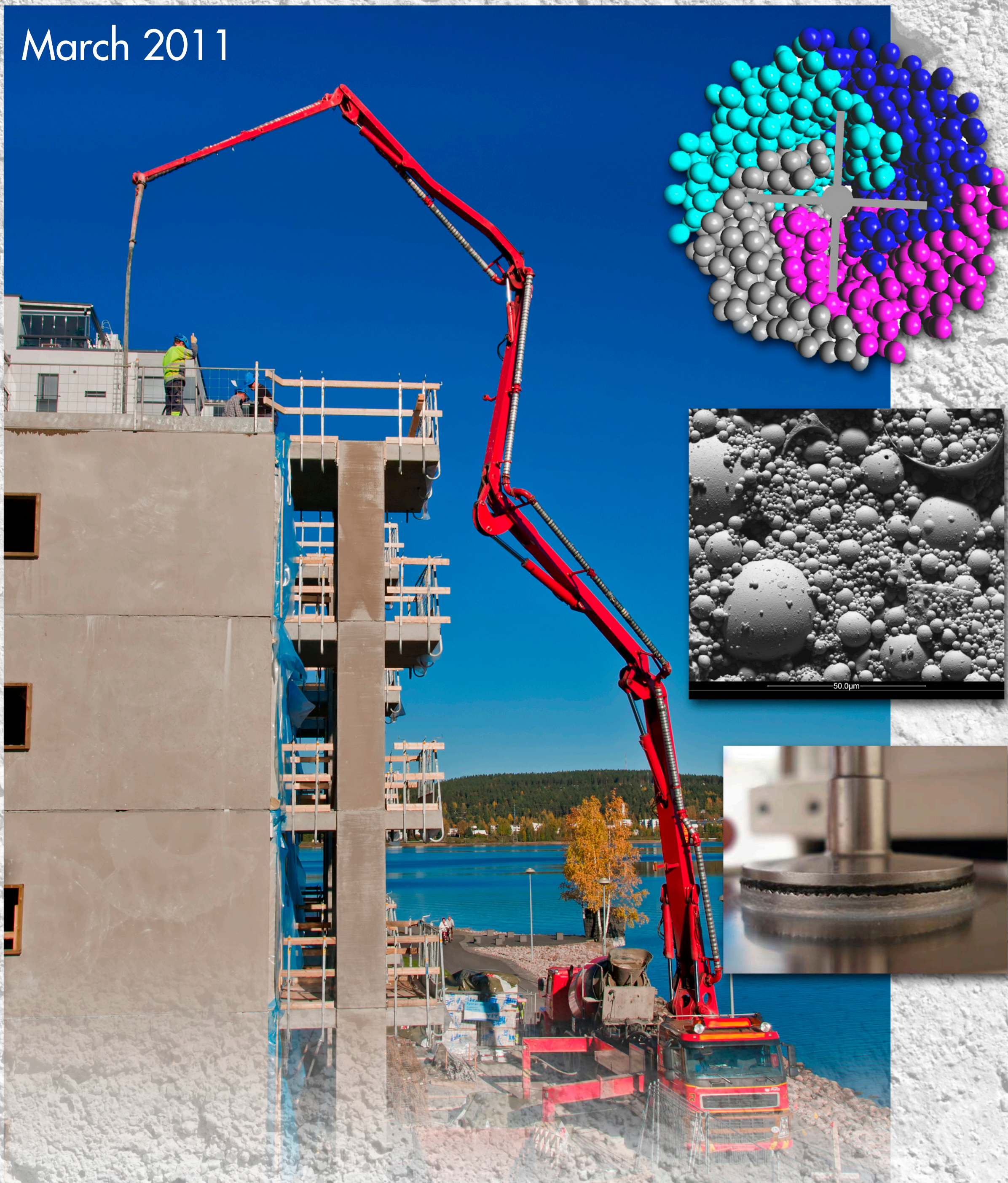
Measurement Science Roadmap for Workability of Cementitious Materials

Workshop Summary Report

Technical Note 1704

March 2011



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NIST Technical Note 1704

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March 2011

U.S. Department of Commerce
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National Institute of Standards and Technology Technical Note1704
Natl. Inst. Stand. Technol. Tech. Note 1704, 58 Pages (March 2011)
CODEN: NTNOEF

Acknowledgments

The participants, facilitators, and keynote speakers of the workshop "Measurement Science Roadmap for Workability of Cementitious Materials" are thanked for their time and dedication in providing the foundation of this report. Their presentations and discussions made it possible to develop a roadmap that could be used by the construction industry and various public sector agencies.

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Special thanks to A. Hunter Fanney, NIST, for his advice and guidance in the planning of the workshop and Felicia Walker for her administrative work.

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Preface

This report summarizes the results of the workshop "Measurement Science Roadmap for Workability of Cementitious Materials," held on March 18, 2011 in Gaithersburg, Maryland and sponsored by the National Institute of Standards and Technology with collaboration from industry, other government agencies and trade groups. These efforts are consistent with the NIST mission "to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life."

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Executive Summary

A workshop "Measurement Science Roadmap for Workability of Cementitious Materials" was held at National Institute of Standards and Technology (NIST) on March 18, 2011 with the purpose of identifying and ranking measurement science and services needs for overcoming technological barriers to the placement of cementitious materials. The workshop had wide participation from the construction industry and public sector agencies.

The outcome of the workshop is a 5-year roadmap outlining Research & Development (R&D) measurement science and services needs of both private and public sectors to improve mixing, placement, consolidation, and finishability of cementitious materials. This roadmap also will provide a framework for the development of new standards and codes for workability measurements of cement-based materials. It will be used to guide NIST programs to ensure that measurement science keeps pace with technological innovation in the field of construction materials.

The one-day workshop included keynote talks and breakout discussion sessions. The keynote speakers were Prof. Kamal Khayat, University of Sherbrooke, and Dr. Ara Jeknavorian, W.R. Grace. At the workshop, the participants were asked to provide input on the following topics as they relate to the measurement science needs for assessment and optimization of fresh properties of cement-based materials:

- Influence of new by-products materials on the properties of fresh concrete (e.g., supplementary cementitious materials or recycled aggregates);
- Anticipate needs for innovative and field-oriented test methods to assess the rheological properties of concrete during mixing, pumping, vibrated concrete, and non-vibrated concrete (Self Consolidating Concrete (SCC));
- Anticipate needs for better test methods for assessment of the fresh properties of grouts and repair materials for special applications, including grouts for post-tensioning tendons, mining, and oil-well applications, and repair materials for nuclear and infrastructure applications.

The information collected was analyzed and summarized in three major thrusts:

- Facilitate quality control, ranked as having the greatest impact, through the development of sensors and test methods, during production and delivery or in-situ.
- Improve the service life of a structure ranked as having the second greatest impact, through a clear understanding or knowledge of the key factors affecting material behavior under field conditions (temperature, relative humidity…). A long service life cannot be achieved if the material (concrete or grout) is improperly placed and cured.
- Reduce the cost of production and improve sustainability through selection of the constituents to achieve the desired performance, in both fresh and in hardened concrete. Methodologies to characterize the materials both in-situ and in the laboratory need to be developed. These methods would allow the detection of constituent incompatibilities and increase the use of alternative materials, supported by the development of performance-based standards.

A detailed roadmap, listing steps to ensure that the three thrusts above, can be achieved in five years, and is described in Chapter 6.

1. Introduction

1.1. Background

Cement-based materials are the most widely used building materials in the construction industry [Mobasher[1],] with many applications that are critical for the nation's infrastructure. Indeed, the applications that are possible with cement-based materials are so diverse that there are many measurement science challenges including characterization of performance for dramatically varying materials requirements, construction constraints, and environmental exposure during construction and over the life of the structure. Durable and sustainable structures cannot be achieved without proper processing of the construction materials [Li[2]]. Processing of cement-based materials includes selecting materials, mixing, placement (e.g. pumping, pouring), consolidation, and finishing. The proper placement of concrete implies that the concrete flows in the forms and can be consolidated without entrapping air or segregating. This cannot be achieved without a clear understanding of the link between the material composition and the fresh concrete properties. The link between composition and fresh properties is still not completely understood today and often relies on empirical knowledge and test methods. Further, the recent demand for more sustainable and green materials has led to an increase in the use of blended cements through the addition of industrial by-products materials such as fly ash, silica fume, and blast furnace slag. Incorporating large fractions of these materials complicates the prediction of fresh properties of cement-based materials because these materials can have properties that vary among regions and even from the same supplier.

Critical to addressing these challenges are the measurement sciences advances. Here, the term measurement science is used in the context of creating critical-solution enabling tools—metrics, models, and knowledge – for the construction industry. This includes the following concepts that were provided to the participants:

- development of performance metrics
- measurement and testing methods
- predictive modeling and simulation tools
- knowledge modeling
- protocols
- technical data
- reference materials
- artifacts
- the conduct of inter-comparison studies and calibrations
- the evaluation of technologies, systems, and practices, including uncertainty analysis
- the development of the technical basis for standards, codes, and practices.

This workshop is an attempt to determine the measurement science needs for fresh concrete properties. This report conveys all the information collected at the workshop. Section 1.2 gives more detail on how the workshop was organized. Chapter 2 gives an overview of the keynote

[1] Mobasher B., "USA-Concrete Construction Industry – Cement Based Materials and Civil Infrastructure (CBM $ CI)", CBM-CI International Workshop, Karachi, Pakistan, 2007

[2] Li, V., "Integrated Structures, and materials design" Mat. & Structure (2007) vol. 40 pp. 387-396

presentations, while Chapters 3 through 5 provide the details for each breakout session. Finally, Chapter 6 summarizes the findings with a roadmap.

