Hindawi Publishing Corporation
Advances in Civil Engineering
Volume 2011, Article ID 280717, 9 pages
doi:10.1155/2011/280717

*Research Article*

# Interaction between Engineered Cementitious Composites Lining and Foundation Subsurface Drain

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Received 8 August 2011; Accepted 5 September 2011

Academic Editor: Tom Baldock



The effect of cyclic loads on the surface profiles of ECC linings cast on foundations comprising crushed stone and compacted soil was investigated. A geotextile was embedded between the crushed stone and ECC lining for some of the samples. After 28 days of water curing, the hardened surfaces were loaded and monitored for roughness and crack development by measuring surface levels and crack widths, respectively. Neither cracking nor significant variations in the lateral profiles were observed on all the samples for all the loads applied. However, significant variations which depended on the foundation types were observed in the vertical profiles. It was concluded that while ECC can resist cracking due to its high strain capacity, its flexibility causes ECC linings to assume the shape of the foundation material, which can increase the surface roughness at certain loading configurations.

## 1. Introduction

An open channel is medium in which a liquid flows with a "free surface," which is defined as the interface between the moving liquid and an overlying fluid at a constant pressure [1] with water and air being the most common liquid and fluid, respectively. Both natural open channels such as rivers, streams, and rivulets or artificial ones such as irrigation canals and storm-water drains tend to have a wide variability in magnitude, shape, and roughness. However, since a free surface exists in the liquids flowing in all these channels, their flows are governed by the same laws of fluid mechanics [2]. Essentially, all open channels have a bottom slope, and the prime motivating force for liquid flow is gravity. As such, the mechanism of the flow can be simulated to the movement of a mass body down a slope due to gravity. Basically, the component of the weight of the liquid along the slope acts as the driving force, while the boundary resistance at the perimeter of the channel acts a resisting force [3]. On the other hand, the component of the liquid perpendicular to the slope of the channel exerts a downward load on the surface of the channel, which is usually lined to enhance the stability and vitality the channel. Moreover, a subsurface drain may be inserted in the foundation of the open channel to separate groundwater from surface water and avoid the buildup of water pressure which can damage the channel lining [4]. Types of subsurface drains include porous concrete, crushed stone, and river gravel [5]. In line with Newton's laws of motion [6], interactive loads are expected at the lining/subsurface drain interface. Essentially, it is desired that after the expiration of these loads, the surface of the open channel must remain stable, water tight, and smooth so as to continually satisfy the key performance requirements that govern supply, hydraulics, durability, and structural integrity [7] and ensure timely and adequate supply of liquids to intended destinations.

Basically, while the selection of a suitable lining material is governed by both structural integrity and economic viability, the interaction between the subsurface drain and lining in response to imposed loads needs to be fully understood to avoid durability and structural failures. Failures emanate from various causes which include uncertainties in loading, deficiencies in construction materials, inadequacies in design, and poor maintenance [8] and often culminate in high or infinite cost to economies and human life [9] due to abortion of crops and flooding among other problems. Despite efforts at design stage to account for all expected loads and predict material behavior, deviations are inevitable during the life time of the open channel. For instance, flooding, human traffic, or light machinery used for maintenance can impose extra loading. Moreover, loading may actually be cyclic in tandem with irrigation cycles or differential in response to differential settlements in expansive soil foundations. When the open channel is loaded, the point of contact of the load is the lining which transfers the load to the channel foundation through the subsurface drain. While the surface of a porous concrete subsurface drain is normally smooth, it is difficult to achieve smoothness on the surface of the crushed stone drain due to some protruding sharp edges of the stones. While the transferred load may be uniformly distributed, there may be upward reaction loads on the lining/subsurface drain interface. For instance, if the subsurface drain comprises crushed stone, the protruding sharp edges of the crushed stones become pin loads that exert isolated upwards forces onto the lining. Depending on the size of the crushed stone, magnitude, and frequency of imposed downwards load, cycles of the upward pin loads may eventually cause the lining material to deform in conformation with properties of the constituent lining material and configuration of the foundation. It is imperative that deformations minimize surface roughness of the lining surface since according to Manning or Chezy [10], an increase in roughness causes a decrease in the velocity of water flowing across a surface. Defined as a measure of the texture of a surface, roughness is quantified by the vertical deviations of a real surface from its ideal form and determines the amount of frictional resistance a liquid experiences as it flows through a surface.

