single ingredient
- Conduct slump and VKelly test
- Repeat for other ingredients

The repeatability for single operator and multiple operators were evaluated during the laboratory mixing process.

The second phase was to run the VKelly test in the field at a number of construction sites.

The third phase was to validate the VKelly test results using the Box Test developed at Oklahoma State University for slipform paving concrete.

Phase I (Laboratory Test)

Matrix

The matrix was selected to obtain the most information within the constraints of the project.

Base Mixture

- 564 lb./yd.^{3} ordinary portland cement
- 5% total air content
- 45/55 fine/coarse aggregate ratio
- 0.45 w/cm

Variables

- Sand: increments of 100 lb./yd.^{3} (+1, +2, +4, -1, -2, and -4)
- Air: increments of 1% (+2 and -2)
- Class C fly ash: increments of 10% (+1, +2, and +3)
- Water: increments of 1 gallon/cubic yard (+1 and +2)

Including the repeated base mixture for repeatability evaluation, a matrix of 24 mixtures was prepared. Mix proportions are shown in Table 3.

Table 3. Mix proportions

Proportions	Plain	Sand						Air		C ash			Water	
		+1	+2	+4	-1	-2	-4	+2	-2	+1	+2	+3	+1	+2
Stone, pcy	1698	1597	1495	1290	1802	1904	2108	1650	1747	1698	1690	1685	1698	1698
Sand, pcy	1389	1489	1589	1789	1289	1189	989	1349	1430	1389	1382	1379	1389	1389
Cement, pcy	564	564	564	564	564	564	564	564	564	508	452	395	564	564
Fly Ash, pcy										56	112	169		
Water, pcy	253	253	253	253	253	253	253	253	253	253	253	253	262	270
WRA, oz/cwt														
AEA, oz/cwt	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Air	5%	5%	5%	5%	5%	5%	5%	7%	3%	5%	5%	5%	5%	5%
w/cm	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.46	0.48
Unit weight, pcy	3904	3903	3901	3896	3908	3910	3914	3816	3994	3904	3889	3881	3904	3904
FA/CA	0.45	0.48	0.52	0.58	0.42	0.38	0.32	0.45	0.45	0.45	0.45	0.45	0.45	0.45

Materials

The following materials were considered as part of the matrix:

- Type I/II portland cement
- Class C fly ash
- Local coarse (1 in. limestone) and fine (gravel) aggregate
- MB AE 90 air-entraining admixture

The gradations of coarse and fine aggregates used in this study are given in Figure 8. Table 4 lists the chemical properties of the SCMs.

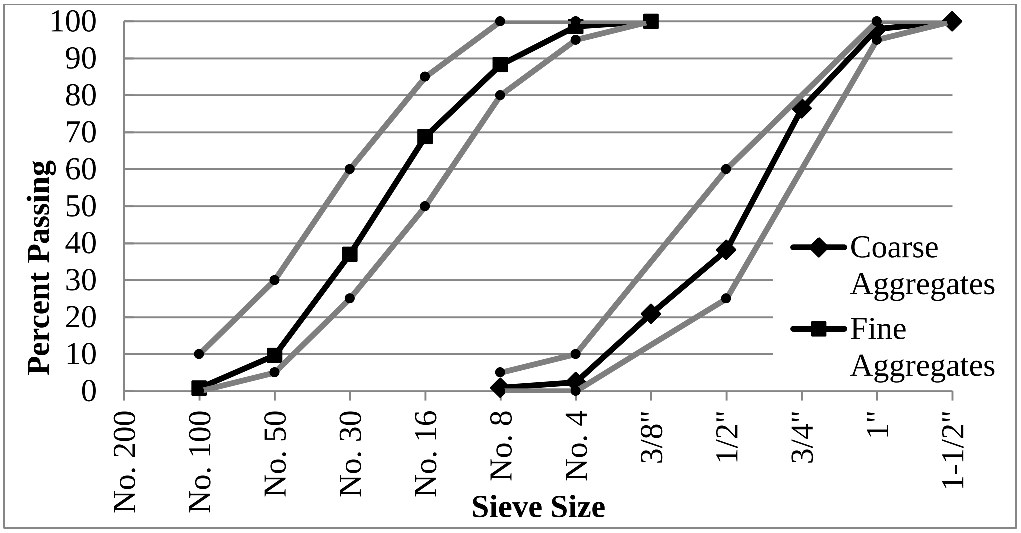


Figure 8. Gradations of coarse and fine aggregates

Table 4. Chemical compositions of cementitious materials

Chemical Composition	Type I/II Cement	Class C Fly Ash
SiO2	20.10	42.46
Al2O3	4.44	19.46
Fe2O3	3.09	5.51
SO3	3.18	1.20
CaO	62.94	21.54
MgO	2.88	4.67
Na2O	0.10	1.42
K2O	0.61	0.68
P2O5	0.06	0.84
TiO2	0.24	1.48
SrO	0.09	0.32
BaO	-	0.67
LOI	2.22	0.19

Tests

The following tests were conducted on samples collected from all of the mixtures:

- Fresh properties, including slump (ASTM C 143), air content (ASTM C 231), and unit weight (ASTM C 138)
- VKelly test

Laboratory Test Results

The test results are shown in Table 5. The VKelly Index gives the test results for the comparison of multiple operators. The percent difference varies from 0.00% to 8.31% for the same test performed by two operators.

