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Comparative Analysis of Rapid Chloride Penetration Testing for Novel Reinforced Concrete Systems

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Submitted by:

Matthew J. Bandelt, Ph.D., P.E.
Associate Professor

Matthew P. Adams, Ph.D., F.ACI
Associate Professor

Seyed Masoud Shirkorshidi
Graduate Research Assistant

New Jersey Institute of Technology
University Heights
Newark, NJ 07102

External Project Manager
Yong Zeng, Senior Engineer and Sadime Absolam, Assistant Engineer
New Jersey Department of Transportation

David J. Goldberg Transportation Complex
1035 Parkway Avenue Trenton, NJ 08625

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16. Abstract

This report provides a summary of rapid chloride penetration testing (RCPT) of ductile concrete materials. The report first introduces a range of ductile concrete materials with varying fiber types, fiber lengths, mechanical properties, material constituents, and durability performance. These materials represent various systems that have been used in several transportation projects to improve the durability of transportation infrastructure. Next, an overview of the RCPT testing program is provided and results are presented with comparisons to representative baseline concrete mixtures used in the industry today. The results show that RCPT experiments may not be indicative of resistance to chloride movement since the experiments measure charge passed, rather than chloride ingress. Recommendations for the need to calibrate RCPT results with long-term chloride ponding experiments are discussed.

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1. Introduction

1.1 Background

Ingress of chlorides through concrete to the surface of steel reinforcement is one of the main causes of corrosion initiation [1]. Several factors, such as concrete quality and permeability, can affect the penetration rate of chlorides and the corrosion performance of reinforced concrete [2]. A denser microstructure can decelerate the chloride penetration and limit oxygen access, while more porosity can accelerate the penetration of chlorides, oxygen, and corrosion initiation [1,3,4].

Chloride penetration experiments can evaluate the chloride penetrability of concrete systems and help to predict corrosion performance. Various methods include ponding according to AASHTO T259, and rapid chloride penetration tests (RCPT) such as ASTM C1202 and NT Build 492 are used to measure the chloride penetration and diffusion coefficients in ductile systems [5–7]. The chloride ponding test is long-term testing. Rapid chloride tests can decrease the testing time to a few hours. Due to the shorter testing time, rapid chloride penetration tests have been of more interest recently. However, these tests are not calibrated for new and emerging concrete systems.

One class of emerging concrete materials are referred to as high-performance fiber-reinforced concrete [8], which are broadly classified as cementitious materials with a high level of ductility due to the incorporation of short, randomly oriented fibers. Due to the dense microstructure and enhanced mechanical and durability specifications, these ductile concrete systems are expected to have more chloride penetration resistance than traditional concrete materials. One important aspect that must be considered, however, is that the presence of fibers in these systems and the incorporation of various supplementary cementitious materials can affect the RCPT results, thereby making it an improper method to evaluate the chloride penetration performance of ductile concrete systems. This project investigates the chloride penetrability of three types of ductile concrete systems alongside two other concrete systems to provide more information on the chloride resistance of ductile concrete systems and the use of RCPT as a method to evaluate ductile concrete systems.

1.2 Research Objectives

The overall objective of this study is to explore the behavior of advanced concrete materials to improve the service life of infrastructure. This research is part of a larger on-going study related to the use highly ductile concrete materials in service life applications of transportation infrastructure. To meet this objective, the researchers have explored systems identified in the literature that improve the mechanical and permeability resistance compared to ordinary concrete materials. In this study, the use of RCPT as a means of assessing chloride penetration in ductile concrete systems is explored.

1.3 Organization of Report

This report is organized into six sections, including this brief introductory section. The major topics of each section are summarized below.

Section 2 provides a summary of ductile fiber-reinforced concrete materials. Mixture specifications and constituents are summarized, and their mechanical behavior is discussed.

Section 3 provides detailed information on the different materials used in this project in each concrete system.

Section 4 discusses the experimental scope of the study, including the mixture design of each concrete system, the experimental plan for mechanical evaluation and chloride penetration resistance of concrete systems

Section 5 summarizes and analyzes the mechanical and chloride penetration testing results. This section also provides analysis of the results in detail and describes the most important observations.

Section 6 summarizes the conclusions of this study.

2. Ductile Concrete Systems

2.1 Overview of Ductile Concrete Materials

Figure 1 shows representative mechanical behavior of normal and ductile concrete systems in compression and tension. The ductile concrete systems shown in Figure 1 are described in more detail in the proceeding sections; however, the systems shown in this figure refer to ultra-high-performance concrete (UHPC), hybrid fiber-reinforced concrete (HyFRC), and engineered cementitious composites (ECC). As can be seen, ductile concrete systems generally have high strain capacity in tension and compression. More strain capacity results in material toughness, ductility, and energy absorption capacity in ductile concrete systems. Also, ductile systems have greater flexural strength and crack resistance. Ductile concrete systems show different cracking behavior compared to normal concrete and allow multiple cracks to form before localization.

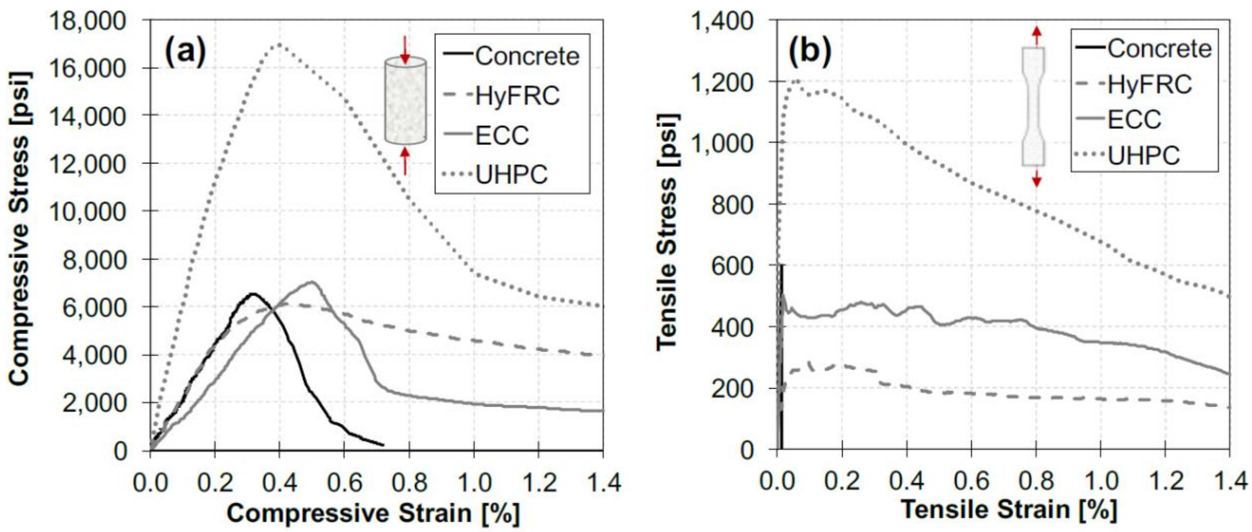

Figure 1: a) Compressive behavior of ductile and normal systems, b) Tensile behavior of ductile and normal systems [9–11]

The ductility described in Figure 1 is achieved through short, randomly oriented fibers that restrain crack openings and allow for the system to have a cracking response in which multiple cracks form as will be discussed in the proceeding sections. Among ductile concrete systems, the mixture design and fiber selection can result in different durability and mechanical responses. UHPC has a denser microstructure than ECC and HyFRC, and has a higher tensile and compressive strength compared to other ductile systems. ECC consists of only fine particles, has a dense microstructure, and the fiber-matrix interaction is designed to achieve the highest level of tensile ductility. Since HyFRC generally contains coarse aggregate, it often has a microstructure similar to that of normal concrete. These changes in microstructure and mechanical response of ductile concrete systems affects the durability response of each system.

