Istanbul Bridge Conference
August 11-13, 2014
Istanbul, Turkey

ENGINEERED CEMENTITIOUS COMPOSITES AS SUSTAINABLE OVERLAY MATERIALS FOR BRIDGE DECK APPLICATIONS

H. E. Yücel[1], M. Şahmaran[2], G. Yıldırım[3] and M. Lachemi[4]

ABSTRACT

All over the world, several deterioration types are being encountered on bridge decks because of mechanical loadings and environmental effects. The deterioration of bridge decks causes serious problems and requires urgent repair of the degraded sections. The most widely used maintenance technique for bridge decks under moderate and/or heavy traffic loads is the placement of an overlay on the existing bridge deck. Although, this technique has been used around the world for the protection and rehabilitation of bridge decks, many cases were observed where premature delaminations and failures took place. Along these lines, new generation composite materials called Engineered Cementitious Composites (ECCs) which can also be used efficiently for overlaying purposes were developed during the last decades. In this paper, concentration is placed upon the utilization of ECCs as effective overlay materials where the performance-based evaluations are mainly made by the specimens incorporating different supplementary cementitious materials. As performance criteria, basic mechanical properties, dimensional stability and rapid chloride permeability of monolithic specimens were evaluated along with the bond properties of overlaid systems. Outcomes of the present paper strongly suggest that with their superior performance, ECCs can be emerging alternatives for the durable repair of bridge decks.

[1]Assistant Professor, Dept. of Civil Engineering, Niğde University, Niğde, Turkey, 51240
[2]Associate Professor, Dept. of Civil Engineering, Gazi University, Ankara, Turkey, 06500
[3]Research Assistant, Dept. of Civil Engineering, Gazi University, Ankara, Turkey, 06500
[4]Professor, Dept. of Civil Engineering, Ryerson University, Toronto, Canada, M5B 2K3

Yücel HE, Şahmaran M, Yıldırım G, Lachemi M. Engineered Cementitious Composites as sustainable overlay materials for bridge deck applications. *Proceedings of the Istanbul Bridge Conference*, 2014.

Istanbul Bridge Conference
August 11-13, 2014
Istanbul, Turkey

Engineered Cementitious Composites As Sustainable Overlay Materials For Bridge Deck Applications

H. E. Yücel[1], M. Şahmaran[2], G. Yıldırım[3] and M. Lachemi[4]

ABSTRACT

All over the world, several deterioration types are being encountered on bridge decks because of mechanical loadings and environmental effects. The deterioration of bridge decks causes serious problems and requires urgent repair of the degraded sections. The most widely used maintenance technique for bridge decks under moderate and/or heavy traffic loads is the placement of an overlay on the existing bridge deck. Although, this technique has been used around the world for the protection and rehabilitation of bridge decks, many cases were observed where premature delaminations and failures took place. Along these lines, new generation composite materials called Engineered Cementitious Composites (ECCs) which can also be used efficiently for overlaying purposes were developed during the last decades. In this paper, concentration is placed upon the utilization of ECCs as effective overlay materials where the performance-based evaluations are mainly made by the specimens incorporating different supplementary cementitious materials. As performance criteria, basic mechanical properties, dimensional stability and rapid chloride permeability of monolithic specimens were evaluated along with the bond properties of overlaid systems. Outcomes of the present paper strongly suggest that with their superior performance, ECCs can be emerging alternatives for the durable repair of bridge decks.

Introduction

Bridge decks may deform as a result of concrete distress caused by heavy repeated traffic loads, freeze-thaw cycles, abrasion, alkali-aggregate reaction, excessive cracking, or spalling by corrosion effect necessitating the repair and/or maintenance applications in time [1]. Although the methods to rehabilitate the bridge decks subjected to heavy traffic loads varies in different countries, the most widely used maintenance technique is the application of overlay material over the existing substratum [2]. While variety of overlay materials that were widely used in the field reported to be adequately durable, the performance is not always stable [1,3] and nearly half of the overlays incorporating traditional concrete materials fail in service [4]. Therefore, the development of new generation overlay materials is desirable for the sake of increased durability and performance characteristics of repair systems.