The index seems not to be linearly correlated to slump results, which confirms that the dynamic VKelly test can indicate more information about a mixture, such as thixotropy, than a static slump test.

Table 5. Laboratory test results

Mix	Slump, in.	Slump Measured by VKelly Test, in.	Air Content, %	Unit Weight, lb./yd.^{3}	VKelly Index in/√s	VKelly Index Statistics Oper 1	Oper 2	Δ	%, Δ
Sand -4	0.75	0.80	4.8	152.4	0.47	0.45	0.49	-0.04	8.31
Sand -2	0.75	1.00	5.3	149.0	0.46	0.46	0.47	-0.01	2.15
Sand -1	0.75	1.00	4.5	151.4	0.46	0.45	0.48	-0.03	6.45
Sand +1	1.00	1.00	5.5	146.4	0.57	0.58	0.56	0.02	2.63
Sand +2	1.00	1.75	5.4	149.6	0.50	0.50	0.49	0.01	2.02
Sand +4	1.10	1.20	4.5	148.9	0.73	0.72	0.74	-0.02	2.74
Air +2	1.50	2.00	7.0	147.4	0.66	0.66	0.66	0.00	0.30
Air -2	1.00	1.00	5.8	147.4	0.64	0.63	0.65	-0.02	3.13
C Ash +1	1.00	1.50	5.0	148.0	0.63	0.64	0.62	0.02	3.17
C Ash +2	1.00	1.10	5.0	148.3	0.68	0.68	0.68	0.01	0.74
C Ash +3	1.25	1.50	5.5	147.4	0.72	0.71	0.73	-0.02	2.09
MAX	1.25	1.50	7.3	148.7	0.69	0.69	0.70	-0.01	1.30
Plain	1.00	1.25	4.5	147.6	0.58	0.58	0.59	-0.01	2.06
Plain(2)	1.00	1.10	4.7	147.8	0.61	0.61	0.61	-0.01	0.99
Plain(2) + 1 Gal	-	1.25	-	-	0.70	0.72	0.69	0.03	4.40
Plain(2) + 2 Gal	-	1.60	-	-	0.74	0.74	0.73	0.01	1.36
Plain(3)	1.25	1.10	5.2	148.6	0.62	0.61	0.63	-0.02	3.38
Plain(4)	1.25	0.90	5.5	148.0	0.68	0.67	0.68	-0.01	1.48
Plain(3) 15 mins	-	1.35	-	-	0.61	0.60	0.62	-0.02	3.11
Plain(3) 30 mins	-	1.05	-	-	0.61	0.61	0.62	-0.01	1.80
Plain(3) 45 mins	-	0.90	-	-	0.55	0.55	0.54	0.01	1.83
Plain(4R) mix	-	1.00	-	-	0.67	0.66	0.69	-0.03	3.86
Plain(4R) 15 mins	-	1.05	-	-	0.67	0.65	0.69	-0.04	5.37

*Note: (2), (3), and (4) denote the second, third, and fourth repeats. (R) denotes remix

The plain mix testing was repeated four times to check the repeatability with a single operator. The measured VKelly Index for the repeated mixes is shown in Figure 9. The standard deviation of the index for the four mixes is 0.037 and is marked as error bars in the plot.

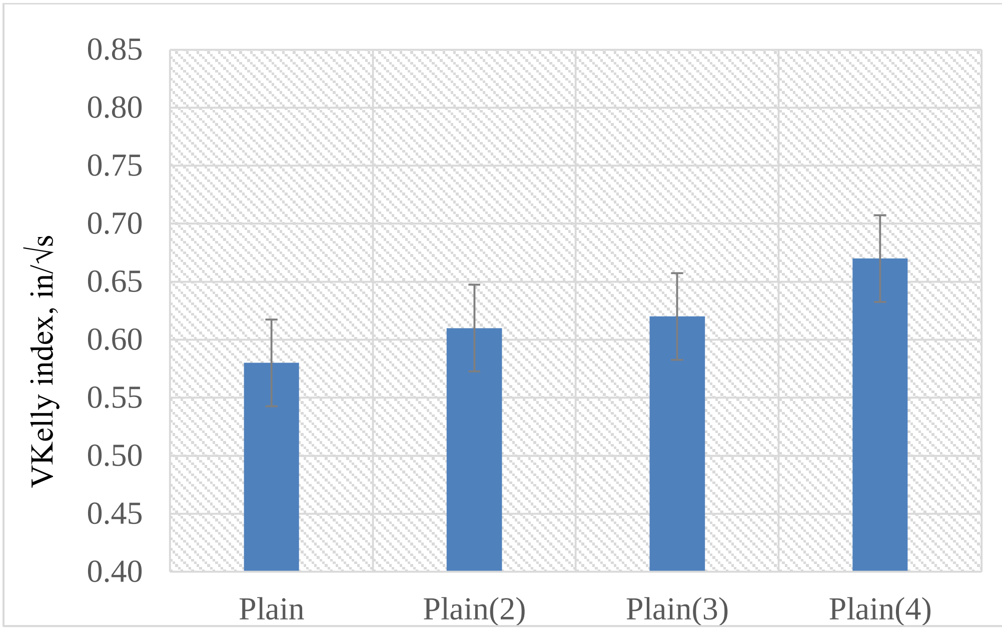


Figure 9. VKelly Index for plain mixes

In order to check the influence of elapsed time and remixing on the VKelly Index for the same mix, the index was measured on one of the four plain mixes at 15 minute intervals up to 45 minutes elapsed time. The index declined as elapsed time increased, as shown in Figure 10. One of the plain mixes was tested right after mixing, right after remixing, and at 15 minutes after remixing, denoted as Plain(4), Plain(4) Remix, and Plain(4) Remix@15 minutes in Figure 10, respectively. The index results are identical for the three measurements. The error bars represent the standard deviation of all the plain tests, i.e., 0.041.

