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Transportation Research Board's Influence on Concrete in Transportation Infrastructure

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Concrete has, is, and will continue to be a major component of the world's transportation infrastructure. It is used in a wide variety of applications, including pavements, bridges, retaining structures, and drainage facilities throughout the highway, maritime, airfield, and rail systems. The original Concrete Committee and subsequent Committees of the Transportation Research Board (TRB) have been studying and researching concrete since the beginning of the Highway Research Board (HRB) in the early 1920s. The members of TRB of the current four Committees comprising the Concrete Section have had a significant impact on concrete uses in transportation through their efforts in TRB and through their own workplace activities.

Over the decades, the mission of the Highway Research Board concrete committees has evolved to address the specific scientific and engineering challenges of the industry, implementing new technologies to address emerging needs and issues while still adhering to the original goal of designing, specifying and constructing durable concrete. Research promoted by the HRB/TRB has considered new and different materials, chemical composition and compatibility of admixtures and cementitious materials, aggregates durability and interaction within concrete, material batching and handling, construction techniques, curing practices, and environmental exposure conditions, to simply name a few contributions. This paper provides an overview of the contributions and accomplishments of the Committees comprising the Concrete

Section over the past 100 years, as well as provide details on current challenges being addressed and insight into future relevancy of the Section in promoting durable, sustainable concrete transportation infrastructure that will meet society's needs.

YESTERDAY

The mission of the Concrete Committees has been fundamentally the same since inception, assuring the durability and performance of concrete used in transportation infrastructure. Characteristics including but not limited to strength, freeze-thaw resistance, scaling resistance, shrinkage, and permeability are as important today as they were in the 1920's when the HRB was formed.

In the early days of the HRB, concrete was primarily composed of cement, aggregates (fine and coarse) and water. Research activities were reported by the Committee on Character and Use of Road Materials. The committee reported in the proceedings of the third annual meeting, in 1923, that "The strength of Portland cement concrete varies with the amount of actual solid material present in a given volume and also varies with the relative parts of this volume that are cement and aggregate. Other conditions remaining the same, the strength of concrete varies with the amount of mixing water. Concrete should be mixed with as little water as will yield a workable mixture for the use at hand. The grading of the aggregate has a decided effect upon the amount of water that may be used to yield a workable mixture, and consequently, upon the strength of the resulting concrete"*(1).* These facts, despite being published almost 100 years ago, remain at the core of modern concrete practice.

In the 1920s, advances in new materials, including *high alumina cements* resistant to acid and alkali waters and accelerators in concrete were the subject of committee work. Although high alumina cements are currently only used in special construction, accelerators have become a primary driver of the high early strength concrete we can achieve to support today's demand for rapid construction *(2). Alkali action* on Portland cement concrete, was a research focus area, aiming to produce carefully made, well cured concrete, rich in cement and of high unit strength and low permeability that could resist attack. The committee also reported on *aggregate research* and using repeated *freezing and thawing* and other types of accelerated tests to evaluate concrete with various aggregate. *Field control of concrete making* was also first reported in 1926, with reports indicating that field practices show the effects of the "water-cement ratio" upon the strength of concrete, and of the size and grading of particles upon economical design. The advantages of measuring granular materials by weight was also recognized *(3,4).*

In the 1930s alkali-silica reactivity (ASR) was recognized as producing significant degradation of concrete, which could be prevented through the use of low alkali cement. Other topics addressed by the committee included use of rail steel reinforcement, shale aggregates, and the magnesium sulfate soundness test *(5,6).* By 1932, the Committee on Materials and Construction had been established and concrete and concrete materials activities were reported henceforth by this committee. Reports completed in the 1930s included those addressing durability topics, such as the impacts of deicers on concrete, soundness of aggregates, abrasion resistance, and durability testing, as well as construction focused topics such as placing and handling, vibration and its effects on bond, early age heat, and curing *(6,7,8,9,10).* This decade saw the number of topics being reported on by the committee increasing, and many of the topics continue to be researched today.