2.2 Ultra-high-performance Concrete (UHPC)

Ultra-high-performance concrete (UHPC) is a type of concrete with a compressive strength greater than 150 MPa and tensile strength of more than 7 MPa [12–19]. UHPC shows a ductile behavior in tension [20–25]. Some of the key parameters in a UHPC design include a low water-to-cement (w/cm) ratio, replacement of coarse aggregates with well-graded fine sand generally ranging between 150 to 600 µm and ground quartz with a particle size of 0.1 to 100 µm, using a large amount of pozzolans such as silica fume and fly ash, and a high dosage of high range water reducer admixtures [16,20,22,24,26–28]. The enhanced homogeneity provided by replacing coarse aggregates with very fine sands results in low porosity and improved mechanical behavior and durability [27]. Using very fine aggregates and silica fume decreases porosity, and fibers are added to the UHPC to increase ductility [27]. The fibers can be effective in arresting crack propagation. According to the literature, two percent by volume is the mostly used amount of fibers in many research and toughness improves [14]. Using hybridization of fibers (i.e., a combination of different types or sizes of fibers) can improve the mechanical properties of UHPC systems [26].

The main deficiencies in UHPC systems include brittle post-cracking behavior because of the high amount of binder and micro-cracking due to autogenous shrinkage [12]. High strength, low permeability, high toughness and durability, high abrasion resistance, high freezing and thawing resistance, and increased load-carrying capacity are the most important benefits of UHPC [12,24,29–33]. Due to UHPC's beneficial properties, it has several applications in high-rise buildings, long-span bridges, rehabilitation, offshore oil platforms, and blast-resistant structures [13,20,27,29,34]. It is also used for joints, precast pre-stressed girders, and bridge decks [14,35,36]. Using UHPC has been proposed to reduce or eliminate reinforcing bars in structural elements and decreases the self-weight by more than 70% with substantial reductions in crack widths [35]. Also, the resistance of UHPC to chloride penetration makes it a good choice for using in chloride exposed environments such as marine structures to prevent reinforcement corrosion [37–39].

2.3 Hybrid Fiber Reinforced Concrete (HyFRC)

Hybridization is a technique of using different types of fibers for maximizing the advantages of various fiber properties [40]. Hybrid fiber-reinforced concrete (HyFRC) uses multiple types of fibers to take advantage of their properties. There are different types of hybridization including:

- Hybridization of fiber mechanical response: The fiber stiffness is the main variable in this form of hybridization. Fibers made of steel or Kevlar with high modulus of elasticity can effectively bridge microcracks, while some fibers with low modulus of elasticity, such as polypropylene, could be used at larger crack widths [40–43].
- Hybridization of fiber size and anchorage: In this category, fibers are divided into microfibers (less than 15mm in length) and macrofibers (greater than 15mm in length) [44]. Microfibers are effective at bridging cracks at an early age that yields increased strength and macrofibers are used to increase post-cracking toughness [40–43].
- Hybridization of fiber function: Fibers that are used to enhance early age properties like drying shrinkage and workability (usually polypropylene) and fibers are used to improve the mechanical properties (usually steel fibers) [40–43,45].

Using hybrid fiber systems has numerous advantages. Strong and stiff fibers can improve the stress at first cracking and ultimate strength, and flexible fibers can enhance the post-cracking strain capacity. Small microfibers bridge microcracks, which lead to higher tensile strength, and large nacrifibers can arrest the propagation of macrocracks and improve the toughness. Hybridization of different lengths of a specific type of fiber can help bridge microcracks and prevent propagation of macrocracks; hybridization of different types of fibers improves the strength and ductility of concrete. Also, durable fibers can increase the strength and/or toughness in aged concrete [42,43]. Fibers also can be divided into metallic (e.g., steel) and nonmetallic (e.g., polymeric) fibers. Metallic fibers improve the energy absorption and control macrocracks due to the high modulus of elasticity and length of steel fibers [46,47]. High amounts of steel fibers can decrease concrete slump significantly [47,48]. Different types of nonmetallic fibers including polyvinyl alcohol (PVA), polyethylene (PE), polypropylene (PP), and polyolefin (PO) fibers have been used in HyFRC. Nonmetallic fibers delay microcrack formation and prevent early age and shrinkage cracks [46,47]. Nonmetallic fibers have good dispersion in concrete and usually there are fewer workability concerns for nonmetallic fibers [48]. Using HyFRC can enhance flexural strength and toughness, ductile performance, matrix stiffness, crack resistance, energy absorption, durability, serviceability, ultimate limit state performance, post cracking stiffness, crack tortuosity, and permeability [40,41,45,49–51].

2.4 Engineered Cementitious Composites (ECC)

Engineered cementitious composites (ECC) are an ultra-ductile micro-mechanically designed cementitious composite that were developed in the early 1990s. A typical mixture design of ECC contains a high cement content (~1000 kg/m^3), fine sand (finer than 200 μm), fly ash, water, admixtures and short, randomly oriented polymeric fibers (e.g. polyethylene, polyvinyl alcohol) typically between 1.5 to 2% by volume [52–54]. Using hybridization of fibers can improve the mechanical properties and corrosion resistance of ECC [55,56]. The ultimate tensile strain of ECC is between 3 and 7 percent according to the coupon tensile specimens which is 350 to 500 times greater than that of ordinary concrete [52,53,57–63]. The ultimate tensile strain range of ECC can change when the tensile specimen size changes [64,65]. The compressive strain capacity of ECC is 0.4 to 0.65 percent, approximately two times greater than fiber reinforced concrete [61,63,66]. The high tensile strain capacity of ECC is due to the macroscopic strain-hardening phenomenon after first cracking accompanied by multiple micro-cracking [52,57,67]. With increasing load, crack widths steadily increase to approximately 60 μm at around 1% strain. After this strain, crack widths tend to remain constant while the number of cracks increases until a dominant crack forms which induces softening of the material [52,54,57].

The strain hardening behavior of ECC is dependent on the fibers, matrix, and interface as composite material constituents. Researchers used micromechanics-based theories to design mixtures that provide bridging action of fibers. Using steady-state crack analysis, steady-state propagation of microcracks, strain hardening behavior, and consequently composite tensile ductility of ECC can be achieved. Due to the unique behavior of ECC, it is expected that the use of ECC can have a direct impact on infrastructure safety, durability, and productivity in the construction industry. Higher energy absorption and a more stable hysteresis loop can be observed in ECC specimens under cyclic loading. According to Li (2003) at a high level of drift, ECC showed no spalling while normal concrete specimens experienced spalling and loss of concrete cover [57]. These results show the high deformation capacity of ECC compared to normal concrete despite the elimination of stirrups [57].

ECC has beneficial properties such as the ability to reduce or eliminate shear reinforcement, compatible deformation with reinforcement, synergic interaction with fiber reinforced polymer (FRP) reinforcement, good durability, high ductility, high damage tolerance, and tight crack width control [57,67–69]. Considering these properties, ECC has the potential to be used in structures requiring durability under severe loading conditions and harsh environments, and can enhance construction productivity. ECC has been used in bridge decks, pavements, as repairing material and infrastructure exposed to harsh environmental conditions [52,58,70–74].

3. Materials

Five different types of concrete systems, including a high-performance concrete (HPC), self-consolidating concrete (SCC), hybrid fiber reinforced concrete (HyFRC), Engineered cementitious concrete (ECC), and ultra-high-performance concrete, are being investigated. Other than UHPC, which was a pre-bagged product, a wide range of materials were used in this study as described in the following subsections.

3.1 Aggregates

Two different coarse aggregates with a nominal maximum size of 3/4 inch for HPC and SCC and 3/8 inch for HyFRC were used. Regular sand with a fineness modulus of 2.75 was used in HPC, SCC and HyFRC. Very fine sand with the nominal maximum size of 300 µm (#50) was used in the ECC mixture. The sieve analysis of sands used in this study is shown in Figure 2.