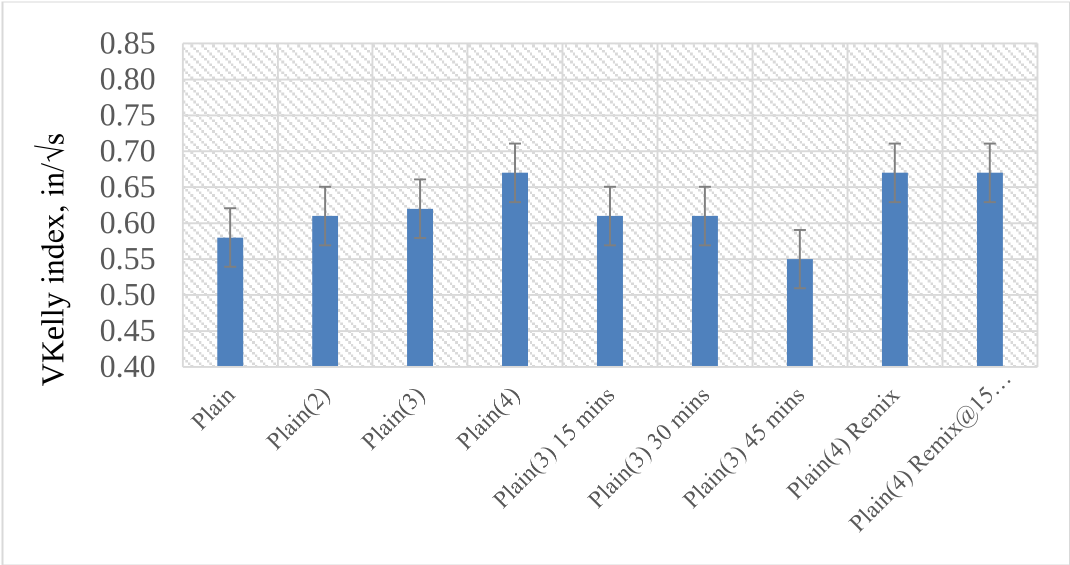


Figure 10. Influence of elapsed time and remixing on VKelly Index

Figures 11 to 14 give the effects of varying fine aggregate content, Class C fly ash, air content, and water content on the VKelly Index. In broad terms, increasing sand content can be seen to increase VKelly Index, as expected (Figure 11).

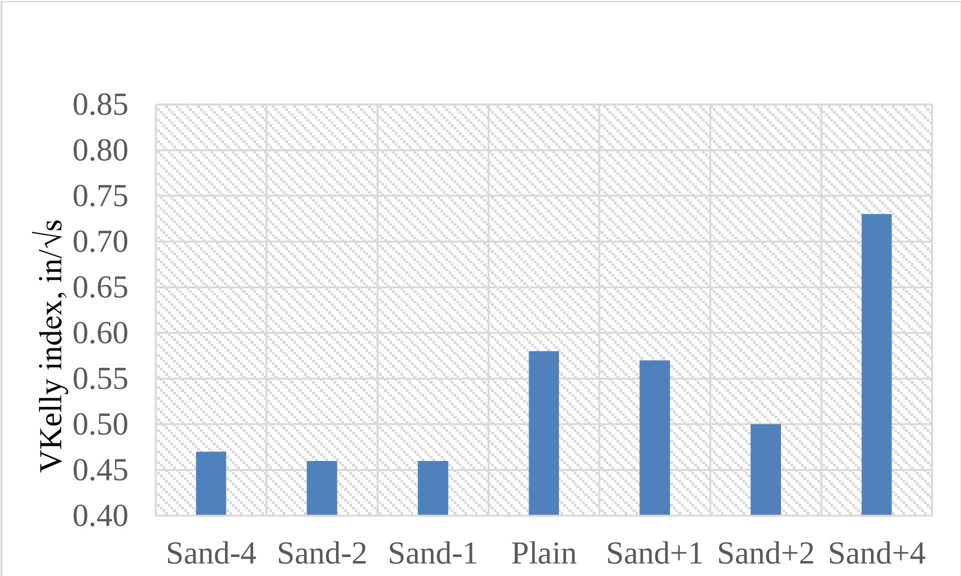


Figure 11. Influence of fine aggregate content on VKelly Index

The index increases linearly with an increased Class C fly ash replacement dosage up to 30%. The Class C fly ash replacement level seems to linearly change the VKelly Index (Figure 12).