During the last decades, concrete technology has been undergoing rapid development. The efforts to modify the brittle behavior of plain cementitious materials such

[1]Assistant Professor, Dept. of Civil Engineering, Niğde University, Niğde, Turkey, 51240
[2]Associate Professor, Dept. of Civil Engineering, Gazi University, Ankara, Turkey, 06500
[3]Research Assistant, Dept. of Civil Engineering, Gazi University, Ankara, Turkey, 06500
[4]Professor, Dept. of Civil Engineering, Ryerson University, Toronto, Canada, M5B 2K3

Yücel HE, Şahmaran M, Yıldırım G, Lachemi M. Engineered Cementitious Composites as sustainable overlay materials for bridge deck applications. *Proceedings of the Istanbul Bridge Conference*, 2014.

as mortars and concretes has resulted in modern concepts of high performance fiber reinforced cementitious composites (HPFRCC). Engineered Cementitious Composites (ECCs) are a newly developed HPFRCC with substantial benefit in high ductility and improved durability characteristics. The most obvious feature that separates ECC from conventional concrete and fiber-reinforced concrete is its superior tensile strain capacity which is in excess of 3 to 5%. The strain capacity of 3 to 5% accounts for more than 300 times that of a normal concrete, allowing for the formation of microcracks that are very close to each other.

While the components of ECC may be similar to FRC, the distinctive strain hardening characteristic of ECC through microcracking is achieved by micromechanical tailoring of the individual components (i.e. cement, sand, and fibers) along with the control of interfacial properties between components (fiber, matrix and fiber-matrix interface) [5-7]. Fracture properties of the cementitious matrix are carefully controlled through mix proportions. Fiber properties, such as strength, modulus of elasticity, and aspect ratio have been customized for use in ECC. The interfacial properties between fiber and matrix have also been optimized in cooperation with the manufacturer for use in this material. Typical mix proportions of ECC using a poly-vinyl-alcohol (PVA) fiber are given in Table 1.

Table 1. Typical mixture design of ECC material.

Cement	**Water**	**Sand**	**Mineral Admixture***	**HRWR****	**Fiber (%)**
1.00	0.58	0.80	1.20	0.013	2.00

* Mineral admixture (Fly ash or ground granulated blast furnace slag)
** High range water reducer; all ingredient proportions by weight except for fiber

While most HPFRCCs rely on a high fiber volume to achieve high performance, ECC uses relatively low amounts, typically 2% by volume, of short, discontinuous fibers. Low fiber volume, along with the common components, allows flexibility during construction. To date, ECC materials have been engineered for self-consolidation casting [8], extrusion [9], shotcreting [10], and conventional mixing in a gravity mixer or conventional mixing truck [11].

Fig. 1 shows a typical uniaxial tensile stress-strain curve of ECC material containing 2% poly-vinyl-alcohol (PVA) fiber [12]. Strain-hardening behavior after first cracking is accompanied by multiple microcracking. The crack width development during inelastic straining is also shown in Fig. 1. Even at ultimate load, the crack width remains smaller than 100 μm. This tight crack width is self-controlled and, whether the composite is used in combination with conventional reinforcement or not, it is a material characteristic independent of rebar reinforcement ratio. Under severe bending load, an ECC beam deforms similarly to a ductile metal plate through plastic deformation with the development of multiple cracks with small crack spacing and tight crack widths (<0.1 mm). Microcracks developed from the first cracking point and spread out in the mid-span of the flexural beam. Bending failure in ECC occur when the fiber bridging strength at one of the microcracks was reached resulting in localized deformation at this section once the modulus of rupture is approached. In compression, ECC materials exhibit compressive strengths similar to high strength concrete (e.g. greater than 60 MPa) [11].