1.2. Scope and objectives

The goal of the workshop was to identify and prioritize measurement science needs for assessing and optimizing the placement and consolidation of fresh cementitious materials. The workshop solicited input from a wide range of construction industries and public sector agencies (see Appendix A for a list of attendees).

The outcome of the workshop is a five-year roadmap outlining R&D, measurement science and service needs for both private and public sectors to improve mixing, pumping, placement, consolidation, and finishability of cementitious materials. This roadmap also provides a framework for the development of new standards and codes for workability measurements of cement-based materials. NIST will use this roadmap to help guide its program and to ensure that measurement science keeps pace with technological innovation in the field of construction materials. Participants were selected from a wide range of industry and academia. Over 100 invitations were sent, and over 30 persons responded and came to NIST.

The one-day workshop includes keynote talks and breakout discussion sessions. The keynote speakers were Prof. Kamal Khayat, University of Sherbrooke, and Dr. Ara Jeknavorian, W.R. Grace. At the workshop, the participants were asked to provide input on the following topics as they related to the measurement science needs for assessment and optimization of the fresh properties of cement-based materials:

- Influence on fresh properties of new by-product materials (e.g., supplementary cementitious materials or recycled aggregates);
- Development of innovative and field-oriented test methods to assess the rheological measurements of concrete: mixing, pumping/vibrated concrete/non-vibrated concrete (SCC);
- Development of better test methods for assessment of the fresh properties of grouts for special applications, including grouts for post-tensioning tendons, mining, and oil-well applications;
- Development of better test methods for the assessment of the fresh properties of repair materials, including those for nuclear and infrastructure applications.

At the request of the participants, the two last topics, related to grouts and repair materials, were combined into one breakout session. Each participant attended two breakout sessions (group 1 and 2 for each session). In the rest of the report, the three breakout sessions are referred to by: new by-products (chapter 3), field tests methods (chapter 4) and grout and repair materials (chapter 5).

At each breakout session, the participants were asked to discuss the following three topics:

1. <u>Characteristics of future construction/repair (building or infrastructure) environments</u>: This element was aimed at creating a very broad vision on the construction site in the future (+5 years or more). What tools or measurement science would be utilized in construction while decreasing cost/time and improving quality assurance, sustainability, and durability?

2. Critical technologies to enable optimization of fresh cementitious materials properties: This would capture the participants' thoughts in answering two key questions: a) What technology is needed that may not exist to complete the picture from topic #1 (imagine tools that do not exist)? b) What are the limits or impediments of today's methodologies to implement topic #1?
3. Broad technical and non-technical challenges to technology development and implementation: Here, the discussion would focus on the following issues: a) What are the challenges to develop the technology and methodologies needed, discussed under topic #2; b) How could the utilization of the technology from topic #2 (education, training, standards, codes) be increased?

At the end of the discussion, the participants from each session were asked to suggest "Critical measurement science barriers". Suggestions were compiled in a list and, subsequently, each participant was asked to select their top three items from the list. All votes could be placed on one barrier, if desired. The top three selections were further explored. The participants of the sessions were divided in three groups with the task of answering the following questions on each of the top three selections:

- Technology innovation or improvement needed to overcome the measurement science barrier
- Measurement science challenges and potential solutions: Provide two to three challenges and the potential solutions
- Stakeholders and roles. The list below was provided and the participants were asked to check all that apply and to specify how they would participate:
    - Government (Federal, State)
    - National Laboratories
    - Industry
    - Trade groups
    - Standard Organizations
    - Academic Research
    - Other Non-Profits
    - International
- Relative impacts if the barrier was solved by assigning a number from low [1] to High [5] on the following impacts:
    - Reduction of cost of production
    - Improve sustainability
    - Improve service life
    - Support a healthy work environment
    - Facilitate quality control

This report provides all the information collected during the discussion, including details contained in the clarification provided in the last topic of the breakout sessions.

2. Keynote speakers

Two keynote presentations were given to provide overviews of construction industry needs for the placement of concrete by Prof. Kamal H. Khayat, University of Sherbrooke, and Dr. Ara A. Jeknavorian, W.R. Grace. They were titled "Rheology and Performance of Cement-Based Materials," and "If I Only Had a Rheometer - Limitations of the Slump Test to Adequately Qualify Concrete Workability," respectively. These presentations provided background information through examples from practice and research that served as motivation for further discussion in the breakout sessions. A common theme in both presentations is that a better understanding of concrete rheology can lead to increased production efficiency, improved quality assurance, increased adaptability for new applications, lower environmental impact, and reduction of costs. Some recurring topics discussed in both presentations are provided here, as perceived by the authors:

- The widely used slump test is inadequate for describing fresh concrete properties for many applications, including pumping and finishability.
- Measurements of rheological properties, such as yield stress, viscosity, or thixotropy, are, in general, better characterizations of fresh concrete properties than is slump. Determining fresh concrete performance based on rheology science would reduce or eliminate catastrophic placement failure and ensure quality control.
- Better understanding of concrete rheology opens doors for innovative applications, such as Self Consolidating Concrete (SCC), pumping, and repair materials. Furthermore, advanced formulations of concrete could be made to optimize flow properties as conditions change from initial batching, to pumping, placement, and finally finishing.
- Characterization tools that are easy to use and linked to rheological science are needed for quality control and mixture design, including the capability to evaluate rheological properties from a concrete truck.
- Increased use of a wider range of new materials (e.g., Supplementary Cementitious Materials (SCM), manufactured vs. natural sand) is needed to ensure sustainability and reduce cost. These new materials cannot be incorporated into concrete without an improved characterization methodology, metrology to determine the effect of new materials on concrete properties (fresh and hardened), and advanced rheology science to better control flow. An important challenge that arises with the increased use of new materials is the need to move from prescriptive to performance-based specifications.
- Predictive tools or models for workability, if possible with linkage to strength and service life, need to be developed.
- There is a need to better understand the physics of pumping. For example, inclusion of tribology concepts would help determine the effect of friction of concrete on the flow in the pipe.

3. Breakout Session on New By-Products

The push to broaden the use of cement-based materials and make them more sustainable has led to increased use of supplementary cementitious materials (SCMs). According to ACI definition[3], SCMs are “inorganic material such as fly ash, silica fume, metakaolin, or ground-granulated blast-furnace slag that reacts pozzolanically or hydraulically.” In the future, other types of materials could be envisioned. Usually these products are produced as by-products of other industries. For instance, fly ash is a by-product from coal combustion, and silica fume is a by-product of electric arc furnaces. The SCM used in concrete at a construction site needs to improve the desired properties and not negatively affect others. For instance, silica fume can reduce alkali silica reaction or increase sulfate resistance, but it should not reduce the workability significantly. The use of SCMs and other admixtures makes possible the design of concrete that is tailored to a particular application.

To expand the type of SCMs available and to ensure performance-based concrete design, it is necessary to identify and prioritize measurememt science barriers to their further and higher volume use.

3.1. Characteristics of future construction/repair (building or infrastructure) environment

Construction of tomorrow will need to be sustainable, making use of all available materials, including by-products from other industries that will increase the sustainability and that reduce the carbon footprint of the cementitious material. Nevertheless, the final product (i.e., the concrete structure) must have a predictable service life and a reasonable life cycle cost. The use of new by-products creates challenges for characterization, optimization of the final product, and predicting performance. Monitoring the performance during the service life of the structure is important to ensure safety and predict maintenance schedules and anticipated costs. The future construction attributes identified during the workshop are listed below.

- By-product materials as replacement of cement or other constituents, such as:
    - Higher usage of SCMs, limestone, and other filler materials
    - Non-portland cement-based systems (geopolymers, calcium sulfoaluminates)
    - Recycled concrete and recycled returned concrete as aggregate
    - Increased utilization of fibers (polymers, metal, hybrids)
    - Nanomaterials

- A better understanding of the materials’ performance would allow:
    - Complex mixtures (ternary or quaternary mixes) to optimize cement usage reduction in order to lower carbon footprint, and reduce environmental impacts
    - Optimized aggregate gradations to better use recycled aggregates or reduce cement paste content
    - Non-steel reinforcement for special applications, and corrosion reduction
    - Self-sensing, self-healing concretes to increase service life while reducing repair costs

[3] ACI, 2010, “ACI Concrete Terminology,” American Concrete Institute, Farmington Hills, MI, http://terminology.concrete.org (accessed May 20, 2010).

    - Robust concrete formulations, better performance control
    - Better control the effects of temperature
    - Increased use of prediction tools through modeling of performance, based on the composition of the concrete
    - Real time characterization of chemical and physical properties

- Other general considerations
    - Specialty concretes such as SCC, pervious, ductile, Ultra High Performance Concrete (UHPC), rapid set cements for specific applications
    - Water supply and quality
    - Greater needs for pre-fabrication, fast track

3.2. Critical technologies to enable optimization of fresh cementitious materials' properties

To increase the use of by-products while ensuring performance-based concrete, accurate and reliable testing methodologies are needed to characterize the materials. Tools, including models to predict the performance from the composition of the materials (including both cement and by-products), need to be available for the field, not just as laboratory research tools. A list of critical technologies was drafted by the participants.