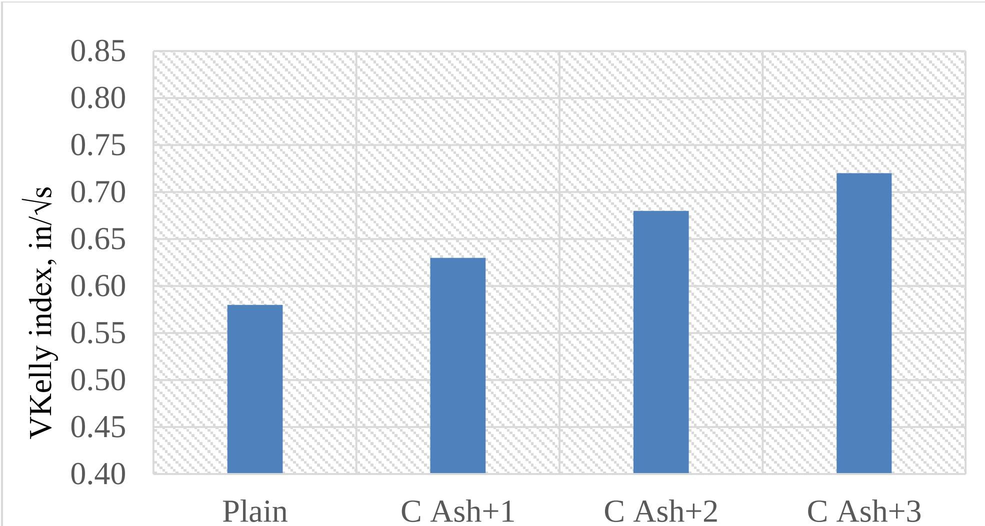


Figure 12. Influence of Class C fly ash replacement on VKelly Index

It is not clear why the variation with air content was nonlinear (Figure 13).

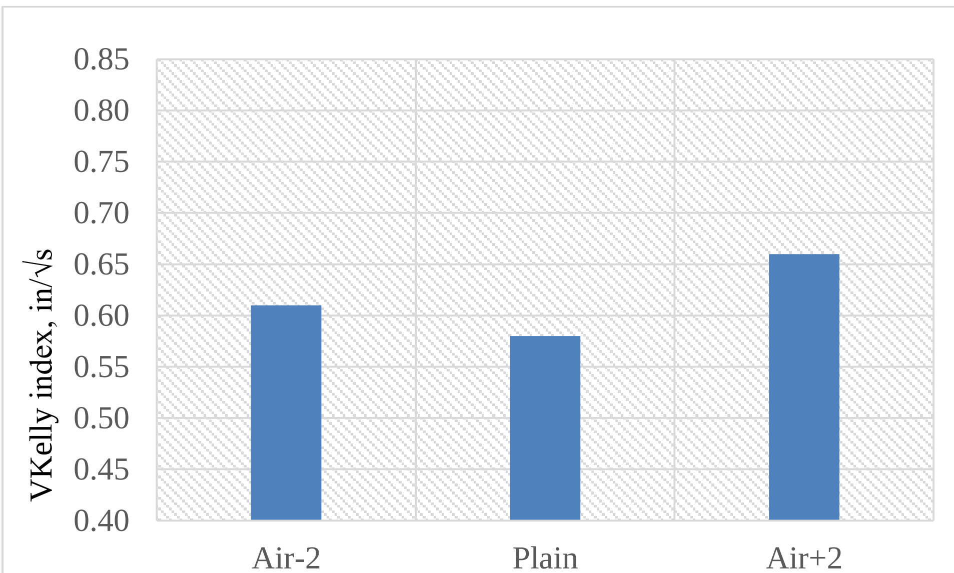


Figure 13. Influence of air content on VKelly Index

As expected, adding water to the system increased workability and the VKelly Index (Figure 14).

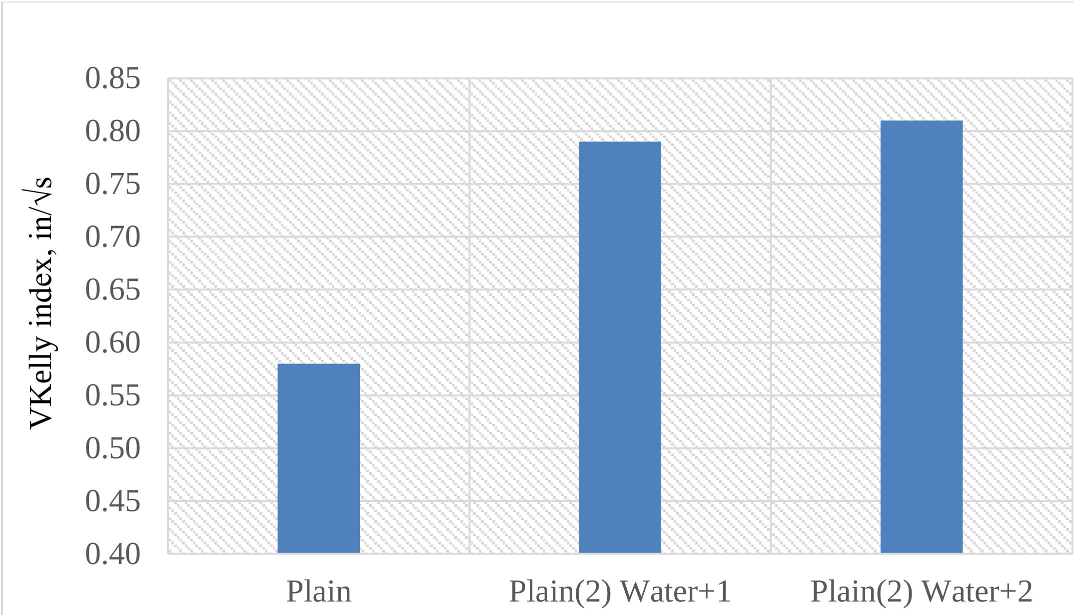


Figure 14. Influence of water content on VKelly Index

Phase II (Field Test)

The VKelly test was conducted on several slipformed highway paving sites in the states of Minnesota (MN) and Missouri (MO) (Figure 15).