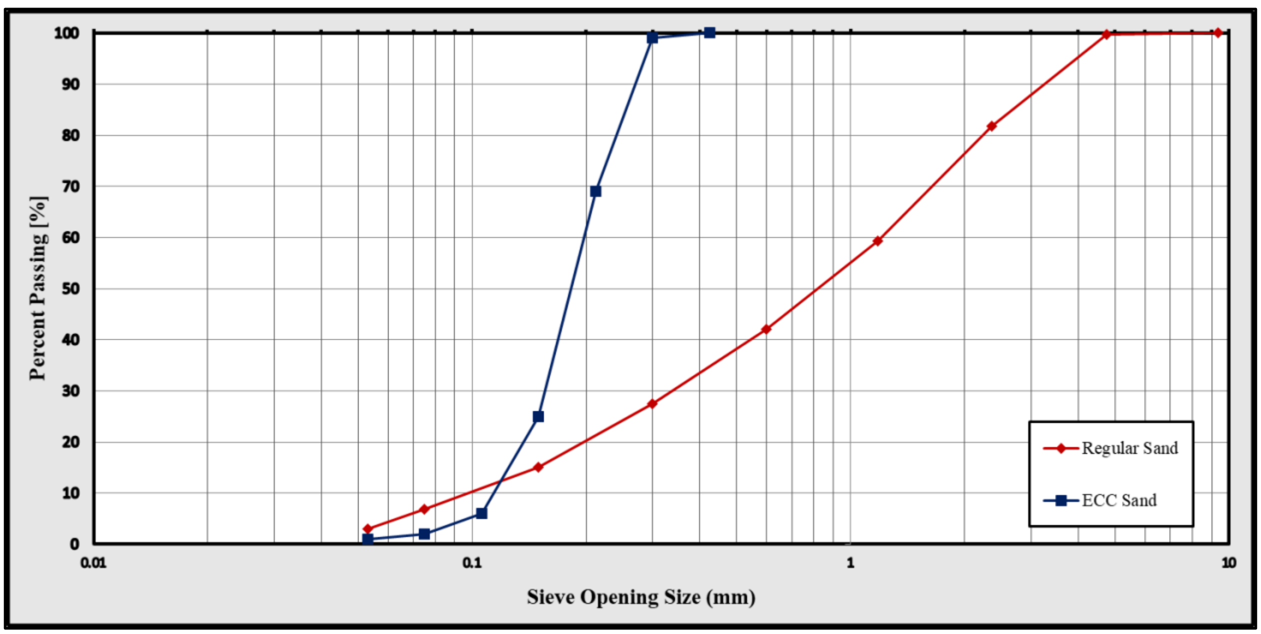

Figure 2: Sands sieve analysis

3.2 Cement and Supplementary Cementitious Materials (SCMs)

A Type I portland cement was used in all systems. Different types of SCMs based on mixture designs were used in each system. Slag and micro-silica were used in the HPC mixture design. Fly ash class F was the SCM used in ECC and HyFRC, and slag was used in SCC mixture.

Detailed information about the content of each material in different mixtures will be provided in the next section.

3.2 Admixtures

Four different types of high-range water reducers, two different types of air entertaining agents, and two different types of viscosity modifying agents were used. Glennium 7710, Viscocrete 6100, Glennium 3030NS, and ADVA 190 were used in order in HPC, SCC, HyFRC, and ECC mixtures in calibrated dosages. Master Air AE 90 and Sika Air were the air-entraining agents in HPC and SCC mixtures. Rheomac VMA 362 and VMAR-3 were used as viscosity modifying agents in HyFRC and ECC. A Premia 150 admixture (High range water reducer and accelerator) was used based on the recommended dosage of the supplier for pre-bagged UHPC.

3.3 Fibers

Two different types of steel fibers and one type of PVA fibers were used in this project. RECS 15 PVA fibers with a length of 8 mm, aspect ratio of 200 and tensile strength of 1600 MPa were used in ECC and HyFRC mixtures. A hooked Dramix© 3D 55/30BG steel fiber with a length of 30 mm, aspect ratio of 55 and Tensile strength of 1100 MPa was used in HyFRC. The steel fibers used in UHPC were straight fibers with a length of 13 mm, aspect ratio of 65, and tensile strength of more than 2000 MPa. Figure 3 shows different fibers used in this project. The fiber dosage in each concrete system is summarized in the next section.

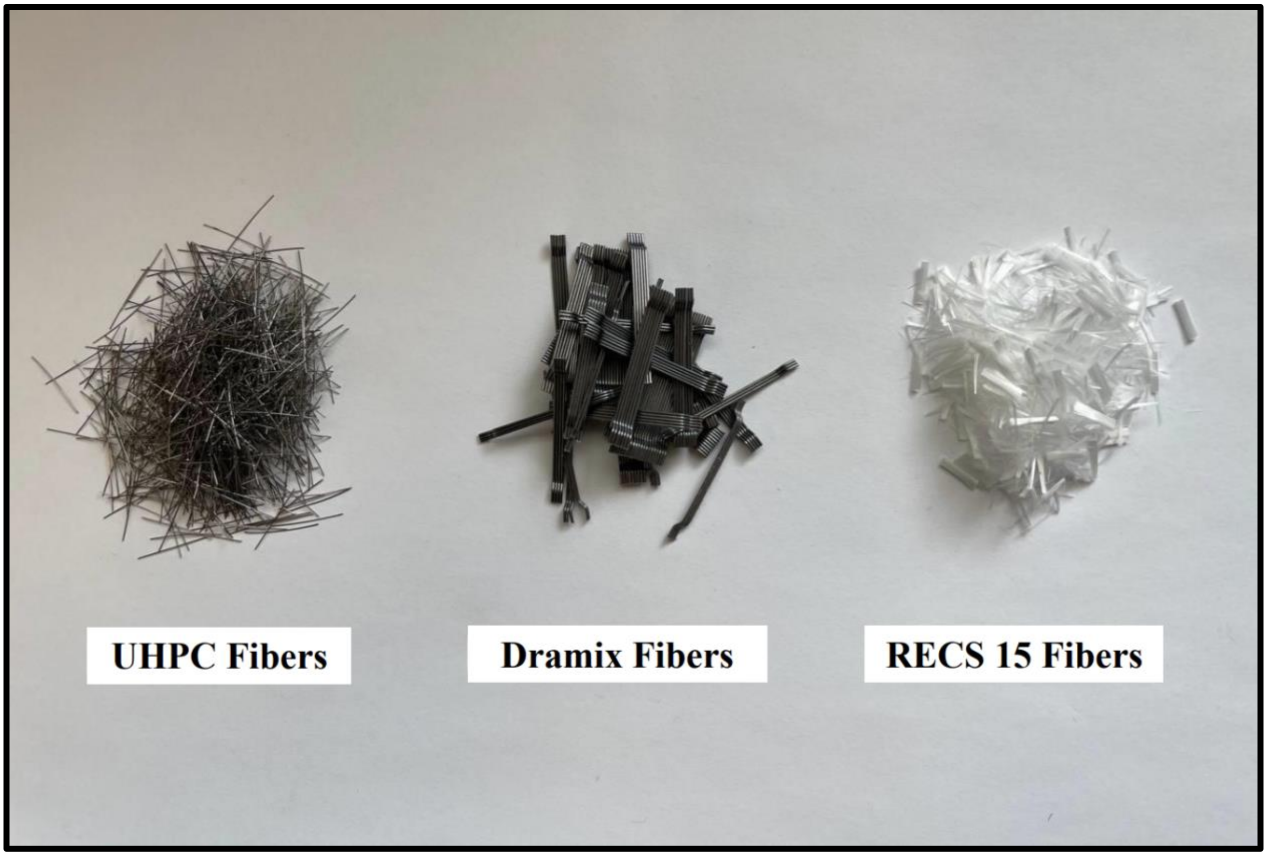

Figure 3: Steel and PVA fibers

4. Experimental Program

4.1 Mixture Design

The experimental phase was divided into two main parts. The first part was to find the optimum mixture design for each concrete system based on the available and local materials. Five different types of concrete, including a high-performance concrete mixture (HPC) with compressive strength of more than 8000 psi, a self-consolidating concrete with a compressive strength of 7000 psi, and three ductile concrete systems, including a pre-bagged UHPC (JS 1000 from Ductal Lafarge including two percent by volume of steel fibers), self-consolidating HyFRC (SC-HyFRC) and ECC were cast. Table 1 summarizes the mixture design and constituents of each concrete system except for UHPC, which was a pre-bagged product.