- On-site testing
    - New mixture proportioning methodologies
    - Improved (real-time) characterization of chemical and physical characteristics
    - Sensors for quality control of specific properties
    - Concrete rheometer that is field-friendly and robust
    - Feedback loop from site to plant
    - Field tests that are scientifically-based, robust, inexpensive, user-friendly, and operator independent (segregation, sticking test, formwork pressure, air content)
    - Monitoring of properties with time
    - Quality control methods

- R&D needed
    - Methodologies for assessing material interactions/incompatibilities
    - Laboratory equipment/tests to simulate field processes (placement, pumping, etc.)
    - Effects of time and environment (temperature, wind, etc.)
    - Fundamental particle characterization
    - Modeling (particle interactions, flows, complex flow geometries, formwork pressure)
    - Development of concrete rheometer in fundamental units for specialty concretes (e.g., fibers), roller-compacted concrete
    - Robust admixtures
    - Controlled orientation of fibers
    - Documented information/data from start to finish
    - Knowledge lacking on which properties or tests are essential for characterization of fresh concrete properties, such as rheological properties
    - Relate SCM mixture characteristics to scaling, freeze-thaw resistance, carbonation

- Rheological properties specified based on field processes
- Education and training
- Decreased timeline for technology and standards acceptance
- Storage, transport, and handling of by-products

3.3. *Broad technical and non-technical challenges to technology development and implementation*

The use of by-products will increase only if some technical barriers are overcome. The most challenging is the high uncertainty in the performance of these products due to materials' variability from different sources and unknown links between the chemical and physical properties of the by-products and the concrete performance. Therefore, better tools or methodologies to characterize the by-products will strengthen their usage. Increased usage of by-products will increase the sustainability of concrete by reducing its carbon footprint. The main non-technical barrier is acceptance of a new by-product stream by the conservative construction industry. Due to the lack of reliable characterization tools to qualify a new by-product, the specifier is less likely to prescribe it, thus not taking advantage of a potential cost reduction of the binder. A list of broad challenges was drafted by the participants.

Acceptance of new materials and new methodologies by construction industry

- Costs, including cost of implementation, carbon taxes
- Education/training; lack of field experience
- Materials and process variability
- Conservative nature of industry; fragmentation of industry
- Safety/health/perception issues
- Demonstration of ease of use
- Time lag for technology transfer, acceptance, and standardization
- Specification based on prescriptive mixture design, instead of performance

The need for new characterization tools

- Binder characterization
- Interactions with other components
- Aggregate characterization
- Measurements in fundamental units
- Robust sensor development
- Fundamental rheological parameters to define performance attributes
  - Bottom-up approach to flow modeling
  - Time-dependent characterization
- Field ready tests that are scientific-based
- Excessively lengthy time for test completion
- Precision/reliability/robustness of test methods
- R&D funding shortages; realism of research
- Computational power

3.4. Critical measurement science (experimental or modeling) barriers

As described in Section 1.2, at the end of the discussion on the topics above (sections 3.1 to 3.3), the participants were asked to suggest "Critical measurement science barriers". The suggestions were compiled in a list shown in Table 1 and, subsequently, they were asked to vote on their top four items (marked by an * in Table 1). The top three selections were further explored. The participants of the sessions were divided into three groups, with the task to complete the forms shown Exhibit 3.1 to 3.6 (pages 18-24). Each participant was able to attend two sessions; thus, each breakout session had a group 1 and 2.

Several measurement science barriers were identified and are listed in **Table 1**. Some of the top measurement science challenges include:

- Robust sensors for field application
- Link of concrete rheological performance to specific applications
- Materials characterization to take into account material variability

Table 1: List of critical measurement science barriers for the "New By-Products" break out session, ordered by number of votes overall. Notes: Group 1 is shaded in grey. The symbol * indicates forms that were completed and are shown as Exhibit 3.1 to 3.6 (pages 18-24).

Barriers (title provided by participants)	**Votes**
* Development of robust sensors that work reliably under field conditions	8
* Fundamental rheological parameters to define performance/application (e.g., stickiness of concrete)	8
* Binder characterization	8
* Material variability	7
* Measurements in fundamental units	5
Length of standardization process	5
* Aggregate characterization and optimization	4
Bottom-up approach to flow modeling	4
Time dependence characterization	4
Environmental impact measurement of CO_2 footprint, embodied energy	2
Modeling linking fresh properties to long term performance	1
Fundamental understanding of the relationship between characteristics of component materials and properties of concrete	1
Lack of trained concrete technologists who understand and appreciate the value of concrete technology	1
Rheology: accurately measuring the rheological properties (equipment limitation)	1
The response time of devices is too long	1
Too many competing technologies/methods for practical implementation	1

Participants were asked to rank the relative impact from low [1] to High [5] for each of the top selections from **Table 1** (marked with an *). **Table 2** summarizes the results collected (see also Exhibits 3.1 to 3.6 [pages 18-24]). For each of the impacts, an average score was calculated to rank the overall impact.

Table 2: Summary of the relative impacts for each of the selected top barriers for the "New by-products" breakout session.

Barriers	Reduction of cost of production	Improve sustainability	Improve service life	Support a healthy work environment	Facilitate quality control
* Development of robust sensors that work reliably under field conditions	3	3	4	5	5
* Binder characterization	5	4.5	4	2	4.5
* Fundamental rheological parameters to define performance/application (e.g., stickiness of concrete)	4	4	5	2	4
* Measurements in fundamental units	4	2	3	3	5
* Aggregate characterization and optimization	3	5	4	1	4
* Material variability	3	4	2	1	5
Average Score	***3.7***	***3.8***	***3.7***	***2.3***	***4.6***

3.5. Priorities for measurement science

The top ranked measurement barriers identified under section 3.4 (marked with an * in **Table 1**) were explored further by the participants. A summary is provided below, and more details are given in the Exhibits 3.1 to 3.6 (pages 19-24).

Development of robust sensors that work reliably under field conditions : On-site monitoring and measurements emerged as essential to ensure quality control and monitoring of performance-based construction. New sensors need to be developed, but identifying the measurable entity that needs to be monitored is also a challenge.

Fundamental rheological parameters to define performance/application (e.g., stickiness of concrete) and measurements in fundamental units : Performance-based design of concrete for a specific application needs to be based on fundamental parameters. This is especially lacking for the fresh properties related to rheological parameters, in part due to the lack of standards and reference materials. Only results in fundamental units can be used to predict performance using quantitative models, as an example.

Materials variability (facilitate quality control) and binder characterization : SCMs are a by-product, and thus the characteristics vary by region or even from one batch to another. Tools need to be developed to ensure that SCMs are delivered consistently and have the desired properties. Methods to characterize the interactions between SCM, cement, and other constituents are essential to determine the sensitivity of the performance of the concrete to variabilities in the ingredients.

Aggregate characterization and optimization : The sources of aggregates are typically local, thus a robust and standardized methodology to characterize the aggregates is necessary. The issue is that the aggregates are an inexpensive product and the value added is low, but the impact on concrete workability and performance can be large.

From **Table 2**, the relative impacts are ranked in the following order:

1. Facilitate quality control
2. Improve sustainability
3. Reduction in cost of production AND Improve service life
5. Support a healthy environment

Exhibit 3: New By-Products

Information provided during the breakout sessions by the participants

3.1 Development of robust sensors that work reliably under field conditions

3.2 Fundamental rheological parameters to define performance/application (e.g., stickiness of concrete)

3.3 Binder characterization

3.4 Material variability

3.5 Measurements in fundamental units

3.6 Aggregate characterization and optimization

The information contained in the forms in this Exhibit are copied verbatim from the forms that the breakout sessions participants filled during the sessions. They are used to develop the roadmap.

Exhibit 3.1: New By-products

Development of robust sensors that work reliably under field conditions

Technology innovation or improvement to overcome measurement science barriers

- Researchers need to get into the field to see what technicians and construction personnel are up against
- We need to measure the right properties (scientific basis for empirical tests)
- Cost of labor and instrumentation is a driving factor-
- Instrumentation in concrete must be reliable and interpretable under all weather conditions - hot, cold, rainy, humid, windy
- Instrument should be operable by a person with a high school education
- The timeline for acceptance of technology is very long: standardization process, implementation (may need demonstration projects by Corps of Engineer, FHWA – state DOT specifications often drive the rest of the industry in that state)

Measurement Science Challenges and Potential solutions

Challenges *(2-3)*:	Potential solutions *(2-3)*:
Researchers need to go to the field	Can be a requirement for university graduation
Measuring the right properties	Research
Cost	Potential savings, contractual incentives
Ruggedness, simplicity (user-friendly)	Get commercial testing labs involved at an early stage in the development
Timeline for acceptance	Demonstration projects, workshops, industry associations

Stakeholders and roles

Government (Federal, State)	Demonstration projects; state DOT specifications can drive industry
National Laboratories	Research; sensor development
Industry	Participate in development and implementation
Trade groups	Sponsor some projects; educate members
Standard organizations	
Academia	Research; emphasize practical experience
Other non-profits	
International	

Relative impacts *(Low [1] to High [5] impact value for each)*

- Reduction of cost of production 3
- Improve sustainability 3
- Improve service life 4
- Support a healthy work environment 5
- Facilitate quality control 5

Exhibit 3.2: New by-products

Fundamental rheological parameters to define performance/application

Technology Innovation or improvement to overcome the measurement science barrier

- More involvement from field/constructors
- Better defined end application
- Better rheometers/measurements
- Establish standard material (e.g. with known stickiness)
- Computational flow modeling
- Understand variability
- Models in expert system form

Measurement Science Challenges and Potential solutions

Challenges *(2-3)*:	Potential solutions *(2-3)*:
Lack of quantitative description	New tests methods
Variability	More data, better raw material characterization
Inadequate test methods	New test methods

Stakeholders and roles

Government (Federal, State)	
National Laboratories	Analyze variability Standard reference materials
Industry	Better definition of field requirements
Trade groups	Better definition of field requirements
Standard organizations	Faster standards development
Academia	Fundamental research work
Other non-profits	
International	

Relative impacts *(Low [1] to High [5] impact value for each)*

- Reduction of cost of production 4
- Improve sustainability 2
- Improve service life 3
- Support a healthy work environment 3
- Facilitate quality control 5

Exhibit 3.3: New by-products

Binder characterization

Technology innovation or improvement to overcome the measurement science barrier

- Fundamental understanding of hydration
- How do various SCMs impact hydration?
- How do variations in cement hydration impact concrete rheology in presence of admixtures, SCM and other fillers?
- Effect of carbon and clay on admixture interaction