Figure 15. VKelly test conducted in the field

The test results are shown in Figure 16. Sites A through H represent the sites in MN, and Site MO is the only test site in MO. The laboratory mix, Plain(3), is included in the plot for comparison purposes.

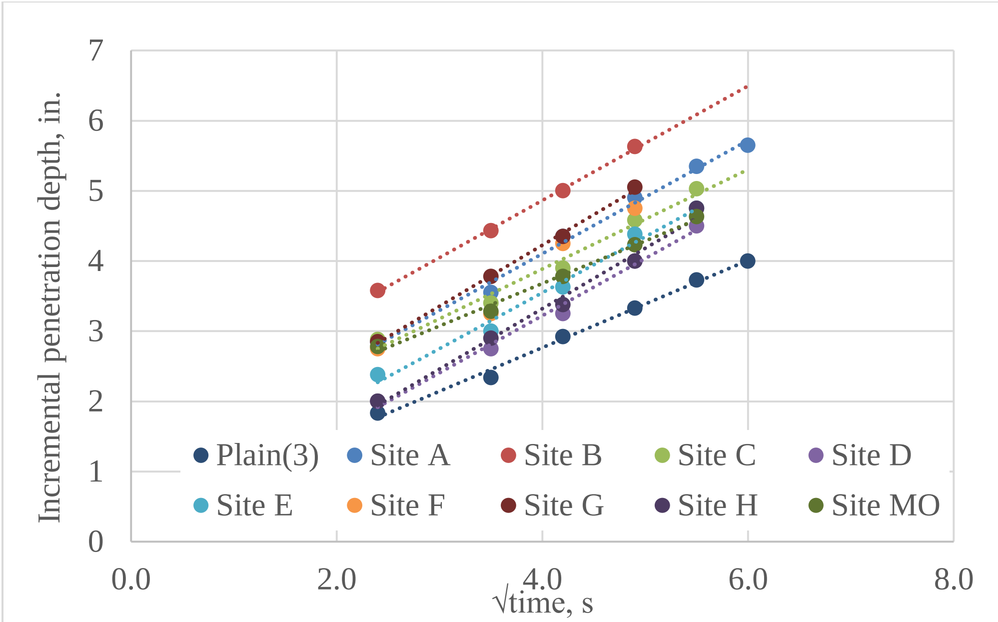


Figure 16. Field test results

Table 6 summarizes the mix proportions, site information, environmental conditions, and test results of each visited site. The VKelly test measured slump for all of the slipform paving mixes; results ranged from 1.0 to 2.0 in. Based on the mix proportions, the lower index value at Site C can be attributed to the lower fly ash replacement dosage (i.e., 20%, while most of others were 30%). Sites F through H generally exhibited higher index values, which are likely due to the effect of modifying the aggregate system on thixotropy, i.e., either introducing coarse sand or intermediate coarse aggregate. Site MO had the lowest cementitious materials content and the highest daily average temperature compared to other sites, which can be a reason why this site had the lowest index value.

Table 6. Mix proportions, site information, and field test results

Site ID Date	Site A 7/17/14	Site B 7/18/14	Site C 7/22/14	Site D 7/21/14	Site E 8/14/14	Site F 8/15/14	Site G 8/29/14	Site H 9/12/14	Site MO 8/27/14
Cement	400	400	547	400	400	400	400	400	390
Fly Ash	170	175	137	170	171	160	171	172	130
Water	228	210	260	215	211	190	211	206	213
Sand	1255	1217	1246	1404	1278	1177	1087	747	1270
Coarse Sand	-	-	-	-	-	-	404	560	-
Coarse Agg.	1806	1560	1652	1649	1839	1367	1616	1806	1397
Intermediate Agg.	-	-	-	-	-	636	-	-	508
Aggregate Type	Limestone	Limestone	Limestone	Quartzite	Granite	Gravel	Gravel	Gravel	Limestone
Air Entraining Agent	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Water Reducer	Type A	Type A	Type A	Type A	Type A	Type A	Type A	Type A	WRDA 82
Air Content	7%	7%	7%	7%	7%	7%	7%	7%	6%
Location	16th st.	I-90 EB	TH 22	CSAH 23	TH 24	TH 65	TH 169	I-35E	Hwy K
Pavement Type	Reconstruct	Unbounded overlay	Reconstruct	Bonded overlay	Bonded overlay	Overlay using fabric	-	Unbounded overlay	New pavement
Pavement Thickness (in.)	9.0	9.5	9.0	5.0	4.0	6.0	-	8.0	12.0
Joint Spacing (ft.)	15.0	15.0	15.0	6.0	6.0	12.0	-	15.0	-
Saw Type	Early entry	Conv.	Conv.	Conv.	Conv.	Conv.	Conv.	Conv.	Conv.
Average Temp. ˚F	66	69	74	79	64	72	73	48	82
VKelly Slump, in	2.00	1.75	2.25	1.50	1.00	1.50	1.00	1.00	1.00
VKelly Index, in/√s	0.81	0.82	0.71	0.82	0.80	0.84	0.87	0.86	0.61

Phase III (Validation of VKelly Test Results)