Table 1: Concrete systems mixture designs

ECC (/Cement Ratio)		SC-HyFRC (Kg/Cu.m)		HPC (lbs./Cu.Yard)		SCC P (lbs./Cu.Yard)	
Cement	1	Cement	397	Cement	435	Cement	473
Fly Ash	1.2	Fly Ash	131	Slag	240	Fly Ash	157
ECC Sand	0.8	Coarse Agg (3/8")	418	Microsilica	25	Sand	1330
Water (W/cm)	0.68(0.31)	Sand	1044	Sand	1253	Coarse Agg. (3/4")	1707
HRWR	0.007	Water	237	Coarse Agg (3/4")	1834	Water	252
VMA	0.018	HRWR (ml/100 kg binder)	880	Water	250	HRWR	as needed
PVA Fiber Volume %	2	VMA (ml/100 kg binder)	2200	HRWR	as needed	Air Entraining	as needed
		Steel Fibers	1.3	Air Entraining	as needed		
		PVA Fibers	0.2				

Multiple trials were evaluated to quality control the mixture designs and calibrate admixtures content in different mixtures. A series of compression tests according to ASTM C39 were conducted to evaluate the compressive strength of each concrete system [67].

4.2 RCPT Testing Protocol

The second part of the experimental phase evaluated the chloride penetration resistance of concrete systems. A series of rapid chloride penetration tests (RCPT) according to ASTM C1202 were done to evaluate the chloride penetration resistance of systems [68]. A series of four inch diameter cylinders were cast and cured for 56 days in a 100 percent moisture curing room and temperature of 23.0 ± 2.0°C [73.5 ± 3.5°F]. Samples with a depth of 50±3 mm were cut from cylinders, epoxy coated, and prepared according to ASTM C1202 before testing in the cells.

Figure 4 shows a series of cut and epoxy coated specimens before testing. Testing cells were assembled and filled with 3% NaCl and 0.3 N Sodium Hydroxide solution. A Giatech Perma test setup was used to run the RCPT. Figure 5 shows the test setup used for rapid chloride penetration testing of concrete systems. The cells were connected to the control panel using lead wires. The current was measured with applying 60 ± 0.1 V across the cells every minute. The test was terminated after six hours.

Figure 4: Cut and epoxy coated specimens before testing

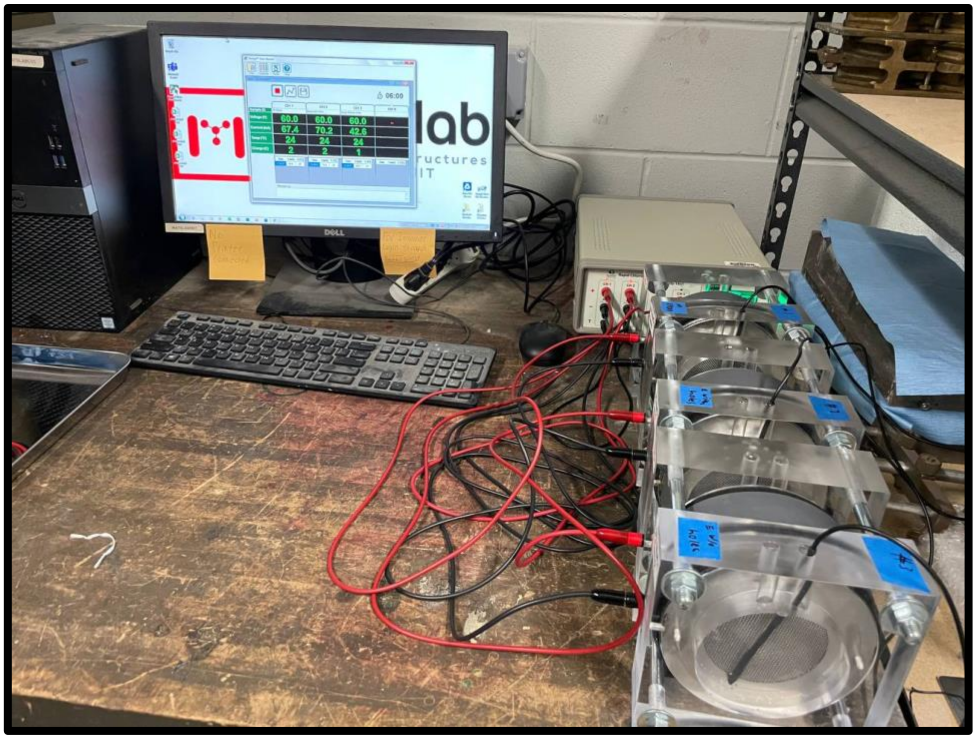

Figure 5: Rapid chloride penetration test setup

The charge passed was calculated in Coulombs for each specimen. Table 2 shows the ASTM C1202 criteria for chloride penetrability based on charge passed for normal concrete systems. The numbers in the table are calibrated for normal concrete systems and can be different for other concrete systems. A more detailed discussion will be provided in Section 5 to provide more information.

Table 2: Chloride ion penetrability based on charge passed

Charge Passed (coulombs)	Chloride Ion Penetrability
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
<100	Negligible

5. Results and Discussion

5.1 Fresh and mechanical properties

SCC P and SC-HyFRC were two self-consolidating mixtures used in this study. In addition to the compressive strength, homogeneity and flow are other important parameters for calibration of admixtures and quality control in self-consolidating mixtures. Figure 6 shows the flow test for SCC P and SC-HyFRC mixtures. The flow was 21 inches for both SCC P and SC-HyFRC mixtures. Both mixtures had good homogeneity, and no segregation was observed. Also, fibers were dispersed properly in the mixture based on visual analysis.

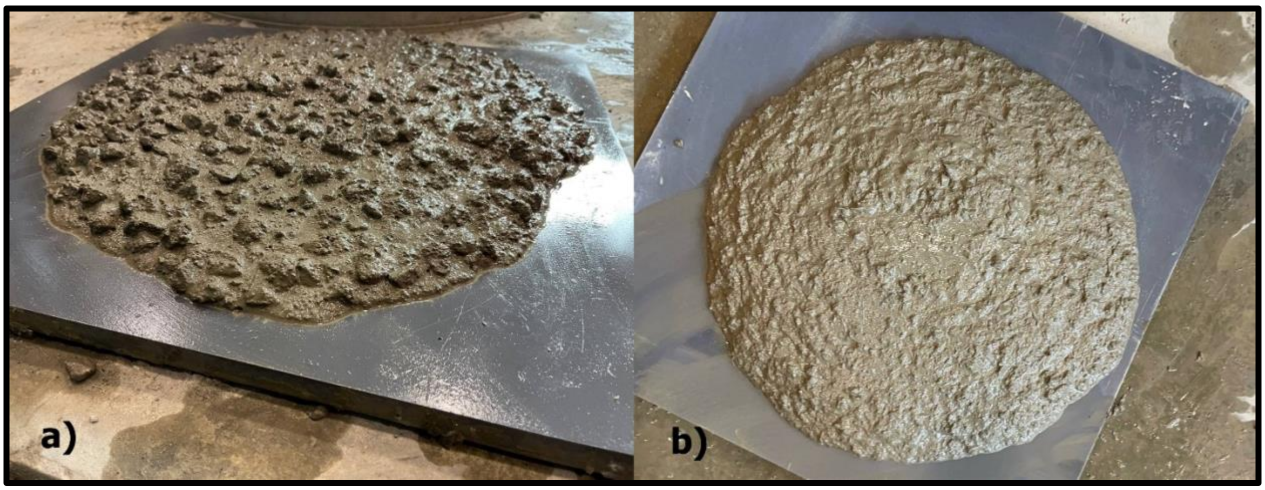

Figure 6: Flow test for a) SCC p and b) SC-HyFRC

The compressive strength results are summarized in Table 3. All concrete systems met the compressive strength criteria as reference mixture designs provided by the New Jersey Department of Transportation and mixture designs extracted from the literature.