Measurement Science Challenges and Potential solutions

Challenges *(2-3)*:	Potential solutions *(2-3)*:
Complex materials undergoing complex reactions-multiphase	Appropriate models – MIT fundamental models but with fundamental principles
Dynamic range of particle size distribution (PSD) over time	Models include properties of PSD
Evolution of chemistry and rheology	More instruments in lab and field to collect more data → robust modeling
	Stronger interaction between chemist, rheologist, technologist and modelers

Stakeholders and roles

Government (Federal, State)	Improve concrete infrastructure; funding
National Laboratories	Accelerate implementation, jobs, resources applied effectively Data, equipment, R&D, coordinate, educate, write specifications
Industry	Cost-effective solution; R&D, apply technology
Trade groups	Visibility, leading technology; shows, papers, publicity
Standard organizations	Alignment of technology and users; write specifications to enable technology adoption-reduce risk
Academia	Train students, more funding, improve reputation; modify teaching to attract students, next generation, judge of technology impartially
Other non-profits	Visibility, spokesman; identify issues, problems
International	Uniformity; broaden problem definition, facilitate technology transfer

Relative impacts *(Low [1] to High [5] impact value for each)*

- Reduction of cost of production 5
- Improve sustainability 4
- Improve service life 4
- Support a healthy work environment 2
- Facilitate quality control 4

Exhibit 3.4: New by-products

Material variability (facilitate quality control)

Technology Innovation or improvement to overcome the measurement science barrier

- Understanding the interactions between constituents used
- Impact of changing ingredients (sensitivity of ingredients)
- Development of reference material database
- Accuracy of ingredient quantities
- Physical and chemical characteristics of individual ingredients

Measurement Science Challenges and Potential solutions

Challenges *(2-3)*:	Potential solutions *(2-3)*:
Variability of materials	Quality control
Compatibility	Trial batching/modeling

Stakeholders and roles

Government (Federal, State)	DOTs
National Laboratories	NIST/ Federal Highway Administration (FHWA)
Industry	Admixtures suppliers
Trade groups	National Ready Mixed Concrete Association (NRMCA), American Coal Ash Association (ACAA)
Standard organizations	ASTM, American Concrete Institute (ACI), Portland Cement Association (PCA)
Academia	
Other non-profits	
International	

Relative impacts *(Low [1] to High [5] impact value for each)*

- Reduction of cost of production 3
- Improve sustainability 4
- Improve service life 2
- Support a healthy work environment 1
- Facilitate quality control 5

Exhibit 3.5: New by-products
Measurement in fundamental units

Technology Innovation or improvement to overcome the measurement science barrier

- Take a measurable fundamental unit and represent it in a user-friendly relative scale that considers the application
- Incorporate "rheology" concepts into field measurements tests

Measurement Science Challenges and Potential solutions

Challenges *(2-3)*:	Potential solutions *(2-3)*:
What is a relative scale?	Lab/research development
What is a fundamental unit?	
What should rheological measurements tell us?	Relate rheology to workability (lab tests verified by field studies)

Stakeholders and roles

Government (Federal, State)	Enforce codes/standards
National Laboratories	Develop test methods based on research
Industry	Implementation, use of technology
Trade groups	Technology transfer
Standard organizations	Adopt a test methods into codes and standards
Academia	Research test methods in fundamental units
Other non-profits	
International	

Relative impacts *(Low [1] to High [5] impact value for each)*

- Reduction of cost of production 4
- Improve sustainability 4
- Improve service life 5
- Support a healthy work environment 2
- Facilitate quality control 4

Exhibit 3.6: New by-products

Aggregate characterization and optimization

Technology Innovation or improvement to overcome the measurement science barrier

- Methodology for characterizing aggregates
- Methodology for blending aggregates
- Equipment/techniques for characterizing aggregates
- Characteristics of aggregates: physical/chemical
- Standard reference materials for evaluating characteristics
- Understanding effects of impurities of aggregates on rheology
- Assessment of influence of aggregate on time-dependent rheology

Measurement Science Challenges and Potential solutions

Challenges *(2-3)*:	Potential solutions *(2-3)*:
Large number of aggregate sources	National database; Robust standards
Complexity of characterization	Education/training/research
Inexpensive product → low value added	Public funding

Stakeholders and roles

Government (Federal, State)	Funding
National Laboratories	Database
Industry	Funding/training/database
Trade groups	Database/training
Standard organizations	Specification
Academia	Research/training
Other non-profits	Funding
International	Research information

Relative impacts *(Low [1] to High [5] impact value for each)*

- Reduction of cost of production 3
- Improve sustainability 5
- Improve service life 4
- Support a healthy work environment 1
- Facilitate quality control 4

4. Breakout Session on Field Test Methods

Performance design of concrete can be achieved only if clear links between the constituent characteristics and the desired properties for a specific application are available. Currently, the concrete mixture is designed by using empirical tests and a trial-and-error approach. This is costly and inefficient, especially with high performance concrete. For instance, it is recognized that "small changes in mix design and even plant tolerances could strongly influence the pumpability of a concrete."[4] Other examples were provided by the keynote speakers. To establish the link between constituents and the final product, it is necessary to understand the influence of each part and the environment (e.g. mixing, temperature, flow geometry). This understanding must be based on a combination of modeling and test methods. The performance needs to be verified by on-site test methods. These test methods are currently not based on fundamental measurement science, but empirically developed to simulate some field situations. If the field situations become complicated, such as pumping long distances in hard-to-access areas, then the empirical tests lack predictive power. Developing a clear understanding of the material flow in complicated geometries and taking into account constituents characteristics and environmental conditions would reduce costs and increase sustainability.

4.1. Characteristics of future construction/repair (building or infrastructure) environment

The construction site of tomorrow should be highly automated for all tests and quality control. To achieve this degree of automation, reliable field tests must be developed to ensure the desired fresh properties and the consistency of concrete upon delivery. A more efficient, highly monitored construction site should result in shorter construction times, increased sustainability, and reduced cost. The future construction attributes identified during the workshop are listed below.

Delivery tests

- Measurements inside a truck to fully characterize the concrete delivered. Help the driver make informed decisions, while reducing field testing.
- Integrated scheduling, delivery method (pumping or truck), feedback to the plant, will reduce construction times, reduce cost, and save energy.
- Tighter constraints on delivery, placement, set-time, and finishing that would require early-age performance tests.
- Better scientifically-based qualifiers for the performance needs for a specific application, such as pervious or SCC.
- More testing acceptance based on fresh properties (e.g., water/cement (w/c), yield stress, viscosity).
- Precast/prefab: modular construction with factory controls.

Performance tests

[4] Knut Kasten, Putzmeister Group, slide presented at the workshop

- A reduced availability of high-quality materials, such as aggregates, will require more characterization of constituents in the field for quality control. Better characterization of constituents also would increase use of local resources, by allowing a wider range of qualified constituents.
- Sensor technology to monitor concrete from mixing to placement and through finishing. Sensors could be implanted in concrete and monitored wirelessly.
- Performance specifications for fresh concrete properties, to accommodate and facilitate the use of more complex material mixtures.
- Fully automated robust performance tests: less manpower and improved quality control.
- Automated real-time feed back loop to monitor desired rheological properties that would determine the need for mixture composition modification (e.g., addition of admixtures, additives, water).

4.2. Critical technologies to enable optimization of fresh cementitious material properties

The construction site today is highly dependent on empirical tests for quality control of the concrete delivered on-site. Often these tests are not related to fundamental properties that could be used to predict the performance of concrete in special applications, such as pumping and pervious concrete. Therefore, technologies need to be developed to obtain a fully automated construction site. Sensors and scientifically-based test methods would be paramount. A list of critical technologies was drafted by the participants.

- Plant testing
    - Material characterization (conformity and consistency), including aggregates (moisture content, shape)
    - Tests to determine the effect of constituents, environment, and process on rheological properties to ensure desired performance at the job site
    - Identification of relevant rheological properties for specific applications
    - Fundamental relationship between hardened performance and properties of the fresh concrete using either analytical or modeling tools. This would allow the development of performance-based specifications that would force the identification of key properties to optimize, assure consistency and uniformity, and adapt to available materials.

- Delivery testing and quality control at the site
    - Automated online testing using sensors to measure fresh concrete properties, either on the truck or arrival at the site
    - Developing efficient and effective methods for determining the performance characteristics, based on rheological science, needed for a concrete to be pumped
    - Feedback between site observation and the plant and delivery system.

- Types of instrument needed
    - Rheometers adapted for testing concrete from SCC to zero slump need to be calibrated using reference materials

- Sensors robust, with a fast response, that are easy to implement and use for measuring: rheological properties, air void system, set time, bleeding, sedimentation
- Modeling should be utilized for interpretation of test results, prediction of properties, ideally in real-time
- Empirical standard tests should be interpreted using rheological science through modeling. Measurements based on rheological science would provide data that can be used in modeling and prediction of flow in complicated geometries.

4.3. Broad technical and non-technical challenges to technology development and implementation

Instrumentation design from the laboratory to the job site is paramount to ensure a high performance of the concrete by guaranteeing the desired properties. This instrumentation would include sensors, rheometers, and other in-line devices that would record all properties of the fresh concrete during production, such as pumping, batching, mixing, and finishing. Testing methods, in order to be useful for predicting performance for a wide variety of applications, need to be based on fundamental rheological science. This could be a combination of testing and modeling. A list of critical challenges was drafted by the participants.