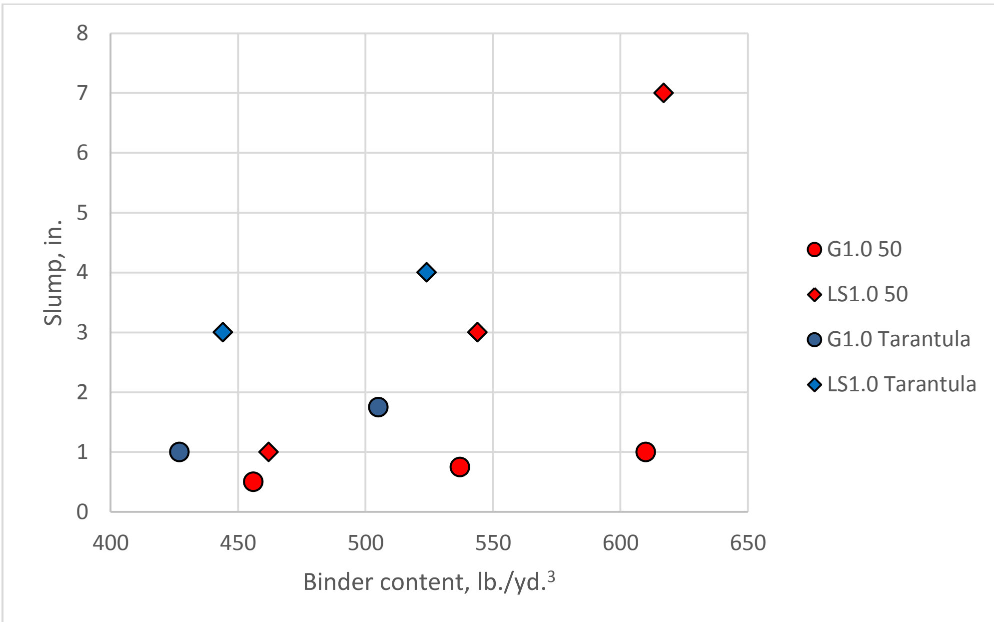
A limitation of the mixtures tested thus far was that all of them may be considered reasonable systems for paving, making it difficult to assess the limits of what may be considered “good” or “bad” data points.

As part of another program investigating concrete mixture proportioning (Taylor et al. 2015), mixtures were being prepared that were deliberately dry to deliberately wet, allowing the team to conduct VKelly tests on a wide range of mixture workabilities.

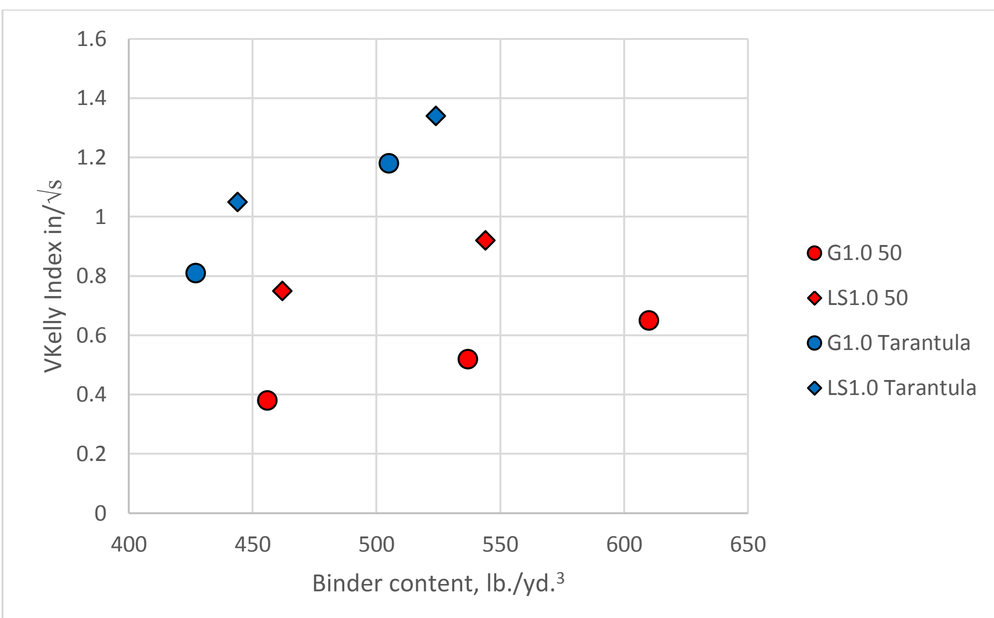
Two types of coarse aggregate were used, limestone and gravel (LS and G) with 1.0 in. nominal maximum size. A single river sand was used for all mixtures. Two combined gradations were used for each aggregate type, one based on a 50/50 mixture of coarse and fine aggregates, and another where the gradations were sieved to fit within a Tarantula curve (Ley et al. 2012). The binder contained 20% class C fly ash, and the w/cm was fixed at 0.42. Two or three binder contents were used for each aggregate system.

Fresh concrete properties were measured using the slump test (ASTM C143 2012), air content test (ASTM C231 2014), the VKelly test, and the Box Test (Cook et al. 2014).

Figure 17 (a) and (b) present the slump and VKelly Index versus binder content, respectively.



(a)



(b)

Figure 17. Slump (a) and VKelly Index (b) versus binder content

Similar trends can be seen in that both the slump and the VKelly Index increase with increased binder content. The aggregate system that fit the Tarantula curve generally gave a better workability, and, surprisingly, the limestone coarse aggregate was more workable than the gravel at similar binder contents.