Table 3: Compressive strength at 28 days

Concrete Type	28 Days Compressive Strength (Psi)	Unit Weight (lbs/Cu.ft)
HPC	8240	153.3
SCC P	6960	150.1
SC-HyFRC	5460	135.2
ECC	6065	120.6
UHPC	20855	155

5.2 Chloride penetration response

The results of the rapid chloride penetration test are summarized in Table 4. According to the results, UHPC had the best chloride penetration performance in all concrete systems. Also, the HPC was in a very low chloride penetration state, according to Table 2. SCC P and ECC showed low and moderate chloride penetrability, respectively. As can be seen in Table 4, due to the "short circuit" and "over current" errors in the Giatech Perma control device, no number was reported for the chloride penetrability of SC-HyFRC. The test was repeated three with dissembling and assembling cells and changing specimens, but no change was observed in the results. Figure 7 shows SC-HyFRC specimen after removing from the cell. The corroded fibers on the surface of the specimen were observed while the test was run for a few seconds before getting the errors.

Table 4: Passed charge for different concrete types

Concrete Type	Passed Charged (Coulombs)			ASTM C1202 Classification
	Specimen 1	Specimen 2	Average	
HPC	381	385	**383**	**Very Low**
SCC P	1399	1533	**1466**	**Low**
ECC	2682	2723	**2702.5**	**Moderate**
UHPC	177	210	**193.5**	**Very Low**
SC-HyFRC	N/A	N/A	**N/A**	**N/A**

Figure 7: SC-HyFRC specimens after removing from the cell

5.3 Discussion

The RCPT results for SC-HyFRC clearly show that fibers can affect the RCPT results. The 30 mm long steel fibers in SC-HyFRC mixture can make a path for passing charge and interrupt the RCPT results. In contrast, the 13 mm long UHPC fibers did not make the same path. Additionally, the dispersion and steel fiber content can affect the RCPT result by creating a fibers network. More fibers content can increase the possibility of creating a network for passing the charge through the specimens.

Based on the RCPT results for the four types of concrete other than SC-HyFRC, ECC had the highest chloride ion penetrability in these concrete systems. Higher chloride ion penetrability can be directly linked to the weaker corrosion performance of concrete systems. Higher chloride penetrability can increase the chlorides ingress into the concrete and accelerate depassivation of reinforcement in concrete and initiate corrosion. However, according to the literature, ECC has better corrosion performance compared to the normal concrete systems [75–79]. Sahmaran et al. 2008, Mihashi et al. 2011, and Paul et al. 2016 investigated the corrosion behavior of ECC compared to plain mortar. According to the results, a lower amount of corrosion current was observed in the corrosion tests for ECC comparing to the mortar. Additionally, ECC prolonged the corrosion propagation period due to the very fine and dense microstructure and improved the ability to maintain the capacity compared to the mortar. Moreover, the amount of steel loss decreased in ECC specimens compared to the plain mortar. In another study, Maalej et al, 2003 compared the corrosion resistance of ECC and ordinary concrete in the pre-cracked state. According to their results ECC specimens experienced less corrosion area and lower level of steel loss, it took a longer time for ECC specimens to achieve same level of corrosion than ordinary concrete. In terms of long-term chloride penetration results, Maalej et al., 2003, Kobayashi et al, 2010 and Miyazato and Hiraishi, 2013 reported the chloride penetration depths and amounts based on the post corrosion testing results in ECC and according to Maalej et al, 2003, the chloride content at the same depth was at a higher level in the ordinary concrete specimens compared to ECC.

Based on a vast literature search, HyFRC and ECC specimens have a lower or comparable chloride concentration compared to ordinary concrete and mortar as can be seen in Figure 8. However, the improved performance of ECC and HyFRC in long-term chloride and corrosion testing contrast the short term RCPT test data presented in this report. Specifically, long-term chloride ponding experiments in the literature show improvements in performance for systems such as ECC and HyFRC as compared to non-ductile concrete systems; however, the RCPT test data shows that these systems perform worse.

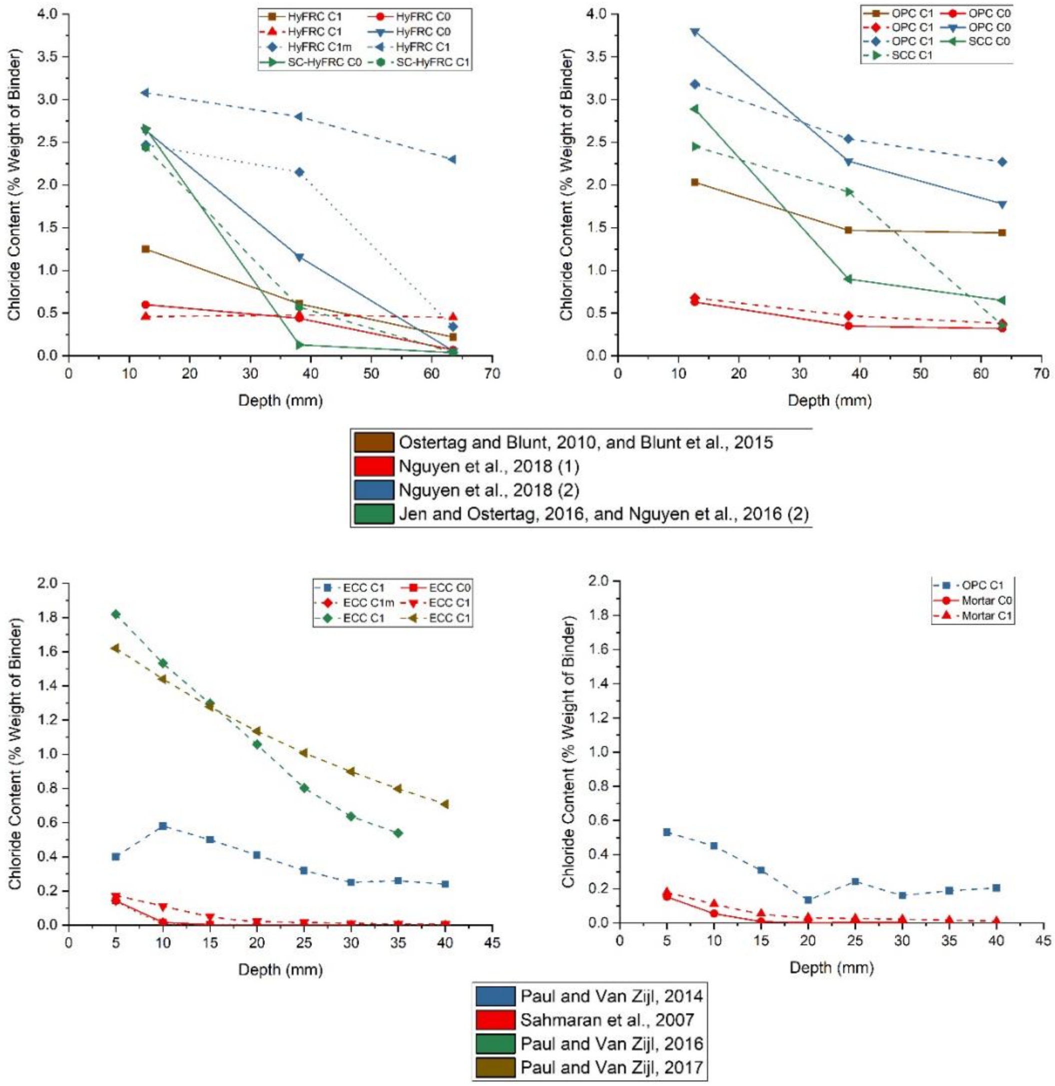

Figure 8 Chloride content at HyFRC and ECC compared to normal concrete and mortar [79–88]

These results show that the existence of polymeric and steel fibers and different microstructures of ductile concrete systems can change the RCPT criterion for chloride ion penetrability based on the passed charge and needs more investigation. RCPT results in ductile concrete systems need to be verified with long-term chloride ponding tests and corrosion results to provide trustable data. This work is on-going by the authors. At the time of writing this report, the authors have been testing the mixtures within this report to long-term chloride ponding according to ASTM G109 [89]. These on-going experiments, which actually measure chloride penetration and not electrical charge passage, show drastically different behavior where ductile concrete materials are performing as well or better than SCC and HPC systems. As a result, the numbers in ASTM C1202 that are summarized in Table 2 may need recalibration in the case of ductile concrete systems.