In the 1940s (particularly after World War II) publications focused on concrete durability were abundant, laying the foundation for the coming Eisenhower Highway Interstate System and much construction in the post-war decades. The list of topics and breadth of their coverage of durability issues included *(11,12)*:

- *Temperature and Moisture Variations in Concrete Pavements,*
- *Measurement of Amplitudes in Paving Concrete Being Compacted by Vibration,*
- *Strength Development of Concrete Stored at Low Temperature,*
- *Readings of a Volumeter lnclosing Portland Cement Pastes and Linear Changes of Concrete,*
- *Effect of Calcium Chloride on the Water Requirements,*
- *Specific Weights and Compressive Strengths of Concretes Made with Plain and Treated Cements.*
- *Effect of Entrained Air on the Bond Strength of Concrete,*
- *Washington Method of Determining Air in Fresh Concrete,*
- *Durability of Portland Cement Concrete Determined by Primary Directional Freezing and Uniform Thawing,*
- *Determination and Use of the Dynamic Modulus of Elasticity of Concrete, and*
- *Weathering Study of Some Aggregates*
- *Dynamic Testing of Concrete with the Soniscope Apparatus,*
- *The Air Requirement of Frost-Resistant Concrete,* (a landmark report by T. C. Powers)
- *The Effect of Substitutions of Fly Ash for Portions of the Cement in Concrete, and*
- *Volcanic Aggregates*

Concrete pavements and the expansion of the highway system were topics of interest from the late 1940s and into the 1950s. After World War II, The American Association of State Highway Officials (AASHO), in conjunction with the HRB and the Public Roads Administration, pursued new systematic experiments assessing the service life of highway pavements through a number of road tests. The road tests were to be jointly financed by multiple state highway agencies and were to provide data to develop longer lasting pavements for increased traffic. The first of these road tests took place in 1950 and 1951 on a stretch of U.S. 301 in LaPlata, Maryland, to measure the impact of round-the-clock traffic on concrete pavements. The HRB administered this road test, which was financed by Maryland and 10 other eastern states, the District of Columbia, Public Roads Administration, truck manufacturers, and the HRB. The results from this and additional road test data established the relationships for structural designs based on expected loadings over the life of a concrete pavement *(14)*.

In 1950, the HRB began publishing information in Highway Research Board Bulletins, with new topics including thermal expansion of concrete, use of curing compounds, and new test methods including the Kelly ball for workability and Swiss Hammer for compressive strength *(15, 16).* Studies of precast and prestressed concrete construction were also of interest in the 1950's *(17, 18, and 19)*.

In addition to the road test reports, bulletins in the 1960s included research findings in the areas of physical and chemical properties and durability performance of cements and aggregates *(20, 23)*, admixtures, and concrete pavement construction (21). A report on fly ash in concrete was published, as interest in this emerging supplementary cementitious material increased *(22, 24, and 25)*.

In 1962, the Materials and Construction Department (MC) formalized Section B, Concrete Division, and established seven Committees. They consisted of:

- MC-B1: Performance of Concrete: Physical Aspects

- MC-B2: Performance of Concrete: Chemical Aspects
- MC-B3: Mechanical Properties of Concrete
- MC-B4: Curing of Concrete
- MC-B5: Chemical Additions and Admixtures for Concrete
- MC-B6: Basic Research Pertaining to Portland Cement Concrete
- MC-B7: Effect of Ice Control

At the same time as the new Committee structure, the HRB moved to publishing papers in Highway Research Records (HRR) in 1963, with the first such publication on materials inventories *(26)*. Other HRRs in the 1960s included topics such as properties of concrete *(27)*, freezing and thawing of concrete and use of silicones *(28)*, alkali-carbonate rock reactions *(29)*, fly ash *(30)*, and numerous aggregate research topics. In 1967, a report of particular interest was by Bryant Mather entitled "Stronger Concrete (31)."

In 1970, the committee codes were changes and the Concrete Section and Committees were renumbered with A2E00 and appropriate A2EXX designations respectively. The Committees continued to be active into the 1970s as the HRB changed its name to the Transportation Research Board to encompass multimodal activities. At this time the Transportation Research Record (TRR) emerged as a key publication featuring committee activities. TRRs published in the 1970s reflect the range of research performed during this decade, with prominent and emerging topics including concrete pavement applications (32, 33), reinforcement corrosion in concrete, permeability of concrete, shrinkage and cracking, and concrete durability. It was also in the 1970s when non-destructive testing procedures began to be reported and environmental considerations received additional research focus.

In the 1980s and 1990s considerable research was turning to rehabilitation of existing concrete. To effectively determine the durability of concrete in service, research continued to progress on the use of non-destructive and in-situ evaluation of concrete infrastructure. Nuclear density testing, radar, and statistical techniques to more effectively evaluate concrete were being researched. Measures to mitigate deterioration of concrete were being studied and implemented. Numerous research reports related to corrosion protection and mitigation, as well as mitigation of shrinkage and cracking were presented at TRB and included in TRRs. Investigations at various times for the impact of all the different types of fibers had on concrete cracking were reported into the early 1990s. At the same time was the research and development of shrinkage reducing admixtures.