Non-technical challenges

- Education of the workforce: the lack of technology education will prevent the use of sophisticated devices
- Large resistance from owners and specifiers to relying on innovative devices until clear economic advantages are demonstrated
- Reduce the time from development to adoption by standards organizations

Technical challenges

- Identification of appropriate parameters to be measured for performance prediction
- Defining main characteristics for simulating concrete flow in pipeline: are yield stress and viscosity enough, or should other factors be considered, such as tribology, and friction?
- Development of in-line sensors or off-line devices to measure viscosity, bleeding, and sedimentation
- Sensors or devices need to be easy to use, accurate, and effective
- Pumping has few research projects in the world, but it is a widely-used delivery method of fresh concrete, yet pumpability is still an empirical science.

4.4. Critical measurement science (experimental or modeling) barriers

As described in Section 1.2, at the end of the discussion on the topics above (sections 4.1 to 4.3), the participants were asked to suggest “Critical measurement science barriers”. The suggestions were compiled in a list shown in Table 1 and, subsequently, they were asked to vote on their top four items (marked by an * in Table 1). The top three selections were further explored. The participants of the sessions were divided into three groups, with the task to complete the forms shown in Exhibit 4.1 to 4.6 (pages 31-37). Each participant was able to attend two sessions; thus, each breakout session had a group 1 and 2.

Several measurement science barriers were identified, and are listed in **Table 3**. Some of the top measurement science challenges include:

- Identification of the key parameters to predict and specify fresh concrete performance, such as pumping or batching
- Development of robust devices and tools to measure the fresh concrete properties, in-line, in real time while mixing or pumping, and also after placement.

Table 3: List of critical measurement science barriers for the "Field Tests Methods" break out session, ordered by number of votes overall. Notes: Group 1 is shaded in grey. The symbol ***** indicates forms that were completed, and are shown as Exhibit 4.1 to 4.6 (pages **31-37**).

Barriers	**Votes**
* What needs to be measured to predict performance?	11
* Performance based specifications	11
* Robust devices and tools- easy to use	9
* Quality control in real time – also after placement	8
* On-line measurements of rheological properties while mixing and pumping	7
Education K - College	7
* Zero slump concrete	7
Test methods correlate to real-life conditions/results. Rheological measurements must be sensitive to those mix design changes that adversely affect placing and consolidation of concrete	5
Predictive models – process/predict/monitor	3
Sensors and instrumentation	3
Better control of concrete delivered to site	1
Identification of plastic properties as indicators of durability performance	1
Real-time field sensors for water and air in concrete and their modeling	1
Measurement of particle shape and texture to predict workability	1
Ability to measure rheological parameters in the truck	0
Dry batching- how to predict workability for specific application	0

The participants were asked to rank the relative impact from low [1] to High [5] for each of the top selections from **Table 3** (marked with an *). Table 4 summarizes the results collected (see also Exhibits 4.1 to 4.6 [pages 31-37]). For each of the impacts, an average score was calculated to determine the top concern of the participants.

Table 4: Summary of the relative impacts for each of the selected top barriers for "Field Tests" breakout session.

Barriers	Reduction of cost of production	Improve sustainability	Improve service life	Support a healthy work environment	Facilitate quality control
* Robust devices and tools- ease of use	5	5	5	2	5
* Quality control in real time – also after placement	3	5	5	2	5
* In-line measurements of rheological properties while mixing and pumping	5	3	4	3	5
* What needs to be measured to predict performance?	3	4	4	3	5
* Zero slump concrete	3	2	4	1	5
* Performance based specifications	*No score provided due to lack of time*				
Average Score	***3.8***	***3.8***	***4.4***	***2.2***	***5***

4.5. Priorities for measurement science

Some top ranked measurement barriers identified under Section 3.4 (marked with an * in **Table 3**) were further explored by the participants. A summary is provided below, and more details are given in exhibits 4.1 to 4.6 (pages 31-37).

What needs to be measured to predict performance? This is a challenge, as most lab tests are not field-ready, and it is not clear how to link material properties and field performance needs. To resolve this challenge, it is paramount that new tests be designed and a better understanding of the impact of rheological parameters on performance be developed through research.

Performance based specifications : More applications of rheological models to predict performance parameters are needed. These parameters can then be specified in design and verified in the field. New standard test methods could then be developed or models could predict the performance.

Robust devices and tools- easy to use: The devices to characterize fresh concrete properties should be field usable, and durable, and use simple calibration requirements and easy interpretation of the results. These devices would allow better quality control in the field. This can only be achieved through a clear understanding of how to transfer technology from the lab to the field.

Quality control in real time – also after placement: New in-situ sensors that would allow fast and reliable characterization of the materials to be used in concrete are needed in the field. Modeling is essential for the interpretation of the results and monitoring of the quality control.

On-line measurements of rheological properties while mixing and pumping : To measure the rheological parameters more advanced sensors are required, along with more sophisticated algorithms to process the results for subsequent interpretation. These methodologies will not be used widely until standards and specifications also are developed. Standard reference materials are needed for calibration.

Zero Slump : These concretes are very stiff, so current rheological devices are not capable of characterizing their flow properties. Often, they are placed using vibration, despite the fact that no test methods or models exist to evaluate the effect of vibration on flow. Nevertheless, their field applications make them desirable for cost-effective special operations.

From **Table 4**, the relative impacts could be ranked in the following order:

1. Facilitate quality control
2. Improve service life
3. Reduction of cost of production AND improve sustainability
5. Support a healthy work environment

Exhibit 4: Field Test Methods

Information provided during the breakout sessions by the participants

4.1 What needs to be measured to predict performance?

4.2 Performance based specifications

4.3 Robust and easy to use devices and tools

4.4 Quality control in real time and after placement

4.5 On-line measurements of rheological properties during mixing and pumping

4.6 Zero-slump concrete

The information contained in the forms in this Exhibit are copied verbatim from the forms that the breakout sessions participants filled during the sessions. They are used to develop the roadmap.

Exhibit 4.1: Field test methods

What needs to be measured to predict performance?

Technology innovation or improvement to overcome the measurement science barrier

- Reduce cost and increase speed of testing
- Make lab tests into field tests
- Identify properties needed for specific applications
- Properties: degree of consolidation, bleeding settling, thixotropy, rheology segregation
- Start with end performance and work back to material properties
- Rank properties

Measurement Science Challenges and Potential solutions

Challenges *(2-3)*:	Potential solutions *(2-3)*:
Lack of fundamental understanding	Collaborative research
Test methods/equipment	Improve existing - interpretation, understanding, create new methods
Specifications acceptance criteria and standards	Fast track with others working with AASHTO, ASTM
Incentives	Tie to good specifications

Stakeholders and roles

Government (Federal, State)	Faster adoption of standards and specs
National Laboratories	Basic/fundamental research
Industry	New market opportunities that new standards create
Trade groups	Training; sharing best practices and benchmarks
Standard organizations	Faster adoption of standards
Academia	Fundamental research; independence; training
Other non-profits	Training
International	Pull technologies from other regions, leading technology becomes an export

Relative impacts *(Low [1] to High [5] impact value for each)*

- Reduction of cost of production 3
- Improve sustainability 4
- Improve service life 4
- Support a healthy work environment 3
- Facilitate quality control 5

Exhibit 4.2: Field test methods

Performance specifications

Technology innovation or improvement to overcome the measurement science barrier

- To address the first barrier, we need more applications of rheological models to predict performance parameters. These parameters can then be specified in design and verified in the field.
- To get this from the research lab to the design office and the field, we need to foster a consistent communication at all levels. Researchers need to go the field and see what people are up against.
- Our tests are mostly about prescription. The performance aspects have not been relied on before, so the tests are not very precise or repeatable under field conditions. They are not reliable enough to stand up in court.

Measurement Science Challenges and Potential solutions

Challenges *(2-3)*:	Potential solutions *(2-3)*:
Acceptance for use of models	Demonstration projects (e.g., US Army Corps of Engineers, FHWA)
Communication at all levels	Basic instruction to all Practical job site experience as requirement for engineering degree
More reliable performance tests	R& D (with verification in field and labs)

Stakeholders and roles

Government (Federal, State)	May need to sponsor demonstration projects; verification of test methods
National Laboratories	Modeling; development of test methods
Industry	Verification of test methods Implementation of test methods
Trade groups	
Standard organizations	Develop and improve standards
Academia	Modify engineering education to interface with field (field experience)
Other non-profits	
International	Exchange information

Relative impacts *(Low [1] to High [5] impact value for each)* – ***not provided by participants***

- Reduction of cost of production
- Improve sustainability
- Improve service life
- Support a healthy work environment
- Facilitate quality control

Exhibit 4.3: Field test methods
Robust and easy to use devices and tools

Technology innovation or improvement to overcome the measurement science barrier

- Devices and tools that survive the construction environment while at the same time taking accurate measurements
  - Long time between necessary calibrations
  - Tests should be able to give “quick” results of the property being measured
  - Minimal preparation and cleaning of test apparatus

<u>Measurement Science Challenges and Potential solutions</u>

Challenges *(2-3)*:	Potential solutions *(2-3)*:
Robust tools	Harden a rheometer for the field environment
Long calibration	
“Fast” tests	
Minimal preparation and cleaning	

<u>Stakeholders and roles</u> (no specific information was provided by the participants only X)

Government (Federal, State)	X
National Laboratories	X
Industry	X
Trade groups	X
Standard organizations	X
Academia	X
Other non-profits	X
International	X

<u>Relative impacts</u> *(Low [1] to High [5] impact value for each)*

- Reduction of cost of production 5
- Improve sustainability 5
- Improve service life 5
- Support a healthy work environment 5
- Facilitate quality control 5

Exhibit 4.4: Field test methods

Quality control in real time and after placement

Technology innovation or improvement to overcome the measurement science barrier

- Sensor-based material characterization
- Improvement of modeling systems to better predict behavior
- Sensors to measure mixture homogeneity
- In-situ sensors to avoid sampling
- Better knowledge and tools to fix or correct potential problems and deficiencies

Measurement Science Challenges and Potential solutions

Challenges *(2-3)*:	Potential solutions *(2-3)*:
Economic	Fully justify the benefits
Reluctance to accept new technologies	Education, incentives
Robustness/reliability	

Stakeholders and roles

Government (Federal, State)	Accept, enforce standards; funding
National Laboratories	Develop sensors
Industry	Use technology and accept it
Trade groups	Facilitate technology transfer
Standard organizations	Develop standards
Academia	Research
Other non-profits	
International	

Relative impacts *(Low [1] to High [5] impact value for each)*

- Reduction of cost of production 3
- Improve sustainability 5
- Improve service life 5
- Support a healthy work environment 2
- Facilitate quality control 5

Exhibit 4.5: Field test methods

In-line measurement of rheological properties like yield stress and viscosity during mixing and pumping

Technology innovation or improvement to overcome the measurement science barrier

- The measurement science barrier could piggy-back on the torque that can be measured from the mixing truck.
- To measure the viscosity and thixotropy, more advanced sensors are required, along with more sophisticated algorithms.
- The first step would involve the initial baseline measurement, and the algorithm would provide the feedback control loop. This technology requires calibration and validation of a wide range of mixture designs to ensure uniformity across the industry.