The Box Test visual rating was assessed for each mix and plotted, as shown in Figure 18. Based on Cook et al. (2014), a Box Test visual rate of 2 is an acceptable ranking and corresponds to a minimum VKelly Index of 0.8 in/√s, which is consistent with the field observations. A VKelly Index of 1.4 in/√s was observed in a mixture with a 3 in. slump, which may be considered too wet for paving; therefore, a value of 1.2 in/√s may be a reasonable upper limit.

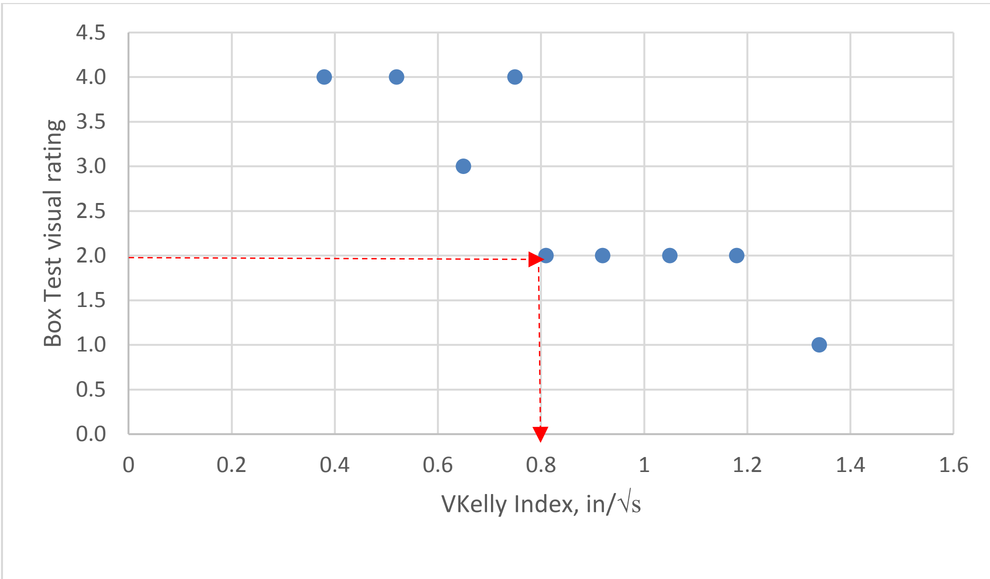


Figure 18. Box Test visual rating versus VKelly Index

CONCLUSIONS AND FUTURE WORK

Conclusions drawn from this study and future work are summarized below.

Conclusions

The data collected to date indicate the following:

- The VKelly test method appears to be suitable for assessing a mixture's response to vibration (workability).
- The VKelly test can report both static and dynamic characteristics while simulating the effect of vibration from paving.
- Multiple-operator variability for the VKelly test appears to be up to 8.3%.
- The VKelly test can be operated in the field, but the intended use is mostly in the laboratory to help design mixtures that perform as required.
- Based on the data collected to date, a VKelly Index in the range of 0.8 to 1.2 in./$\sqrt{s}$ seems to indicate a mixture that is likely to be suitable for slipforming.

It is intended that this test will primarily be used for mixture design purposes, but the test may also find some use as a quality control tool in the field.

Future Work

Further work is required to improve and further validate the VKelly test:

- The recommended ranges should be confirmed both in the laboratory and in the field.
- The frame should be refined so that the system can be operated by one person.
- The VKelly Index should be correlated with the characteristics of a range of different paving machines.

REFERENCES

Abrams, D.A. 1922. Proportioning Concrete Mixtures. *ACI Journal, Proceedings*, 18(2), 174–181.

ACI 116R-00. 2000. Cement and concrete terminology. American Concrete Institute Committee 116, Farmington Hills, MI.

ACI 211.3R-02. 2002. Guide for selecting proportions for no-slump concrete. American Concrete Institute Committee 211, Farmington Hills, MI.

ASTM C29. 2009. Standard test method for bulk density ("unit weight") and voids in 419 aggregate. American Society for Testing and Materials, West Conshohocken, PA.

ASTM C143/C143M. 2012. Standard test method for slump of hydraulic-cement concrete. American Society for Testing and Materials, West Conshohocken, PA.

ASTM C231. 2014. Standard test method for air content of freshly mixed concrete by the 425 pressure method. American Society for Testing and Materials, West Conshohocken, PA.

ASTM C360-92. Test method for ball penetration in freshly mixed hydraulic cement concrete (Withdrawn 1999). ASTM International, West Conshohocken, PA.

ASTM C995-01. Standard test method for time of flow of fiber-reinforced concrete through inverted slump cone (Withdrawn 2008). ASTM International, West Conshohocken, PA.

ASTM C1170-91. 1998. Standard test methods for determining consistency and density of roller-compacted concrete using a vibrating table. ASTM International, West Conshohocken, PA.

Banfill, P.F.G., Yongmo, X., and Domone, P.L.J. 1999. Relationship between the rheology of unvibrated fresh concrete and its flow under vibration in a vertical pipe apparatus. *Magazine of Concrete Research*, 51(3), 181–190.

Bartos, P.J.M. 1992. *Fresh Concrete: Properties and Tests*. Elsevier Science Publishers, Amsterdam.

Bartos, P.J.M. 1994. Assessment of properties of underwater concrete by the Orimet test. In P.J.M. Bartos, Ed., *Proceedings, Special Concretes: Workability and Mixing*. RILEM, Paisley, Scotland, 191–200.