The Strategic Highway Research Program (SHRP) in the 1990s reinforced the impact of ASR on concrete performance. Again, pozzolanic materials were incorporated into concretes and lithium had been identified has mitigating the impacts of ASR. Numerous tests were developed throughout the years and included petrographic examination of the aggregates proposed for use along with relatively rapid tests for expansion in mixtures containing potentially reactive aggregates.

Seeing significant advancement in 1990s research, several generations of concrete admixtures were developed with the aim of altering a wide range of plastic and hardened properties of concrete to achieve high-early-strength and high-performance concrete. Use of admixtures allowed a dramatic reduction in the water-cementitious materials ratio (w/cm) in the concrete mix, which in turn resulted in higher-strength and more-durable concrete. Significant research was also done on the development and use of cementitious and pozzolanic materials, such as fly ash, silica fume, and slag, to replace or supplement the cement content in the concrete mixture. These materials significantly improved the durability of concrete by reducing its permeability. Advances in concrete materials and use of alternative materials was becoming commonplace (34).

By the turn of the century concrete materials and construction technology was advancing at a rapid pace, resulting in significant changes to materials, placement techniques, and evaluation of concrete. Restructuring to best address modern challenges, in 2003 TRB again revised the Committee structure, renumbering the Concrete Section as AFN00 with the four specific committees of:

- AFN10, Basic Research
- AFN20, Hardened Properties
- AFN30 Durability of Concrete
- AFN40 Concrete Materials and Placement Techniques.

A special subcommittee was also developed in the 2000s when the Task Force on Nanotechnology-Based Concrete Materials (AFN15T) was established specific to research and implementation of concrete nanotechnology, an emerging sub-discipline offering potential improvements in a variety of performance areas.

TODAY

In the last decade, improving concrete materials and mixtures have become critical to the current and future focus on sustainability and resilience of transportation infrastructure. Making today's concrete more durable remains a key research area and the focus of much recent work. Many of the research findings of past years is now being combined to achieve the best possible concrete performance.

Other new technologies have emerged. Admixtures such as high range water reducers have been improved for use in concrete to produce self-consolidating concrete (SCC) for placement in hard to consolidate locations. Other materials such as silica fume and supplementary cementitious materials have been blended in different combinations and added to concrete to produce a variety of properties that are required for high strength, fast setting concrete for early opening of facilities such as concrete pavements for highway rehabilitation and airfield runway and taxiway repairs. Other current research initiatives include internal curing, accelerated concrete, alternative cementitious materials, optimized gradations, and mixtures designed using performance specifications (performance engineered mixtures).

Today it is not uncommon for five or more admixtures and cementitious and pozzolanic materials to be included in a mixture in addition to the standard concrete ingredients. Such complex concrete mixtures are significantly different from the simple mixtures produced in the early days of concrete development under the HRB. Yet many specifications and construction practices developed in accordance with basic research of the 1950s are still being applied to today's concrete materials and construction.

In addition, there are still unresolved problems and many unanswered questions associated with today's concrete. For example, excessive shrinkage and shrinkage cracking are being observed in many of the high-performance and high-strength concretes. These unintended consequences impact the durability of the concrete and thus tend to defeat the purpose of using such mixtures. Another important set of issues with today's concrete relates to the timing, duration, and type of curing, and the balance between curing time and speed of construction.

Still another issue is the knowledge gap among many practitioners with regard to the properties of individual concrete ingredients, how the various ingredients interact in the concrete mixture, and how to arrive at the optimum mixture for the type of application and level of exposure to adverse environments. An effective technology transfer plan is needed to convey to practitioners state-of-the art information and the latest research findings on materials and concrete properties.

Throughout the past decade, the concrete committees making up the Concrete Section of TRB have been strong contributors to successful Annual Meetings and provided many publications that have been in included in the Annual Compendium of Papers and in the TRR. The members of the Concrete Committees have collaborated as a section to hold effective and well-attended workshops, poster, and lectern-sections.

As shown in Table 1, there have been 238 contributions to the Annual Compendium of Papers and 207 contributions to the Transportation Research Record related to concrete materials. This demonstrates the wide range of topics that are championed by the concrete section. Eighty-four of the contributions have been deemed as Practice Ready Papers, a distinction from TRB that signifies a paper makes a major contribution to the solution of a current or future challenge. Nearly 20 % of the contributions have been selected as Practice Ready Papers, which helps to emphasize the Section's focus on implementable research. Furthermore, the contributions from the last decade have come from nearly 950 unique authors, illustrating that the research is from a wide-range of stakeholders, ranging from research institutions, industry representatives, and highway agencies.