Measurement Science Challenges and Potential solutions

Challenges *(2-3)*:	Potential solutions *(2-3)*:
Calibration and validation	Specifications and guidelines Round robin testing program
Sensors: reliable and adequate	
Algorithm	

Stakeholders and roles

Government (Federal, State)	Funding, users of technology
National Laboratories	R&D technology plus information transfer
Industry	Validate, identify technology needs
Trade groups	Demonstrations, promotions of new technology
Standard organizations	Ensure standard procedure
Academia	R&D training
Other non-profits	
International	Consensus uniformity of applications of new technology

Relative impacts *(Low [1] to High [5] impact value for each)*

- Reduction of cost of production 5
- Improve sustainability 3
- Improve service life 4
- Support a healthy work environment 3
- Facilitate quality control 5

Exhibit 4.6: Field test methods
Zero-slump mixes

Technology Innovation or improvement to overcome the measurement science barrier

- Technology that is capable of measuring zero to negative slump rheology

Measurement Science Challenges and Potential solutions

Challenges *(2-3)*:	Potential solutions *(2-3)*:
Lack of design	Designing; modeling, investigating
Acceptance by users	Education and training

Stakeholders and roles (no specific information was provided by the participants only X)

Government (Federal, State)	X
National Laboratories	X
Industry	X
Trade groups	
Standard organizations	X
Academia	X
Other non-profits	
International	

Relative impacts *(Low [1] to High [5] impact value for each)*

- Reduction of cost of production 3
- Improve sustainability 2
- Improve service life 4
- Support a healthy work environment 1
- Facilitate quality control 5

5. Breakout Session on Grouts and Repair Materials

Grouts are utilized in a wide variety of applications, ranging from spraying of shotcrete to repair in potentially hazardous (nuclear power plants) or harsh (under water, high temperature) environments, pumping over long distance in underground structures, and in oil wells. This poses a challenge to the development of methodologies that can be used either to predict performance or for quality control. No empirically-based methodologies can account for all field situations. Currently, the industry is fragmented, and each application has adopted specific standards which could potentially benefit with improved communication with other branches of the industry. Therefore, methodologies based on fundamental measurement science that combine modeling and tests would enable prediction of performance for specific applications across industries, utilizing grouts and repair materials for their mutual benefit.

Repair materials' performance criteria are as varied as the substrate or situation in which they need to be applied. They have to flow into the crack or a hole and maintain shape on vertical surfaces. The rheological requirements are very diverse, and composition must be tailored to the application. This cannot be achieved if the links between constituents and performance is not established. These links should include factors such as modeling, qualifying test methods, and field quality control. The impact of the solution would be improved overall quality control, reduction in cost, and sustainability.

5.1. Characteristics of future construction/repair (building or infrastructure) environment

To ensure that the performance of fresh grout matches the application requirements, a combination of modeling, mixture evaluation, test methods, and sensors will be necessary. For instance, the prediction of grout flow through a realistic complicated geometry will be assured without costly trial and error testing. The environment, temperature, or underwater conditions also will be accounted for in the simulation. This will allow the selection of the fresh properties' parameters and the mixture design needed to ensure successful placement. Sensors and test methods will ensure that the characteristics required are met, e.g., measurement of voids in post-tensioned channel.

Grout materials (including repair materials)

- Use of grout or repair materials for aging infrastructure: challenging placement geometry (not easily accessible areas or in decommissioned nuclear power plants and mines), thin layers, small cracks and spaces, long distance flow requirements underground, potential void form in areas that are not visible
- Greater assured use of SCC, fiber-reinforced grout, UHPC, shotcrete, mortar, and lightweight materials for repair applications
- Assured controlled properties of repair materials that match substrate properties and bond well to substrate

- Ability to control rheology of grouts, slurries, repair materials, and oil-well materials using local, variable materials to ensure hardened performance, such as elastic material, bonding, fill form, and performance based properties
- Assured filling of post-tensioning tendon or duct
- Assured performance when using variable materials: e.g., inherent variability in local materials, use of manufactured vs. natural sand
- Control over large scales in time (e.g., many-day grouting operation as with the foundations of a large dam or waste disposal site) and space (e.g. long pipes, large-scale project)
- Assured pumping and placement based on rheology
- Routine use of SCC for mass concrete – this is a newer area; mass concrete is used in large quantities, and assured flow is required
- Lightweight aggregates used when desired (these can have different effects on rheology than do regular aggregates) for internal curing, matching substrate properties, improve performance
- Performance prediction of grout flow in saturated or underwater environments, and other special environments.

Tests methods and measurement science

- Tools and tests that measure parameters that determine performance
- Replacement of flow cones with rheology-based tests
- Automated in-situ control of proportioning and properties of grouts
- Embedded sensors that can detect local properties and performance, e.g., assured filling of grout within a post-tensioned tendon and detection that a form has been properly filled. Can inexpensive embedded sensors in the form or in the material provide this information?
- Automated way to control proportioning, rheology density, and air void analysis of grouts at construction site: in batch processes, solids are bagged and thus controlled, but there is a need for an automated way to control proportioning for continuous processes

5.2. Critical technologies to enable optimization of fresh cementitious materials properties

The vision of a fully automated operation for grout placement requires full understanding of the process from selection of materials to placement. The process demands tools that allow a better understanding of constituent interaction within a complex material, modeling to determine the rheological parameter values, and test methods to guarantee quality control. A list of critical challenges was drafted by the participants.

Material characterization

- Fine aggregate characterization (shape, size, angularity, texture) for effects on rheology to allow a wider range of aggregate sources to be used
- Better understanding of material interactions in complex materials, relation between lab and field shear rates

Test methods

- Automated, in-line systems to measure density, air content, water, and rheology so that local materials can be used and that the automated controls would adjust for variations in properties to ensure final performance
- Sensors needed to enable continuous processes to replace batch processes
- Still missing valid test methods to measure rheological properties of grout

Modeling

- Models and experiments are needed to determine effects of material variables on rheological properties such as air, SCM, fine aggregates, natural or manufactured sand, and local materials. This information would enable a fully automated system.
- Assess rheology needed for challenging repair applications, identification of appropriate performance criteria
- Identification of performance criteria for specific application

Placement

- Control of mixing, homogeneity of the grout
- Selection criteria of materials and mixture design to ensure desired air entrainment in post-tensioning (PT) grouts, stability of foamed oil well slurries and water retention.

5.3. Broad technical and non-technical challenges to technology development and implementation

The principal roadblock for performance-based use of grouts is the lack of standards. Standards cannot be developed without first identifying the key parameters that need to be measured. Grout is used in very diverse applications; therefore, characterization of the constituents (e.g., particle size and shape, chemical composition) and modeling are paramount to predict performance. Uniformity in fundamental definitions of the rheological parameters and how to measure it would allow more collaboration between various standards organizations and foster faster development of new technologies. A list of technical challenges was drafted by the participants.

Material characterization

- Characterization of particles, including but not limited to shape, size, and angularity. It is necessary to identify what is required to develop methods for performing the characterization

Test methods

- How to measure an air bubble distribution in fresh material
- Identification of precisely what needs to be measured – materials, length scale, time scale
- No standards for mixing on site

Modeling

- Lack of models to connect necessary rheological properties to performance needed for challenging repair situations

Standards and training

- Standardize definitions for grout, slurry, and mortars across all standards and codes. Slurry, grout, and mortar are similar mixtures of cement, water, and sand, but the names are used loosely and confuse the comparison between standards made in various application areas (e.g., oil-well slurries vs. post-tensioning wire ducts). There are prescriptive aspects to these definitions but they also should include performance aspects.
- Better interchange of standards and technology between American Petroleum Institute (API), American Concrete Institute (ACI), American Society of Civil Engineers (ASCE), (Post-tensioning Institute (PTI), and International Concrete Repair Institute (ICRI)
- Standardized training for SCC use in repair applications

5.4. Critical measurement science (experimental or modeling) barriers

As described in Section 1.2, at the end of the discussion on the topics above (sections 5.1 to 5.3), the participants were asked to suggest “Critical measurement science barriers”. The suggestions were compiled in a list shown in **Table 5** and, subsequently, they were asked to vote on their top four items (marked by an * in **Table 5**). The top three selections were further explored. The participants of the sessions were divided in three groups, with the task to complete the forms shown in Exhibit 5.1 to 5.4 (pages 45-49). Each participant was able to attend two sessions; thus, each breakout session had a group 1 and 2.