Bartos, P.J.M., Sonebi, M., Tamimi, A.K. (Eds.). 2002. *Workability and rheology of fresh concrete: compendium of tests*. RILEM TC 145-WSM. RILEM, France.

Chidiac, S.C., Maadani, O., Razaqpur, A.G., and Mailvaganum, N.P. 2000. Controlling the quality of fresh concrete. *Magazine of Concrete Research*, 52(5), 353–363.

Cook, D., Ghaeezadeh, A., and Ley, T. 2013. *Investigation of optimized graded concrete for Oklahoma*. Final Report OTCREOS11.1-38-F. Oklahoma State University, Stillwater, OK.

Cook, D., Ghaeezadah, A., and Ley, T. 2014. A workability test for slip formed concrete pavements. *Construction and Building Materials*, 68, 376–383.

EN12350-2:2000. 2000. Testing fresh concrete – Part 2: Slump test. European Committee for Standardization, Brussels, Belgium.

EN12350-3:2000. 2000. Testing fresh concrete – Part 3: Vebe test. European Committee for Standardization, Brussels, Belgium.

EN12350-4:2000. 2000. Testing fresh concrete – Part 4: Degree of compactability. European Committee for Standardization, Brussels, Belgium.

EN12350-5:2000. 2000. Testing fresh concrete – Part 5: Flow table test. European Committee for Standardization, Brussels, Belgium.

Ferraris, C.F. 1999. Measurement of the rheological properties of high performance concrete: state of the art report. *Journal of Research of the National Institute of Standards and Technology*, 104(5), 461–478.

Ferraris, C.F., and de Larrard, F. 1998. Modified slump test to measure rheological parameters of fresh concrete. *Cement, Concrete, and Aggregates*, 20(2), 241–247.

Hackley, V., and Ferraris, C.F. 2001. *The Use of Nomenclature in Dispersion Science and Technology*. Special Report 960-3. National Institute of Standards and Technology, Gaithersburg, MD.

Juvas, K. 1990. Experiences in measuring rheological properties of concrete having workability from high-slump to no-slump. In H.-J. Wierig, Ed., *Proceedings of RILEM Colloquium on Properties of Fresh Concrete*, University of Liverpool, London, 179–186.

Juvas, K. 1994. Very dry precasting concrete. In P.J.M. Bartos, Ed., *Proceedings, Special Concretes: Workability and Mixing*. RILEM, Paisley, Scotland, 153–168.

Koehler, E., and Fowler, D. 2003. *Summary of concrete workability test methods*. Research Report ICAR 105-1. The University of Texas at Austin.

Koehler, E., and Fowler, D. 2007. *Aggregates in self-consolidating concrete*. Research Report ICAR 108-2F. The University of Texas at Austin.

Ley, T., Cook, D., Fick, G. 2012. *Concrete Pavement Mixture Design and Analysis (MDA): Effect of Aggregate Systems on Concrete Mixture Properties*. National Concrete Pavement Technology Center, Ames, IA.

Mindess, S., Young, J.F., Darwin, D. 2003. *Concrete*. 2nd ed. Pearson Education, Inc., Upper Saddle River, NJ.

Powers, T.C. 1968. *Properties of Fresh Concrete*. John Wiley & Sons, New York.

Sachan, A.K., and Kameswara Rao, C.V.S., 1988. A cone penetration test for workability of fibre reinforced concrete. *Materials and Structures*, 21(126), 448–452.

Scanlon, J.M. 1994. Factors influencing concrete workability. In *Significance of tests and properties of concrete and concrete-making materials*. P. Klieger, and J.F. Lamond, Eds. American Society for Testing and Materials, Philadelphia, PA.

Szecsy, R.S. 1997. Concrete rheology. Ph.D. Dissertation, University of Illinois at Urbana-Champaign, Urbana, IL.

Tattersall, G.H., and Banfill, P.F.G. 1983. *The rheology of fresh concrete*. Pitman Publishing, Marshfield, MA.

Tattersall, G.H. (1991). *Workability and Quality Control of Concrete*. London: E&FN Spon.

Taylor, P., Yurdakul, E., Wang, X., and Wang X. 2015. *Concrete Pavement Mixture Design and Analysis (MDA): An Innovative Approach to Proportioning Concrete Mixtures.* Technical Report TPF-5(205). National Concrete Pavement Technology Center, Iowa State University, Ames, Iowa.

Tymkowicz, S. and Steffes, R. 1996. Vibration study for consolidation of Portland cement concrete. Semisesquicentennial Transportation Conference Proceedings, Iowa State University, Ames, Iowa.

United States Patent 3,863,494. 1975. Device for measuring the workability and compaction of fresh concrete. February 4, 1975.

United States Patent 4,332,158. 1982. Slump testing device. June 1, 1982.

United States Patent 4,794,799. 1989. Method of and an apparatus for measuring the properties, particularly the compactability of a stiff mass to be cast. January 3, 1989.

United States Patent 4,930,346. 1990. Method for the determination of the properties of moldable materials, particularly for the determination of the plastic and rheologic properties thereof. June 5, 1990.

Wilby, C.B. 1991. *Concrete materials and structures*. Cambridge University Press, Cambridge, MA.

Wong, G.S., Alexander, A.M., Haskins, R., Poole, T.S., Malone, P.G., and Wakeley, L. 2000. *Portland-Cement Concrete Rheology and Workability: Final Report*. FHWA-RD-00-025. Federal Highway Administration, McLean, VA.