Table 1: Recent contributions to the Transportation Research Board in topics related to concrete materials

Year	Contributions to the Annual Compendium of Papers	Contributions to the Transportation Research Record	Number Designated as Practice Ready Papers
2009	25	21	0
2010	23	55	4
2011	18	19	5
2012	21	22	13
2013	20	16	14
2014	24	18	12
2015	33	16	18
2016	21	13	12
2017	21	17	6
2018	32	10	0
TOTAL	**238**	**207**	**84**

Research Needs Statements (RNSs) are an important contribution from the concrete committees, and over the last decade sixteen research needs statements have been developed by the Committees, as shown in Table 2. In addition to helping to guide the direction and selection of workshop and session topics, nine of these RNSs have become funded projects under the NCHRP program. To become funded under NCHRP, the RNSs must been championed by an AASHTO committee or by a state transportation agency, and the high percentage of the RNSs that have been funded demonstrates the Concrete Section's focus on addressing challenges and developing technologies that would greatly benefit transportation agencies.

Table 2: Research Needs Statements developed by the Concrete Section from 2009 to 2019.

Committee	
AFN10	6
AFN20	3
AFN30	2
AFN40	5
TOTAL	**16**

TOMORROW

Concrete is continually evolving. 100 years ago when the HRB began, concrete was rather simplistic, comprised of sand, stone, cement, and water. Through the century a lot has changed to the raw materials, use of many additional types of materials, the knowledge of chemical interactions within concrete, and how best to handle, place, and cure concrete just to name a few. The challenge to the concrete community in the future is to promote and develop a thorough and comprehensive understanding of the properties of concrete and of its multiple ever-changing ingredients.

Many changes have occurred to the sources and production of cement, including the raw materials and fuel used and the grinding of the clinker. Today's cements are much finer than those of the 1950s and 1960s. Research in the basic properties of cement is needed to evaluate the effect of such properties as fineness, chemical composition on the heat of hydration, and on concrete shrinkage. Much like the internet was not envisioned 100 years ago, concrete of the future may contain significant materials yet to be envisioned; however, the trajectory of needs and development lets us imagine the future of concrete.

Newer concretes, referred to as meta-concretes, possess novel functionality and superior performance through advanced manufacturing processes such as nanotechnology. Modern concrete bears both structural and functional features, which has been intensively researched, but multi-functional features of concrete structures related to heat, light, sound, and vibration have not been systematically investigated. However, multi-functional meta-concrete provides improvement of traditional properties, such as mechanical and transport properties, and endorsement of the novel functionalities such as sensing, self-cleaning, and energy harvesting by taking advantage of nanotechnology in cement and concrete.

Compressive strength is important for sizing compression elements and our industry has made considerable progress in increasing the compressive strength of concrete, however, designers of long bridges and tall structures may also specify a high modulus of elasticity (MOE) to limit lateral deformations. An increase of MOE is often introduced by the increase of the compressive strength that always results in the increase of the price. Many research projects have studied reinforcing cement composites with carbon nanotube (CNT) and carbon nanofibers (CNF). When well dispersed [35, 36], a very small amount of CNT or CNF (less than 0.1% by weight of cement) can substantially improve the flexural strength, reduce autogeneous shrinkage, enhance piezoresistivity, and delay on set of corrosion of reinforcing bars.

The quality of concrete in service will always be affected by the environment, resulting a gradient porous microstructure from the surface, which in turn, accelerates the migration and deterioration processes of the surface. Surface treatment of concrete with various chemicals such as silane, siloxane and resin; inorganic agents, such as water glass (sodium silicate), have been widely used in research and practice [37,38]. Use of nanoparticle for surface treatment often encounters the issue of the penetration of nanoparticle into the concrete. Recently, silica-based nanomaterials have been used directly for surface treatment of hardened concrete, which shows the possibility of improving the quality of the surface by the design of the material and the treatment technique [39,40]. The findings indicate the potential of using nanosilica in reducing the transport properties of cement concrete. Furthermore, studies showed that the optimization of the microstructural and compositional properties of the surface concrete lead to the enhancement of the durability, such as calcium leaching resistivity [41], sulfate attack resistivity [41], chloride ion resistivity [42], carbonization resistivity [43].