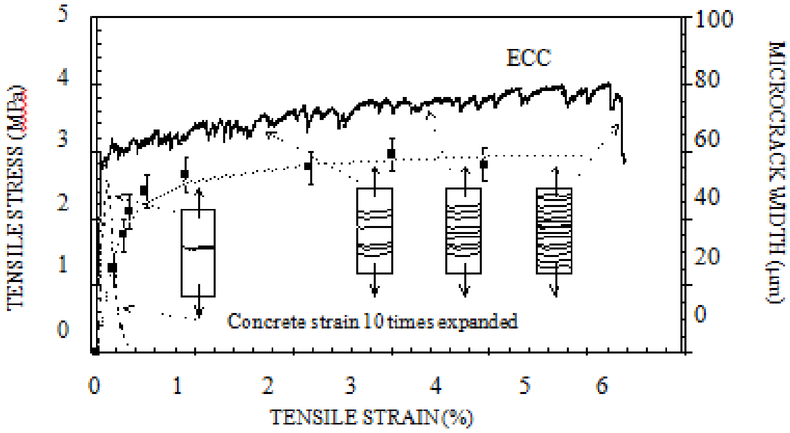

Figure 1. Typical tensile stress-strain curve and crack width development of ECC.

Superior tensile characteristics and high deformability of ECC make the material attractive as an ideal overlay material. Therefore, in the present study, performance analysis of ECC specimens incorporating low-calcium fly ash (class-F FA) (F_ECC) and ground granulated blast furnace slag (S_ECC) was presented in addition to the micro-silica concrete (MSC) which is widely used for overlaying purposes on bridge decks. Throughout the study, bond performances of overlaid materials (overlay + substrate concrete) together with some mechanical and durability properties of monolithic specimens were evaluated.

Performance Analysis of ECC as an Overlay Material

Basic Mechanical Properties, Dimensional Stability and Chloride Ion Penetrability of Proposed Materials in Monolithic Form

Basic Mechanical Properties

In a study by Yucel [13], basic mechanical properties of F_ECC, S_ECC and MSC specimens including compressive strength, flexural strength and flexural deformation were investigated in detail. The tests were conducted by using at least six different Ø10×20 cm cylinders at the ages of 1, 7, 28 and 90 days according to ASTM C 39 and results were tabulated in Table 2.

Table 2. Compressive strength results of overlay materials.

Mix ID	Compressive Strength (MPa)			
	1 d.	7 d.	28 d.	90 d.
F_ECC	17.1	31.1	53.8	65.6
S_ECC	24.6	44.1	71.2	74.1
MSC	32.8	46.3	68.7	72.0

As it is seen from Table 2, for the first 1 day of curing, strength gain in the MSC specimens was significantly higher compared to the ECC mixtures. At the ages of 7 days of curing, the compressive strength test results were similar for both S_ECC and MSC mixtures. However, the strength gain was more pronounced for S_ECC beyond 7 days of curing. Between the ages of 28 days and 90 days high amount of strength gain was achieved by F_ECC mixture, but still it has the lowest compressive strength at all ages. Comparing the compressive strength results of ECC specimens, reason for the higher early strength of slag-ECC specimens can be predicated to the predominant reaction of slag with alkali hydroxide during the early hydration period. This result is also partially a result of the higher rate in hydration of the slag due to its large specific surface area (425 m^2/kg) compared to that of FA (290 m^2/kg). High surface area provides more nucleating sites and OH^- ions as well as alkalis into the pore fluid. Despite the changes in results however, all the mixtures showed compressive strengths higher than 45 MPa at 28 days of age. This value could significantly exceed that of normal concrete strength (30 MPa), and fulfill engineering requirements in most projects.