6. Conclusions and Future Work

6.1 Summary and Major Findings

This study investigated the chloride ion penetration resistance of ductile concrete systems alongside two different concrete systems using rapid chloride penetration testing (RCPT. The ductile concrete systems used in this study were an ultra-high performance concrete (UHPC), an engineered cementitious composite (ECC), and a self-consolidating hybrid fiber reinforced concrete (SC-HyFRC). The non-ductile concrete systems include a self-consolidaing concrete (SCC P) and a high-performance concrete (HPC), both of which meet specifications of the New Jersey Department of Transportation. The ductile concrete systems are representative of a broad class of cementitious materials that have high levels of ductility due to the presence of short, randomly oriented fibers. The ductile concrete systems were selected to represent a broad range of materials that have varying mechanical and durability properties.

The RCPT results show that the UHPC and HPC systems have very low chloride ion penetrability, and SCC P and ECC have low and moderate chloride ion penetrability, respectively. Using the RCPT method, no results could be derived for SC-HyFRC chloride ion penetrability. It is hypothesized that the long steel fibers in SC-HyFRC can pass charge through the specimen and interrupt the RCPT results. As a result, it was found that there is a possibility that the fiber content and dispersion can affect the RCPT results by creating a network in the fibers that results in a passing charge.

Unlike the steel fibers used in UHPC and SC-HYFRC, ECC contains polymeric fibers which also affected the RCPT results in a different way. Specifically, the polymeric fibers do not provide an electrical pathway for the charge to pass through, but do change the pore network which can influence the charged passed in an RCPT experiment.

6.2 Future Research Needs

The results of this study, when compared with chloride ponding tests in the literature show conflicting results in the durability of ductile concrete systems. RCPT testing measures charged passed through a system and does not necessarily indicate how chlorides will move through a material or how the material will respond to reinforcement corrosion.

As a result of this conflicting behavior, the findings from this study should be used in comparison to chloride ponding tests to investigate the durability of ductile concrete systems. At the time of writing of this report, long-term ponding experiments are being tested and analyzed by the authors. The findings from these two studies will be used to make recommendations for recalibration of criterion for chloride ion penetrability based on charge passed, or suggestions for appropriate testing methods to evaluate the durability of ductile concrete systems.

References

[1] U. Angst, B. Elsener, C.K. Larsen, Ø. Vennesland, Critical chloride content in reinforced concrete - A review, Cem Concr Res. 39 (2009) 1122–1138. https://doi.org/10.1016/j.cemconres.2009.08.006.

[2] S. Ahmad, Reinforcement corrosion in concrete structures, its monitoring and service life prediction—a review, Cem Concr Compos. 25 (2003) 459–471.

[3] M. Li, V. Lin, J. Lynch, V.C. Li, Multifunctional carbon black engineered cementitious composites for the protection of critical infrastructure, in: High Performance Fiber Reinforced Cement Composites 6, Springer, 2012: pp. 99–106.

[4] C. Andrade, R. Buják, Effects of some mineral additions to Portland cement on reinforcement corrosion, Cem Concr Res. 53 (2013) 59–67.

[5] ASTM C1202. Standard test method for electrical indication of concrete's ability to resist chloride ion penetration., West Conshohocken (PA): American Society for Testing and Materials. (2010).

[6] AASHTO T259-80, Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration, American Association of State Highway and Transportation Officials, Washington, D.C., USA. (1980).

[7] N.B. 492, Concrete, Mortar and Cement-based Repair Materials: Chloride Migration Coefficient from Non-steady-state Migration Experiments, Nordtest Method, (1999).

[8] A.E. Naaman, H.W. Reinhardt, Characterization of high performance fiber reinforced cement composites—HPFRCC, in: High Performance Fiber Reinforced Cement Composites, 1996: pp. 1–24.

[9] M.J. Bandelt, S.L. Billington, Bond behavior of steel reinforcement in high-performance fiber-reinforced cementitious composite flexural members, Mater Struct. 49 (2016) 71–86.

[10] D.M. Moreno, W. Trono, G. Jen, C. Ostertag, S.L. Billington, Tension stiffening in reinforced high performance fiber reinforced cement-based composites, Cem Concr Compos. 50 (2014) 36–46.

[11] K. Wille, A.E. Naaman, Fracture energy of UHP-FRC under direct tensile loading, in: FraMCoS-7 International Conference, 2010: pp. 65–72.

[12] I.S. Cornelia Magureanu Camelia Negrutiu, and Bogdan Heghes, Mechanical Properties and Durability of Ultra-High-Performance Concrete, ACI Mater J. 109 (n.d.). https://doi.org/10.14359/51683704.

[13] Y.B. Wang, J.Y.R. Liew, S.C. Lee, D.X. Xiong, Experimental study of ultra-high-strength concrete under triaxial compression, ACI Mater J. 113 (2016) 105–112. https://doi.org/10.14359/51688071.

[14] M.A. Ibrahim, M. Farhat, M.A. Issa, J.A. Hasse, Effect of material constituents on mechanical & fracture mechanics properties of ultra-high-performance concrete, ACI Struct J. 114 (2017) 453–465. https://doi.org/10.14359/51689717.

[15] M. Dawood, R. Kahraman, N.G. Ozerkan, M.G. Sohail, A. Belarbi, B. Gencturk, A. Jain, B. Wang, Advancements in Concrete Mix Designs: High-Performance and Ultrahigh-Performance Concretes from 1970 to 2016, Journal of Materials in Civil Engineering. 30 (2017) 04017310. https://doi.org/10.1061/(asce)mt.1943-5533.0002144.

[16] B. Graybeal, J. Tanesi, Durability of an Ultrahigh-Performance Concrete, Journal of Materials in Civil Engineering. 19 (2007) 848–854. https://doi.org/10.1061/(asce)0899-1561(2007)19:10(848).

[17] I. Recommendations, Association Française de Génie Civil, (2002).

[18] G.– A. Bărbos, Long-term Behavior of Ultra – High Performance Concrete (UHPC) Bended Beams, Procedia Technology. 22 (2016) 203–210. https://doi.org/10.1016/j.protcy.2016.01.045.

[19] J. Ma, M. Orgass, F. Dehn, D. Schmidt, N. v Tue, Comparative investigations on ultra-high performance concrete with and without coarse aggregates, in: International Symposium on Ultra High Performance Concrete, Kassel, Germany, 2004: pp. 205–212.

[20] N.M. Azmee, N. Shafiq, Ultra-high performance concrete: From fundamental to applications, Case Studies in Construction Materials. 9 (2018). https://doi.org/10.1016/j.cscm.2018.e00197.

[21] M. Shafieifar, M. Farzad, A. Azizinamini, Experimental and numerical study on mechanical properties of Ultra High Performance Concrete (UHPC), Constr Build Mater. 156 (2017) 402–411. https://doi.org/10.1016/j.conbuildmat.2017.08.170.