Photocatalysis is the most commonly researched feature of concrete with the desire of air purifying, self-cleaning, etc. Semi-conductor, such as nanoTiO_2 has often been applied to endow materials with these properties. NanoTiO_2 has been added into concrete to make a self-cleaning concrete structure. However, the huge amount of nanoTiO_2 required to make concrete makes it impractical in large scale uses considering the price, therefore the surface treatment of concrete with nanoparticle is a more practical way. Nanosilica could act as binder of the functional nanoparticles with concrete matrix, and making the surface more photocatalytical. SiO_2 can reduce the release of photocatalysts on the surface of cement pastes after the simulated raining.

Heat is the most earth-abundant energy source that can be directly converted into electrical energy using the thermoelectric (TE) effect [44]. A good TE material should have high Seebeck coefficient and electrical conductivity to achieve higher power output, while the low thermal conductivity is desired to maintain the temperature difference across the material. To explore the feasibility of developing concrete with TE behaviors, limited research has been performed using steel or carbon fiber in concrete to attempt to increase TE effect of concrete [45-47].

Piezoelectric materials can directly convert mechanical energy into electricity or vice versa. These materials are widely used as actuators, sensors, transducers and energy harvesters. Concrete structures are widely exposed to mechanical loading, deflection and vibration, which provides abundant opportunity for piezoelectric based concrete materials for energy harvesting and sensing applications.

Despite recent advancements, developing meta-concrete with unique properties (thermal, electrical, optical and magnetic) are still in their infancy. Many scientific and technological challenges need to be addressed in future studies. The scientific and technological importance of developing meta-concrete is evident, and their potential impact is remarkable to the design, construction and testing of future infrastructures. Fortunately, the rapid revolution in nanotechnology and processing techniques are opening up exciting venues to create meta-concrete through additive manufacturing, modular construction, and artificial intelligent design and construction.

While nanotechnology will significantly impact concrete performance for the foreseeable future, we must still be cognizant of the other more macro materials, construction practices, and testing methods that will impact the future performance of concrete. Concrete additives are rapidly changing. There is a need to evaluate the basic properties of the various admixtures, fibers, and cementitious and pozzolanic materials. Issues associated with the use of these materials in concrete, including setting time, plastic and hardened shrinkage, and the need for extensive curing should be investigated. Future research should produce a catalog of the types and dosage or proportion of these materials in concrete, and the specific level of performance and strength achieved with each.

The industry has moved toward internal curing of concrete. The use of high cement content, silica fume, and low w/cm ratio has made the concrete denser but more prone to shrinkage and thermal cracking. Curing compounds and even surface curing are no longer effective in preventing all types of shrinkage or cracking. New materials and methods of curing will certainly be developed in the future.

New construction practices continue to be developed as concrete characteristics and applications change. Accelerated construction will become more prevalent and methods to place and cure concrete in a timely manner will need to be developed. 3D printing, while still in its infancy, is rapidly growing to provide faster and safer construction using concrete. These new materials and methods will require new tests for concrete to assure consistency and quality during placement and to assure durability for 75, 100, or more years of service. New technologies are needed to enable testing of the workability and air content of mixtures in a nonintrusive manner. Perhaps a nonintrusive device will be developed for measuring the concrete workability from the concrete stream during discharge. In addition, the concept of 28-day strength may become obsolete as an acceptance requirement. Concrete mixtures of the future may reach their ultimate strength in hours rather than days. This accelerated development of strength may alter the microstructure of the concrete. Research will be needed to better understand the physical and chemical properties of hydration, as well as the extent of microcracking and volume change in the paste matrix. We are already seeing alternative cementitious materials being developed and such products may require entirely new test methods.

The next century offers great opportunities for extending the life of the transportation infrastructure. An important focus of our vision of the future of concrete should be on the longevity of pavements and structures. The life of bridges, pavements, and supporting concrete structures should at least double in the next century. This life extension will occur through the improved quality control of materials, methods, and design and construction practices. Technical innovations in the production, transport, placement, finishing, and curing of concrete will play a role in reducing the variation of properties from one batch of concrete to another. The emphasis in the early part of the next 100 years will be on long-term performance standards, materials, optimization techniques, the science of chemical admixtures, and advances in understanding of aggregate-paste transition zones. Beyond that we cannot be certain but we are assured that the expertise, knowledge, and dedication of the people in the concrete industry that participate in the Concrete Committees of the Transportation Research Board will play a significant role in future advancements.

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