In Table 3, average flexural strength (modulus of rupture –MOR) and deformation results of proposed materials obtained under four-point bending loading by using at least six different prism specimens were shown. As seen from Table 3, even though MSC mixture has the highest compressive strength at early ages, and similar compressive strength at later ages, ECC prisms show a substantially higher ultimate flexural strength in comparison to that of MSC prisms. MOR of ECC mixtures values varied from 11.51 to 12.04 MPa showing that increase in the values of flexural strength of S_ECC was not that of drastic compared to the values of F_ECC for the first 28 days as in the compressive strength test results. Moreover, for all specimens, no significant flexural strength gain was observed beyond the age of 28 days. The most probable reason for this trend may be attributed to the fact that flexural strength is governed by more complex material properties, such as tensile first cracking strength, ultimate tensile strength and tensile strain capacity, particularly in the case of strain hardening cementitious materials [14].

Table 3. Flexural properties of overlay materials.

Mix ID	**Flexural Strength (MPa)**				**Deformation (mm)**			
	1 d.	**7 d.**	**28 d.**	**90 d.**	**1 d.**	**7 d.**	**28 d.**	**90 d.**
F_ECC	5.35	8.80	11.51	11.82	4.18	4.78	4.43	3.99
S_ECC	6.74	10.89	12.04	12.58	3.18	3.23	3.05	2.94
MSC	4.97	6.30	7.00	7.56	0.55	0.41	0.28	0.27

Ultimate mid-span beam deflection capacity, which reflects the material ductility, of the mixtures ranged between the values of 0.28 and 4.43 mm for the first 28 days. As seen from Fig. 2, MSC mixture is a brittle material with sudden fracture failure, on the other hand, F_ECC and S_ECC samples have significantly higher deformation capability than MSC at all testing ages. Among the ECC mixtures, F_ECC showed the highest deflection capacity, therefore ductility, at all ages. The improvement in the mid-span beam deflection capacity with the use of class-F FA can be attributed to the fact that the addition of FA has a tendency to reduce PVA fiber/matrix interface chemical bond and matrix toughness while increasing the interface frictional bond, in favor of attaining high tensile strain capacity [15,16]. The overall decrease in the mid-span beam deflection capacity for S_ECC specimens might be associated with higher lime content and reactivity of slag which in turn causes enhanced fracture toughness, bond strength and the chemical bond between mortar matrix and fibers.

Although S_ECC mixtures exhibit smaller deformation capacity, their flexural deflection capacity is still around or more than 3 mm at 28 days of age. The 3.0 mm deformation is nearly equivalent to almost 2.0% strain capacity on the tensile face of the beam. This deflection capacity remains almost 200 times higher than that in normal concrete and conventional fiber reinforced concrete [17].

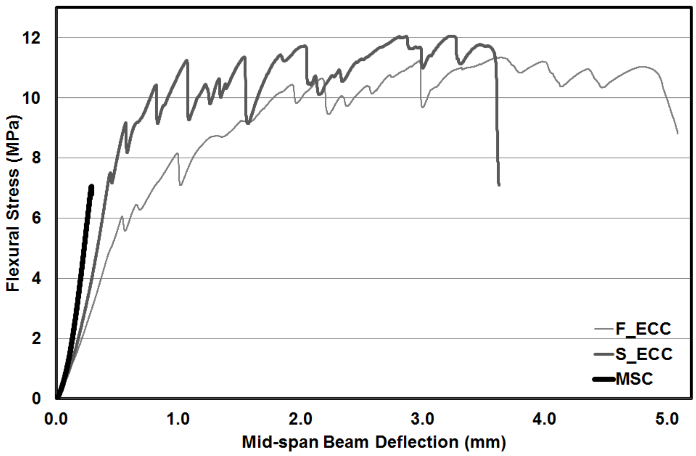

Figure 2. Flexural strength – mid-span beam deflection curve of overlay materials at 28 days of age.

Dimensional Stability

Shrinkage-originated cracking is a major problem especially for flat structures such as highway pavements, bridge deck overlays, slabs and walls. Although they are informative, free shrinkage tests alone cannot offer sufficient information on the behavior of concrete structures because virtually every concrete structure is restrained in some way, either by reinforcement or by the boundary condition of the structure. Yucel [13] concentrated on the drying and restrained shrinkage characteristics of F_ECC, S_ECC and MSC monolithic overlay mixtures. The results were presented in Fig. 3.