Several measurement science barriers were identified, and are listed in **Table** 5. Some of the top measurements science challenges include:

- Identification and measurement of the key rheological parameters to link flow performance to characteristics of constituents (e.g., SCM, type of cement, aggregate), taking into account the influence of environment, such as temperature, pressure, geometry constraint, and processing
- On-site quality control of performance of grouts, such as rheological properties, and air content
- Development of standards that could be used across various applications would increase harmonization between standards organizations. More efficient use of R&D resources by encouraging collaborative efforts between standards organizations in areas of common interest for test development.

Table 5: List of critical measurement science barriers for the "Grout and Repair Materials" break out session, ordered by number of votes overall. Notes: Group 1 was shaded in grey. The symbol ***** indicates forms that were completed and are shown as Exhibit 4.1 to 4.4 (pages 45-49).

Barriers	**Votes**
* Lack of information of relevant rheological properties affecting field performance (temperature, pressure, geometrical constraints, modeling science)	9
* On-site verification of materials (rheological) properties	7
* Variations of grout materials and their properties with processing and environmental conditions/time	6
Determine the effect of SCM on rheological properties of grout (measure or model). Characterization of SCMs to allow for their increased use in grouts, what material properties would limit their usage	5
* Key testing parameters, what properties should we be measuring and interpretating	5
In-line measurement/control of grout/mortar: density, water content, air content and distribution	4
Reduce barriers between all of the specifying agencies and increase consensus on testing protocols between these organization	4
Field performance tests to measure parameters necessary for a successful grouting operation: rheology, density, segregation, flowability	3
Measure relative quantity of grout constituents during mixing or pumping	3
Admixture incompatibility with SCM or cement: temperature influence, how to predict or detect before field usage	1
Better understanding of material interaction in complex systems (technical data, performance metrics)	1
Detection of large voids before grout/mortar sets (incomplete filling of space)	0
Measure air bubble size distribution in fresh concrete	0

The participants were asked to rank the relative impact from low [1] to High [5] for each of the top selections from **Table 5** (marked with an *). **Table 6** summarizes the results collected (see also Exhibits 5.1 to 5.4 [page 45-49]). For each of the impacts, an average score was calculated to determine the top concerns of the participants.

Table 6: Summary of the relative impacts for each of the selected top barriers for the "Grout and Repair Materials" breakout session

Barriers	Reduction of cost of production	Improve sustainability	Improve service life	Support a healthy work environment	Facilitate quality control
* Lack of information on relevant rheological properties affecting field performance (temperature, pressure, geometrical constraints, modeling science)	5	4.5	5	3	5
* Key testing parameters, what properties should we be measuring and interpretating	5	4	4	3	5
* Variations of grout materials and their properties with processing and environmental conditions/time	5	4	5	1	5
Field performance tests to measure parameters necessary for a successful grouting operation: rheology, density, segregation, flowability	3	5	5	1	5
Determine the effect of SCM on rheological properties of grout (measure or model). Characterization of SCMs to allow for their increased use in grouts, what material properties would limit their usage	3	5	5	1	2
* On-site verification of materials (rheological) properties	3.5	1	4.5	1	5
Reduce barriers between all of the specifying agencies and increase consensus of testing protocols between these organization	3	3	3	1	3
Average score	***3.8***	***3.7***	***4.4***	***1.3***	***4.2***

5.5. Priorities for measurement science

Some of top ranked measurement barriers identified under section 5.4 (marked with a * in **Table 5**) were further explored by the participants. A summary is provided below, and more details are given in the Exhibits 5.1 to 5.4 (pages 45-49).

Lack of information of relevant rheological properties affecting field performance (temperature, pressure, geometrical constrains, modeling science) : The grout properties for each application should be known to ensure performance based specifications. Modeling could be one way to ensure the link between the material properties and the application needs.

On-site verification of materials' (rheological) properties : Tools to measure at the job site do not exist, or are empirical and do not allow proper interpretation to ensure quality control. There is a clear need for on-site rheological testing tools and testing protocols to be developed.

Variations of grout materials and their properties with processing and environmental conditions/time : Grout is a complex system; therefore, simple information such as shear rate cannot be determined for a grout application. The knowledge of how materials behave in the application, taking into account temperature and pressure changes, is essential to relate material properties with performance

Key testing parameters, what should we be measuring or interpreting: There is a need for accurate capture of rheological measurements in both the laboratory and the field, free from artifacts. There is a lack of field measurement techniques, international standards and performance-based specifications

From **Table 6**, the relative impacts could be ranked in the following order:

1. Improve service life
2. Facilitate quality control
3. Reduction of cost of production
4. Improve sustainability
5. Support a healthy work environment

Exhibit 5: Grout and Repair Materials

Information provided during the breakout sessions by the participants

5.1 Lack of information of relevant rheological properties affecting field performance (temperature, pressure, geometrical constraints, modeling science)

5.2 Key testing parameters, what properties should we be measuring and interpretating

5.3 Variations of grout materials and their properties with processing and environmental conditions/time

5.4 On-site verification of materials (rheological) properties. What needs to be measured to predict performance?

The information contained in the forms in this Exhibit are copied verbatim from the forms that the breakout sessions participants filled during the sessions. They are used to develop the roadmap.

Exhibit 5.1: Grout and Repair Materials
Lack of information of relevant rheological properties affecting field performance (temperature, pressure, geometrical constraints, modeling)

Technology innovation or improvement to overcome the measurement science barrier

- Identify key rheological properties for each application
- Modeling of flow properties relevant to the field behavior/performance
- Develop specifications for equipment to perform the measurements

Measurement Science Challenges and Potential solutions

Challenges *(2-3)*:	Potential solutions *(2-3)*:
Lack of knowledge of properties affecting performance	More R&D relating the rheological properties to performance (bond, stability, filling ability, penetration, pumping, processing)
Development of ideal systems to build and verify models	Testing and verifying models (shadow performance, fill and flow, air void stability, pressure blending)
Actual testing of the key properties (rheology)	Develop required testing tools (rheometer or sensor)

Stakeholders and roles

Government (Federal, State)	Add value
National Laboratories	
Industry	Create commerce
Trade groups	
Standard organizations	X
Academia	Collaborative research
Other non-profits	
International	Export technology

Relative impacts *(Low [1] to High [5] impact value for each)*

- Reduction of cost of production 5
- Improve sustainability 4.5
- Improve service life 5
- Support a healthy work environment 3
- Facilitate quality control 5

Exhibit 5.2: Grout and Repair Materials
On-site verification of materials (rheological) properties

Technology innovation or improvement to overcome the measurement science barrier

- Tools and equipment must give accurate measurements, be able to test grouts, and be reliable for on-site use
- Standard test method is needed
- Proper interpretation of results
- Robust: not too sensitive to field conditions

Measurement Science Challenges and Potential solutions

Challenges *(2-3)*:	Potential solutions *(2-3)*:
Contains particles – normal analytical solution not applicable	Tools that can measure fluids w/particles
Analytical/numerical solutions available are limited	Powerful models/ collaborations

Stakeholders and roles (no specific information was provided by the participants only X)

Government (Federal, State)	X
National Laboratories	X
Industry	X
Trade groups	
Standard organizations	X
Academia	X
Other non-profits	
International	X

Relative impacts *(Low [1] to High [5] impact value for each)*

- Reduction of cost of production 3.5
- Improve sustainability 1
- Improve service life 4.5
- Support a healthy work environment 1
- Facilitate quality control 5

Exhibit 5.3: Grout and Repair Materials
Variations of grout materials and their properties with processing and environmental conditions and with time

Technology innovation or improvement to overcome the measurement science barrier

- Knowledge of flow conditions (e.g., shear rate); how materials behave in the process; temperature change, behavior under pressure
- Measurement to simulate field conditions
- Characterization of material properties and relationship with performance

Measurement Science Challenges and Potential solutions

Challenges *(2-3)*:	Potential solutions *(2-3)*:
Complex system, parameters (e.g., temperature, organic materials, pressure)	Better testing Better interpretation
Relationship between characterization and properties	Models and knowledge

Stakeholders and roles

Government (Federal, State)	X
National Laboratories	X
Industry	X
Trade groups	X
Standard organizations	X
Academia	X
Other non-profits	X
International	X

Relative impacts *(Low [1] to High [5] impact value for each)*

- Reduction of cost of production 5
- Improve sustainability 4
- Improve service life 5
- Support a healthy work environment 1
- Facilitate quality control 5

Exhibit 5.4: Grout and Repair Materials

Key testing parameters, what should we be measuring and interpreting?

Technology innovation or improvement to overcome the measurement science barrier

- Accurate capture of rheological measurements in both the laboratory and the field (free from artifacts)
- Limited field measurement techniques
- Lack of international standards
- Lack of performance specifications

Measurement Science Challenges and Potential solutions

Challenges *(2-3)*:	Potential solutions *(2-3)*:
Non-standard test Non-standard equipment Non-standard protocol	Develop standards, equipment, reference materials Identify artifacts (pug flow and wall slip, bleeding)
Industry acceptance of new tools and specifications	Development of value

Stakeholders and roles

Government (Federal, State)	X
National Laboratories	X
Industry	X
Trade groups	X
Standard organizations	X
Academia	X
Other non-profits	
International	X

Relative impacts *(Low [1] to High [5] impact value for each)*

- Reduction of cost of production 5
- Improve sustainability 4.5
- Improve service life 4
- Support a healthy work environment 3
- Facilitate quality control 5

6. Roadmap

6.1. Overview

A roadmap is something one uses to select a path starting from one point to reach a desired destination. There may be different criteria for the selected path; most scenic, shortest, fastest and so forth. In this case, our starting point is current construction practices, and our destination is the future of construction practices. What needs to be done to reach that destination defines the path we take. In this workshop, the participants were asked to imagine what a future concrete construction site could look like, and then find the critical technologies needed to obtain that futuristic construction site. From here, the participants were asked to list the broad technical and non-technical challenges to implement the critical technologies, and then to determine the measurement science needed.