[22] C. Shi, Z. Wu, J. Xiao, D. Wang, Z. Huang, Z. Fang, A review on ultra high performance concrete: Part I. Raw materials and mixture design, Constr Build Mater. 101 (2015) 741–751. https://doi.org/10.1016/j.conbuildmat.2015.10.088.

[23] A. Spasojevic, Structural implications of ultra-high performance fibre-reinforced concrete in bridge design, Epfl, 2008.

[24] P. Richard, M. Cheyrezy, Composition of reactive powder concretes, Cem Concr Res. 25 (1995) 1501–1511.

[25] V.H. Perry, Ultra-High-Performance-Concrete Advancements and Industrialization—The Need for Standard Testing, Adv Civ Eng Mater. 4 (2015) 20140028. https://doi.org/10.1520/acem20140028.

[26] Z. Wu, C. Shi, W. He, D. Wang, Uniaxial compression behavior of ultra-high performance concrete with hybrid steel fiber, Journal of Materials in Civil Engineering. 28 (2016) 06016017. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001684.

[27] M. Zhou, W. Lu, J. Song, G.C. Lee, Application of Ultra-High Performance Concrete in bridge engineering, Constr Build Mater. 186 (2018) 1256–1267. https://doi.org/10.1016/j.conbuildmat.2018.08.036.

[28] B.A. Graybeal, Material property characterization of ultra-high performance concrete, United States. Federal Highway Administration. Office of Infrastructure …, 2006.

[29] A.R. Khaloo, H. Karimi, S. Asadollahi, M. Dehestani, A New Mixture Design Method for Ultra-High-Strength Concrete, ACI Mater J. 114 (2017) 215–224. https://doi.org/10.14359/51689475.

[30] M.A. Saleem, A. Mirmiran, J. Xia, K. Mackie, Ultra-high-performance concrete bridge deck reinforced with high-strength steel, ACI Struct J. 108 (2011) 601–609.

[31] J. Fládr, P. Bílý, J. Vodička, Experimental Testing of Resistance of Ultra-high Performance Concrete to Environmental Loads, Procedia Eng. 151 (2016) 170–176. https://doi.org/10.1016/j.proeng.2016.07.366.

[32] R. Gao, Z.M. Liu, L.Q. Zhang, P. Stroeven, Static properties of plain reactive powder concrete beams, in: Key Eng Mater, Trans Tech Publ, 2006: pp. 521–527.

[33] K. Habel, P. Gauvreau, Response of ultra-high performance fiber reinforced concrete (UHPFRC) to impact and static loading, Cem Concr Compos. 30 (2008) 938–946.

[34] Y. Su, C. Wu, J. Li, Z.X. Li, W. Li, Development of novel ultra-high performance concrete: From material to structure, Constr Build Mater. 135 (2017) 517–528. https://doi.org/10.1016/j.conbuildmat.2016.12.175.

[35] A.E.N. and K. Chandrangsu, Innovative Bridge Deck System Using High-Performance Fiber-Reinforced Cement Composites, ACI Struct J. 101 (n.d.). https://doi.org/10.14359/12998.

[36] M.-C. Tang, High performance concrete—past, present and future, in: Proceedings of the International Symposium on UHPC, Kassel, Germany, 2004: pp. 3–9.

[37] Y. Tanaka, K. Maekawa, Y. Kameyama, A. Ohtake, H. Musha, N. Watanabe, The innovation and application of UHPFRC bridges in Japan, Designing and Building with UHPFRC. (2011) 149–188.

[38] E. Denarié, D. Jacomo, N. Fady, D. Corvez, Rejuvenation of maritime signalisation structures with UHPFRC, 2013.

[39] P. Mazzacane, R. Ricciotti, F. Teply, E. Tollini, D. Corvez, MUCEM: The builder's perspective, Proceedings UHPFRC. (2013) 3–16.

[40] S.G. Chasioti, F.J. Vecchio, Effect of fiber hybridization on basic mechanical properties of concrete, ACI Struct J. 114 (2017) 375–384. https://doi.org/10.14359/51689479.

[41] S.G. Chasioti, F.J. Vecchio, Shear behavior and crack control characteristics of hybrid steel fiber-reinforced concrete panels, ACI Struct J. 114 (2017) 209–220. https://doi.org/10.14359/51689164.

[42] C.X. Qian, P. Stroeven, Development of hybrid polypropylene-steel fibre-reinforced concrete, 30 (2000) 63–69.

[43] N. Banthia, M. Sappakittipakorn, Toughness enhancement in steel fiber reinforced concrete through fiber hybridization, Cem Concr Res. 37 (2007) 1366–1372. https://doi.org/10.1016/j.cemconres.2007.05.005.

[44] S.P. Shah, Do Fibers Increase the Tensile Strength of Cement-Based Matrix?, ACI Mater J. 88 (n.d.). https://doi.org/10.14359/1195.

[45] J.S. Lawler, D. Zampini, S.P. Shah, Microfiber and macrofiber hybrid fiber-reinforced concrete, Journal of Materials in Civil Engineering. 17 (2005) 595–604. https://doi.org/10.1061/(ASCE)0899-1561(2005)17:5(595).

[46] N. Ganesan, P. v. Indira, M. v. Sabeena, Tension stiffening and cracking of hybrid fiber-reinforced concrete, ACI Mater J. 110 (2013) 715–721.

[47] A. Sivakumar, M. Santhanam, Mechanical properties of high strength concrete reinforced with metallic and non-metallic fibres, Cem Concr Compos. 29 (2007) 603–608. https://doi.org/10.1016/j.cemconcomp.2007.03.006.

[48] K.H. Yang, Tests on concrete reinforced with hybrid or monolithic steel and polyvinyl alcohol fibers, ACI Mater J. 108 (2011) 664–672.

[49] Y. Chi, L. Xu, Y. Zhang, Experimental study on hybrid fiber–reinforced concrete subjected to uniaxial compression, Journal of Materials in Civil Engineering. 26 (2014) 211–218.

[50] E.T. Dawood, M. Ramli, Contribution of hybrid fibers on the hybrid fibers on the properties of high strength concrete having high workability, Procedia Eng. 14 (2011) 814–820. https://doi.org/10.1016/j.proeng.2011.07.103.

[51] H.R. Pakravan, M. Latifi, M. Jamshidi, Hybrid short fiber reinforcement system in concrete: A review, Constr Build Mater. 142 (2017) 280–294. https://doi.org/10.1016/j.conbuildmat.2017.03.059.

[52] H. Ma, S. Qian, Z. Zhang, Z. Lin, V.C. Li, Tailoring Engineered Cementitious Composites with local ingredients, Constr Build Mater. 101 (2015) 584–595. https://doi.org/10.1016/j.conbuildmat.2015.10.146.

[53] M. Sahmaran, M. Lachemi, K.M.A. Hossain, R. Ranade, V.C. Li, Influence of aggregate type and size on ductility and mechanical properties of engineered cementitious composites, ACI Mater J. 106 (2009) 308–316.

[54] Y. Zhu, Y. Yang, Y. Yao, Use of slag to improve mechanical properties of engineered cementitious composites (ECCs) with high volumes of fly ash, Constr Build Mater. 36 (2012) 1076–1081. https://doi.org/10.1016/j.conbuildmat.2012.04.031.

[55] K.T. Soe, Y.X. Zhang, L.C. Zhang, Material properties of a new hybrid fibre-reinforced engineered cementitious composite, Constr Build Mater. 43 (2013) 399–407.

[56] S.F.U. Ahmed, H. Mihashi, Corrosion durability of strain hardening fibre-reinforced cementitious composites, Australian Journal of Civil Engineering. 8 (2010) 13–26. https://doi.org/10.1080/14488353.2010.11463959.

[57] V.C. Li, On Engineered Cementitious Composites (ECC), Journal of Advanced Concrete Technology. 1 (2003) 215–230. https://doi.org/10.3151/jact.1.215.