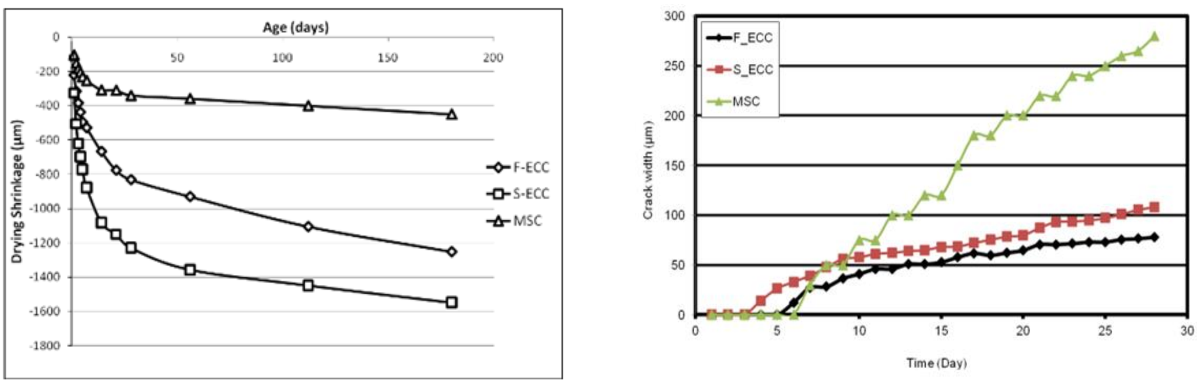

Figure 3. a) Drying shrinkages of overlay mixtures b) Crack width-time relations of overlay mixtures under restrained shrinkage.

The drying shrinkage strains of overlay materials at the age of 180 days ranged between 451 and 1548 micro-strain. ECC mixtures with slag exhibited the highest drying shrinkage of 1548 µε at the end of 180 days. The usage of fly ash in ECC reduced the drying shrinkage deformation. A possible mechanism contributing to the reduction of drying shrinkage in F_ECC could be matrix densification due to FA addition which may prevent internal moisture evaporation [18]. The matrix densification is typically attributed to the shape, pozzolanic property, and micro-filler effect of FA. An alternative mechanism is that unhydrated FA particles act as aggregates, which provide restraint to shrinkage, and the coarser pore structure, which results in decreased surface tension when a meniscus is formed and, thus, lower shrinkage forces exerted on the surrounding cement paste [19-21]. The increase in the drying shrinkage of ECC with the use of slag might be due mainly to pozzolanic reaction and enhanced pore size refinement mechanism of slag especially at earlier ages. The experimental results also revealed that the drying shrinkage of ECC overlay materials is above triple that of the MSC reference overlay mixture. This is due to the very high cementitious materials (Portland cement and mineral admixture) content, and absence of large volume of coarse aggregates. The previous results showed that the restraining effect of the micro-silica sand in the ECC mixtures was too small to contribute significantly to drying shrinkage [22].

Restrained shrinkage behavior of the proposed overlay materials was simulated by the ring specimens cast next to a steel ring. Cracking pattern, crack number and crack width were measured as a function of age with a portable microscope. Measurements were taken at three different locations along each crack and the average values from two ring specimens were plotted in Fig. 3-b. Crack numbers monitored over the F_ECC, S_ECC and MSC mixtures, and average, minimum and maximum crack widths are presented in Table 4.

Table 4. Compressive strength results of overlay materials.