In all three sessions, **the futuristic vision of the construction site** involved a fully automated site. The automation included scheduling the construction with tighter delivery of the concrete or grout based on early-age performance needs for the specific application. This would include the automatic characterization of all constituents of the concrete or grout, which would allow significant use of local materials and compensation for variation of the material properties into the mixture design. All the decisions should be performance-based. This would require knowledge of the influence of the environment (temperature, duration of application, substrate interaction for repairs) and of the application (type of placement, length of pumping, under water). Obviously, automation implies sensors and test methods to monitor the performance and the properties required for the application (pumping, zero slump concrete, repair) and type of cement-based materials used (SCM, grouts, concrete, shotcrete).

The **critical technologies** needed to have such a fully automated and performance-based construction site are:

- Materials characterization:
    - SCM and aggregate properties need to be known, quickly obtainable and possibly in-situ
    - Constituent interactions need to be measurable or predictable to establish compatibility
- Link composition to performance
    - Models to predict performance from constituents and field conditions (geometry of application, environment, placement method, curing)
    - Performance should include hardened properties and entities such as density, air content, and rheological properties
    - Guidance of selection criteria for materials and/or properties (air content, rheological parameters) needed to achieve specified performance.
- Quality control or test methods to measure the performance or other properties required. The measurements should be in fundamental units so that they can be used for calculation of performance or as verification of model outputs.

To achieve the critical technologies, the following **broad technical and non-technical challenges** were identified:

- Characterization of the constituents in such a fashion that the properties identified can be used to predict performance of fresh and hardened concrete and grouts.
- Determination of the fundamental parameters to be measured for specific applications. This would answer questions such as: Would a concrete be pumpable if the viscosity is in a certain range, or are tribology related factors dominant, or a combination of the two? A repair material needs to flow into a crack that has a specified shape and geometry. What characteristics should the material have? Would it be viscosity (what value), interaction with the substrate, or setting time?
- Sensors or test methods to measure the properties required and to verify the performance. For example, after flowing through a long pipe, the air content, entrapped air, sedimentation, and setting time should be determined in-situ for quality control.
- Sensors or test methods also should be used to characterize the constituents and the interactions among them, which are potential incompatibilities.
- Models that predict the performance from composition would be valuable, especially if they can relate the application to the performance and properties needed. "What if" scenarios could then be used to optimize the composition of the material needed for an application.

6.2. Critical measurement science barriers

The definition of measurement science is used in the context of creating critical-solution enabling tools—metrics, models, knowledge and standards – for the concrete construction industry. The measurement science barriers, missing tools needed to ensure sustainable concrete construction, were discussed in Sections 3.4, 4.4, and 5.4. This allowed the identification and prioritization of the barriers. In **Tables 1, 3**, and **5**, all the barriers are listed and ranked. Upon close examination and comparison of Tables **1, 3,** and **5**, the priorities for each breakout session yield the following three themes of measurement science needs:

- Sensors and test methods
- Better understanding or identification of key parameters to be measured to determine the fresh material properties
- Material characterization for the constituents of the concrete or grout.

From **Tables 2, 4** and **6**, the relative impacts of removal of the critical measurement science barriers, discussed above, could be ranked overall in the following order:

1. Facilitate quality control
2. Improve service life
3. Reduction of cost of production AND improve sustainability
5. Support a healthy work environment.

Therefore, if the relative impacts and the critical science barriers identified above are linked, the following statements could be drawn:

- Facilitating quality control requires development of sensors and test methods, on-line or in-situ.

- To improve the service life of a structure, a clear understanding or knowledge of the key factors affecting the materials behavior under field conditions (e.g., temperature, relative humidity) is paramount. A long service life cannot be achieved if the material (concrete or grout) is improperly placed and cured. Thus, the parameters to be monitored must be identified to ensure that the concrete or grout has the required long term performance.
- To reduce the cost of production and improve sustainability, the constituents of the concrete or grout need to be selected to ensure that the desired fresh and hardened material performance is obtained. Methodologies to characterize the materials both in-situ and in the laboratory need to be developed. These test methods would allow the detection of constituent incompatibilities and an increased use of new by-products.

Obviously, other combinations of the relative impacts and the critical measurement science barriers could be developed as well. For instance, sensors and test methods also could help in reducing cost and improving service life.

6.3. Summary of the roadmap

The purpose of the workshop was to develop a roadmap outlining the R&D, measurement science, and services needs of both private and public sectors to improve mixing, placement, consolidation, and finishability of cementitious materials. This roadmap also provides a framework for the development of new standards and codes for workability measurements of cement-based materials. Therefore, the following major areas were identified as critical for the futuristic vision of the concrete construction site to become a reality. They will constitute the pathway to achieve the construction practices of the future.

- **Standards to characterize the composition of by-products and other constituents**
    - Laboratory tests such as scanning electron microscopy, X-ray diffraction and ultrasonic systems
    - In-situ quality control tests to ensure that the material satisfies the specification upon delivery
    - Protocol for evaluation of new by-products

- **Determination of the key parameters for satisfactory performance for specific applications**
    - Pumping of grout or concrete
    - Repair materials in harsh environment
    - Zero slump
    - Underwater placement of concrete or grout
    - Influence of environment on flow of concrete and grout (temperature, duration of application)
    - Self-consolidating concrete (SCC)
    - Different placement methods, mixing and finishing

- **Sensors and test methods to measure at least one of the following properties**
    - Rheological measurement in fundamental units to replace the slump cone

- In-situ fresh properties such as density, air content, sedimentation, and air void distribution, sedimentation
- Process monitoring from batching to in-place concrete or grout
- Sensors to ensure quality control of the material (e.g., air content distribution, sedimentation) after placement and finishing

This is an ambitious roadmap that clearly cannot be achieved through the efforts of any one organization. Therefore, collaboration between all the stakeholders will be required. The national laboratories and academia could provide the fundamental research component. The standards organizations should facilitate and accelerate the adoption of new standards. The end-users, government (State and Federal), and industry, could facilitate the adoption of new technology by promoting their development, requesting the use of new methodologies (e.g., sensors, standards, by-products) in their specifications for new infrastructure projects. Trade groups could help demonstrate the validity of new technology by providing training, sharing best practices, and sponsoring research projects.

While the futuristic vision of construction practices, described by the participants, is an ideal that might never be fully achieved, as critical measurement science barriers are overcome and critical technologies are developed, construction practices will be significantly improved, and as a consequence, economic security, sustainability, and quality of life will be enhanced.

Appendix

A. List of attendees

Session A: New By-Products; Session B: Field Tests Methods;
Session C: Grouts and Repair Materials
Number after session for group 1 or group 2

Name	Company	Session A	Session B	Session C
John Gruber	Bechtel National		B1	C2
David Berg	Carmeuse Lime and Stone	A1	B2	
Philippe Francisco	CERIB	A1	B2	
Zen (Byong-Wa) Chun	Custom Building Products		B2	C1
David Goss	David Goss Consulting	A1		
Maria Guimaraes	EPRI		B1	C2
Ahmad Ardani	FHWA	A1	B2	
Jussara Tanesi	FHWA		B1	
Rick Meininger	FHWA			C1
Trey Hamilton	Florida	A2		C1
Novrita Idayanti	Indonesia Research Inst. of Science	A1		
Kejin Wang	Iowa State University	A1		C2
Euidam Jeong	Kangwon National University		B1	C2
Hyunju Kang	Kangwon National University		B1	C2
Laurent Barcelo	Lafarge	A1	B2	
John Casola	Malvern		B1	C2
Peter Taylor	National Concrete Pavement Technology Center		B (phone)	
Judith Terrill	NIST			
Nicholas Dagalakis	NIST			C1
Steven Satterfield	NIST			
William George	NIST			
Jake Phillip	NRC			
Colin Lobo	NRMCA	A2	B1	
Rachel Detwiler	PCI	A2	B1	
Knut Kasten	Putzmeister		B (phone)	
Vijay Gupta	RTI	A2		C1
Didier Lootens	SIKA	Phone		
Jiri "George" Grygar	TXI	A2	B1	
Dimitri Feys	University of Sherbrooke		B1	C2
Kamal Khayat	University of Sherbrooke		B1	C2
Ferron Raissa	University of Texas at Austin	A1		C2
Daman Panesar	University of Toronto		B2	
Scott Hart	US Army Corps of Engineers	A2	B1	
Brian Green	US Army Engineer Research and Development Center		B2	C1
Eric Koehler	Verifi	A2	B1	
Celik Ozyildirim	Virginia DOT	A1 (phone)		
Ara Jeknavorian	WR Grace	A1	B2	

B. Agenda

8:00 AM	Registration
8:30 AM	Introduction by Dr. Jonathan Martin, Materials and Construction Research Division Chief, Engineering Laboratory
8:50 AM	Introduction to workshop goals by Dr. Chiara Ferraris
9:15 AM	**Keynote Speaker**: Prof. Kamal Khayat, University of Sherbrooke, *"Relationship between Rheology and Performance of Cement Based Materials*"
10:15 AM	*Break*
10:30 AM	**Keynote Speaker**: Dr. Ara Jeknavorian, W.R. Grace, *"If I Only had a Rheometer: Limitations of the Slump Test to Adequately Qualify Concrete Workability."*
11:30 AM	*Lunch – Tables reserved in the west wing*
12:30 PM	**Breakout Sessions**
2:00 PM	**Breakout Sessions**
3:30 PM	*Break* - preparation of summary of breakout session (Facilitators)
4:00 PM	**Plenary closing**
5:30 PM – 6:30 PM	**Lab tours**
7:30 PM	***Dinner** – Buca di Beppo*

Breakout sessions

- Lecture Room A: New by-products (e.g., SCMs)
- Lecture Room B: Field test methods
- Lecture Room C: Test methods and grouts
- Lecture Room D: Test methods and repair materials