[58] M.D. Lepech, V.C. Li, Water permeability of engineered cementitious composites, Cem Concr Compos. 31 (2009) 744–753. https://doi.org/10.1016/j.cemconcomp.2009.07.002.

[59] Y. Ke-Quan, D. Jian-Guo, L. Zhou-Dao, L.C.K. Y., Mechanical Properties of Engineered Cementitious Composites Subjected to Elevated Temperatures, Journal of Materials in Civil Engineering. 27 (2015) 4014268. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001241.

[60] V.C. Li, Advances in ECC research, ACI Special Publications. 206 (2002) 373–400.

[61] S.H. Said, H.A. Razak, The effect of synthetic polyethylene fiber on the strain hardening behavior of engineered cementitious composite (ECC), Mater Des. 86 (2015) 447–457.

[62] V.C. Li, Engineered cementitious composites (ECC)-tailored composites through micromechanical modeling, in: 1998.

[63] B.S. Mohammed, V.C. Khed, M.S. Liew, Optimization of hybrid fibres in engineered cementitious composites, Constr Build Mater. 190 (2018) 24–37. https://doi.org/10.1016/j.conbuildmat.2018.08.188.

[64] D.M. Moreno, W. Trono, G. Jen, C. Ostertag, S.L. Billington, Tension-stiffening in reinforced high performance fiber-reinforced cement-based composites under direct tension, in: High Performance Fiber Reinforced Cement Composites 6, Springer, 2012: pp. 263–270.

[65] K.S. Douglas, S.L. Billington, Strain rate dependence of HPFRCC cylinders in monotonic tension, Mater Struct. 44 (2011) 391–404.

[66] V.C. Li, T. Kanda, Engineered cementitious composites for structural applications, Journal of Materials in Civil Engineering. 10 (1998) 66–69. https://doi.org/10.1061/(ASCE)0899-1561(1998)10:2(66).

[67] V.C. Li, S. Wang, C. Wu, Tensile strain-hardening behavior or polyvinyl alcohol engineered cementitious composite (PVA-ECC), ACI Mater J. 98 (2001) 483–492.

[68] V.C. Li, Applications of engineered cementitious composites (ecc), Springer, 2019. https://doi.org/10.1007/978-3-662-58438-5_9.

[69] G. Yildirim, M. Şahmaran, M.K.M. Al-Emam, R.K.H. Hameed, Y. Al-Najjar, M. Lachemi, Effects of compressive strength, autogenous shrinkage, and testing methods on bond behavior of high-early- strength engineered cementitious composites, ACI Mater J. 112 (2015) 409–418. https://doi.org/10.14359/51687188.

[70] M.F. Kai, Y. Xiao, X.L. Shuai, G. Ye, Compressive behavior of engineered cementitious composites under high strain-rate loading, Journal of Materials in Civil Engineering. 29 (2017) 1–8. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001781.

[71] H. Liu, Q. Zhang, V. Li, H. Su, C. Gu, Durability study on engineered cementitious composites (ECC) under sulfate and chloride environment, Constr Build Mater. 133 (2017) 171–181. https://doi.org/10.1016/j.conbuildmat.2016.12.074.

[72] V.C. Li, T. Horikoshi, A. Ogawa, S. Torigoe, T. Saito, Micromechanics-based durability study of polyvinyl alcohol-engineered cementitious composite, Materials Journal. 101 (2004) 242–248.

[73] M. Şahmaran, V.C. Li, Durability of mechanically loaded engineered cementitious composites under highly alkaline environments, Cem Concr Compos. 30 (2008) 72–81.

[74] S. Qian, V.C. Li, H. Zhang, G.A. Keoleian, Durable and sustainable overlay with ECC, 9th International Conference on Concrete Pavements: The Golden Gate to Tomorrow's Concrete Pavements. 2 (2008) 918–933.

[75] M. Sahmaran, V.C. Li, C. Andrade, Corrosion resistance performance of steel-reinforced engineered cementitious composite beams, ACI Mater J. 105 (2008) 243–250.

[76] M. Maalej, S.F.U. Ahmed, P. Paramasivam, Corrosion Durability and Structural Response of Functionally-Graded Concrete Beams, Journal of Advanced Concrete Technology. 1 (2003) 307–316. https://doi.org/10.3151/jact.1.307.

[77] S.F.U. Ahmed, H. Mihashi, Corrosion durability of strain hardening fibre-reinforced cementitious composites, Australian Journal of Civil Engineering. 8 (2010) 13–26. https://doi.org/10.1080/14488353.2010.11463959.

[78] H. Mihashi, S.F.U. Ahmed, A. Kobayakawa, Corrosion of Reinforcing Steel in Fiber Reinforced Cementitious Composites, Journal of Advanced Concrete Technology. 9 (2011) 159–167. https://doi.org/10.3151/jact.9.159.

[79] S.C. Paul, G.P.A.G. van Zijl, Chloride-induced corrosion modelling of cracked reinforced SHCC, Archives of Civil and Mechanical Engineering. 16 (2016) 734–742. https://doi.org/10.1016/j.acme.2016.04.016.

[80] S. Chandra Paul, G. P. A. G. van Zijl, Crack Formation and Chloride Induced Corrosion in Reinforced Strain Hardening Cement-Based Composite (R/SHCC), Journal of Advanced Concrete Technology. 12 (2014) 340–351. https://doi.org/10.3151/jact.12.340.

[81] M. Sahmaran, M. Li, V.C. Li, Transport properties of engineered cementitious composites under chloride exposure, ACI Materials Journal. 104 (2007) 604–611.

[82] S.C. Paul, G.P.A.G. van Zijl, Corrosion Deterioration of Steel in Cracked SHCC, International Journal of Concrete Structures and Materials. 11 (2017) 557–572. https://doi.org/10.1007/s40069-017-0205-8.

[83] C.P. Ostertag, J. Blunt, Effect of crack control in hybrid fiber reinforced concrete composites on corrosion rate of steel reinforcing bars, Fracture Mechanics of Concrete and Concrete Structures. 1 (2010) 415–422.

[84] J. Blunt, G. Jen, C.P. Ostertag, Enhancing corrosion resistance of reinforced concrete structures with hybrid fiber reinforced concrete, Corrosion Science. 92 (2015) 182–191. https://doi.org/10.1016/j.corsci.2014.12.003.

[85] W. Nguyen, J.F. Duncan, T.M. Devine, C.P. Ostertag, Electrochemical polarization and impedance of reinforced concrete and hybrid fiber-reinforced concrete under cracked matrix conditions, Electrochimica Acta. 271 (2018) 319–336. https://doi.org/10.1016/j.electacta.2018.03.134.

[86] W. Nguyen, J.F. Duncan, G. Jen, C.P. Ostertag, Influence of matrix cracking and hybrid fiber reinforcement on the corrosion initiation and propagation behaviors of reinforced concrete, Corrosion Science. 140 (2018) 168–181. https://doi.org/10.1016/j.corsci.2018.06.004.

[87] W. Nguyen, G. Jen, J.F. Duncan, C.P. Ostertag, Effect of hybrid fiber reinforcement on corrosion-induced damage of reinforced concrete, (2016). https://doi.org/10.21012/fc9.181.

[88] W. Nguyen, J.F. Duncan, P.J.M. Monteiro, C.P. Ostertag, Multi-Scale Characterization of Corrosion Initiation of Preloaded Hybrid Fiber-Reinforced Concrete Composites, Key Engineering Materials. 711 (2016) 195–202. https://doi.org/10.4028/www.scientific.net/kem.711.195.

[89] ASTM G 109-13, Standard Test Method for Determining the Effects of Chemical Admixtures on the Corrosion of Embedded Steel Reinforcement in Concrete, Annual Book of ASTM Standards. 07 (2013) 1–5. https://doi.org/10.1520/G0109-07R13.2.