Mix ID	**Crack Width (μm)**			**Crack Number**
	Average	**Minimum**	**Maximum**	
F_ECC	78	40	100	7
S_ECC	108	80	125	8
MSC	165	50	280	2

For the MSC control specimens, two cracks were observed in each specimen. The average and maximum crack width of the two specimens were 165μm and 280 μm at 28 days. For F_ECC and S_ECC specimens, 7 and 8 cracks were formed at 28 days, respectively. The average crack widths at the end of 28 days were 78 μm and 108 μm for F_ECC and S_ECC specimens, respectively. The crack width of these ECC microcracks was significantly lower than the crack width of MSC localized cracks, and the former retains its load carrying capacity after crack formation. Restrained ring shrinkage tests results during 28 days period after casting are shown in Fig. 3-b. Because of significant differences between these two crack widths, only maximum crack width of MSC specimens were considered in Fig. 3-b. As seen in Fig. 3-b, both ECC mixtures showed some degree of multiple cracking. Basically, the width of a crack developed very fast in the first few days after crack formation. From then on the rate of development diminished its intension or stabilized. On the other hand, the crack width of MSC mixture still wants to go upward after 28 days. Wang et al. [23] reported that as crack width increases from 100 μm to 500 μm, the permeability coefficient increases nearly seven orders of magnitudes from 1.0 x 10^{-11} m/sec to 1.0 x 10^{-4} m/sec. However, for crack widths under 100 μm, the permeability coefficient remains nearly identical to that of uncracked concrete, suggesting that for crack widths below this threshold there is no significant increase in permeability after cracking. Crack widths under 100 μm were also found to have same effective chloride diffusion coefficient as uncracked concrete [24]. Taking these into account, the test results show that ECC overlay materials has significantly greater resistance to restrained shrinkage cracking than MSC, despite its higher drying shrinkage value. This is due to the large tensile strain capacity of ECC overlay materials, which leads to a negative shrinkage cracking potential and great dimensional compatibility with existing concrete.

Chloride Ion Penetrability

Yucel [13] studied the chloride ion penetrability of proposed overlay materials through rapid chloride permeability test (RCPT). Chloride ion permeability test results of the specimens for overlay mixtures at 28 and 90 days are presented in Fig. 4. They are expressed in terms of the total electrical charge in coulomb, which provides an indirect measure of the resistance of F_ECC, S_ECC and MSC mixtures to chloride ion penetration. The classification ranges given in the ASTM C 1202 are also illustrated graphically in Fig. 4 by horizontal gridlines. The data presented in Fig. 4 show that F_ECC, S_ECC and MSC mixtures exhibited sufficient resistance to chloride ion penetration with the total charge exceeding 2863 coulomb, 878 coulomb and 212 coulomb, respectively, at the age of 28 days. Although, all of these values are acceptable for chloride ion penetrability, MSC and S_ECC mixtures show better performance than F_ECC mixture as very low chloride ion penetrability.

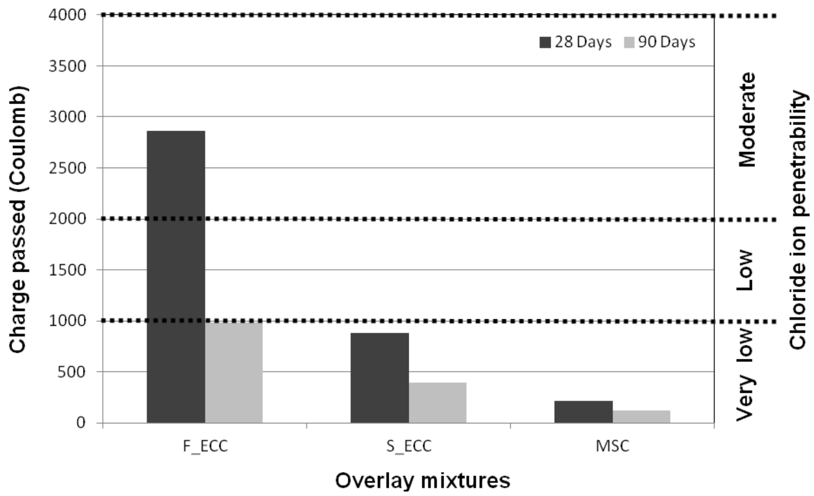

Figure 4. Chloride ion penetrability of overlay mixtures with charge passed.

Bond Performance of the Proposed Materials

An ideal overlay material must guarantee the attainment of specific characteristics to serve efficiently in the field. Apart from the other parameters, maybe the most important property of an overlay is the bonding performance between the material and substratum where it is applied over. Bond properties of F_ECC, S_ECC and MSC overlay mixtures were assessed by Sahmaran et al. [25]. In this study, slant shear tests were utilized to evaluate the bond strength of overlay mixtures. The slant shear test which measures bond strength under combined shear and compression stresses has become one of the most widely accepted methods for evaluating the bond of repair materials to concrete substrates. In this test, the repair material is bonded to a substrate concrete specimen on a slant elliptical plane inclined at an angle of 30° from the loading axis to form a Ø10×20 cm composite cylinder and composite bi-layer specimens were subjected to compression loading. Table 5 shows the results of slant shear tests of F_ECC, S_ECC, and MSC bi-layer composite cylinder specimens including the modes of failure.

Table 5. Slant shear bond strength test results and failure mode.

Mix ID	**Bond Strength (MPa)**			**Failure Mode**
	1 Day	**7 Days**	**28 Days**	**28 Days**
F_ECC	7.1	14.7	21.7	All through substrate
S_ECC	8.3	17.4	24.3	All through substrate
MSC	10.4	14.1	15.6	4 through slanted interface 2 through a monolithic rupture

The test results show that ECC specimens resulted in bond strength that are approximately 15-20%, higher than the MSC specimens. It can be concluded that the addition of ECC layer could significantly improve the bond stress measured by slant shear test. Three different failure modes were observed as substrate, slanted interface and monolithic rupture in this slant shear test. The failure type for MSC/concrete specimens was interface debonding or monolithic rupture. In all cases of ECC-substrate bi-layer specimens, the failure plane occurred preferentially through the substrate, for both types of ECC mixtures. This is due to the effectiveness of the ECC with its high adhesion strength that did not allow the interface to fail. Failure through the substrate concrete is always desirable, because failure through the substrate concrete demonstrated that the existing substrate is the weakest component of the ECC/concrete system. Consequently, the bond strength increased greatly through the utilization of ECC compared to MSC.

Conclusions

The results of studies summarized in this paper largely confirm the overlay performance of ECCs as efficient materials to be used in bridge deck applications. To sum up, ECC materials possess comparable compressive strength to that of MSC mixtures although flexural strength of MSC was found to be significantly lower than ECCs. MSC is a brittle material with sudden fracture failure, on the other hand, F_ECC and S_ECC samples have significantly higher deformation capability than MSC at all testing ages. Drying shrinkage deformations of ECCs were found to be higher than MSC mixtures although the effect of drying under restraining conditions was realized through the formation of multiple microcracks in the case of ECC specimens on contrary to MSC specimens where localized cracks having wider widths were monitored. ECC mixtures show low and very low chloride ion penetrability like MSC, according to the results of rapid chloride permeability test implying that permeability values of ECC mixtures are acceptable for overlay materials. Based on the slant shear test results, it can be concluded that ECC can achieve adequate bond strength with other concretes. All ECC-substrate bi-layer specimens had failure plane occur preferentially through the substrate, for both types of mixtures. On the other hand, for MSC-substrate specimens, the failure type was interface debonding or monolithic rupture.

Acknowledgments

The authors gratefully acknowledge the financial assistance of the Scientific and Technical Research Council (TUBITAK) of Turkey provided under Project: MAG-108M495, and Gaziantep University Scientific Research Centre provided under project MF.10.09.

References

1. Russell HG. Concrete bridge deck performance. Transportation Research Board National Research, 2004.
2. Krauss PD, Lawler JS, Steiner KA. Guidelines for selection of bridge deck overlays, sealers and treatments. National Cooperative Highway Research Program (NCHRP) Transportation Research Board of The National Academies, 2009.
3. Emmons PH. Concrete repair and maintenance illustrated: problem, analysis, repair strategy and techniques. 1994; 155-164.
4. Mather B, Warner J. Why do concrete repairs fail. Interview held at University of Wisconsin, Department of Engineering Professional Development, Wis. http://aec.engr.wisc.edu/resources/rsrc07.html>, 2004.
5. Li VC. ECC – Tailored composites through micromechanical modeling. *Fiber Reinforced Concrete: Present and the Future,* CSCE, Montreal; 1998 64-97.
6. Li VC. On engineered cementitious composites (ECC) – A review of the material and its applications. *Advanced Concrete Technology* 2003; **1** (3): 215-230.
7. Li VC, Wang S, Wu C. Tensile strain-hardening behavior of PVA-ECC. *ACI Materials Journal* 2001; **98** (6): 483-492.
8. Kong HJ, Bike S, Li VC. Development of a self-compacting ECC employing electrosteric dispersion/stabilization. *Cement and Concrete Composites* 2005; **25** (3): 301-309.
9. Stang H, Li VC. Extrusion of ECC-material. *High Performance Fiber Reinforced Cement Composites 3 (HPFRCC 3)* 1999; 203-212.
10. Kim YY, Kong HJ, Li VC. Design of engineered cementitious composite (ECC) suitable for wet-mix shotcreting. *ACI Materials Journal* 2003; **100** (6): 511-518.
11. Lepech M, Li VC. Large scale processing of engineered cementitious composites. *ACI Materials Journal* 2008; **105** (4): 358-366.
12. Weimann MB, Li VC. Hygral behavior of engineered cementitious composites (ECC). *International Journal for Restoration of Buildings and Monuments* 2003; **9** (5): 513-534.
13. Yücel HE. Design of crack-free, durable and ductile concrete for sustainable highway rigid pavement overlays. PhD. Thesis. University of Gaziantep, Turkey; 2013.
14. Qian S, Zhou J, Rooij MR, Schlangen E, Ye G, Breugel KV. Self-healing behavior of strain hardening cementitious composites incorporating local waste materials. *Cement and Concrete Composites* 2009; **31** (9): 613–621.
15. Wang S, Li VC. Engineered cementitious composites with high volume fly ash. *ACI Materials Journal* 2007; **104** (3): 233–241.
16. Şahmaran M, Li VC. Durability properties of micro-cracked ECC containing high volumes fly ash. *Cement and Concrete Research* 2009; **39** (11): 1033-1043.
17. Qian S, Li VC. Simplified inverse method for determining the tensile properties of strain hardening cementitious composites. *Advanced Concrete Technology* 2008; **6** (2): 353–363.
18. Maslehuddin M, Saricimen H, Al-Mani A. Effect of fly ash addition on the corrosion resisting characteristics of concrete. *ACI Materials Journal* 1987; **84** (1): 42-50.
19. Bisaillon A, Rivest M, Malhotra VM. Performance of high-volume fly ash concrete in large experimental monoliths. *ACI Materials Journal* 1994; **91** (2): 178-187.
20. Zhang MN. Microstructure, crack propagation, and mechanical properties of cement pastes containing high

volumes of fly ashes. *Cement and Concrete Research* 1995; **25** (6): 1165-1178.

21. Şahmaran M, Yaman İÖ, Tokyay M. Development of high volume low-lime and high-lime fly-ash-incorporated self consolidating concrete. *Magazine of Concrete Research* 2007; **59** (2): 97-106.

22. Şahmaran M, Lachemi M, Hossain KMA, Ranade R, Li VC. Influence of aggregate type and size on the ductility and mechanical properties of engineered cementitious composites. *ACI Materials Journal* 2009; **106** (3): 308-316.

23. Wang K, Jansen D, Shah S, Karr A. Permeability Study of Cracked Concrete. *Cement and Concrete Research* 1997; **27** (3): 381-393.

24. Şahmaran M, Li M., Li VC. Transport properties of engineered cementitious composites under chloride exposure. *ACI Materials Journal* 2007; **104** (6): 604-611.

25. Şahmaran M, Yücel HE, Yıldırım G, Al-Emam M, Lachemi M. Investigation of bond between concrete substrate and ECC overlays. *Materials in Civil Engineering* 2014; **26** (1): 167-174.