Previous researchers have elucidated that cyclic loading, deficiencies in the construction materials as well as instabilities in the foundation culminate in durability problems for linings [11–13]. For instance, while plain concrete is the most commonly used lining material owing to its low cost and easy handling [14], the material has inherent deficiencies related to its material structure which diminish both its early age performance and long-term durability [15]. The brittleness of plain concrete causes it to respond to excessive stress by developing through cracks which are apt to expansion, allowing the ingress of aggressive agents which cause further deterioration of the open channel [16]. Moreover, the sections between the cracks are prone to both lateral and vertical displacement in response to consecutive loading or differential settlements in the foundation culminating in increases in the roughness of the open channel lining.

Efforts to address some of the shortcomings of concrete have led to the development of fiber-reinforced materials in recent years [17]. High performance fiber-reinforced cementitious composites (HPFRCC) such as engineered cementitious composites (ECC) exhibit excellent crack dispersion capacity and high ductility. With a strain capacity approximately 350 times that of normal concrete or other fiber-reinforced concrete, ECC can achieve maximum ductility in excess of 3% under uniaxial loading [17, 18].

While concrete has been in use since the 19th century [19], ECC was only developed in the 1990s [20] and hence research is still ongoing to validate wider applicability of the material. In view of the foregoing, this study sought to clarify the interaction of ECC linings under load with various foundation configurations.

## 2. Experimental Program

ECC-lining surfaces were monitored for variations in roughness and crack development. Three subsurface conditions were investigated, that is, compacted soil, crushed stone and crushed stone with a separator inserted between the ECC lining/crushed stone interface. The roughness of the lining and crack development were assessed by monitoring the levels on fixed nodes on each surface and the progression of crack widths, respectively. To simulate the fluctuations of actual loading during cycles of flow, the samples were subjected to cyclic loading.

*2.1. Materials.* ECC premix powder was used for the lining material while sandy soil, 20 mm angular crushed stone and a geotextile separator were used for the foundation. The premix comprised cement, sand, fly ash and PVA fiber 12 mm in length, 0.04 mm in diameter, 1690 MPa in tensile strength and 40.600 MPa in modulus of elasticity. The proportions of the mix components are shown in Table 1. An ECC paste was prepared by adding the premix ECC powder and water containing 3 admixtures, namely, type A (poly carboxylic acid-based superplasticizer), type B (CSA type antishrinkage agent), and type C (poly (ox) alkaline based-expansive agent for air content adjustment) to an electric mixer. The room temperature was kept at 20°C throughout the mixing stage. The mixer was covered and run for 2 minutes soon after addition of water to avoid losses of the finer components of the mix. While the mixer was running, its cover was removed and mixing was continued until 10 minutes elapsed. The ECC paste was then transferred onto a tray and the homogeneity of the fresh mix was corroborated through hand mixing and any identified lumps discarded.

*2.2. Testing Procedure.* Samples M1, M2, and S1 were prepared in 250 mm × 250 mm × 50 mm forms as detailed in Figure 1. Each sample comprised 5 units detailed in Table 2 according to subjected loading. A 40 mm foundation was prepared on the base of each form. The crushed stone in samples M1 and M2 was vibrated for 2 minutes to eliminate voids, while the sandy soil in sample S1 was compacted to 90% standard compaction which is the minimum compaction recommended for open channel embankments [21]. The ECC paste was poured over the foundation to form a 10 mm thick lining. A 250 mm × 250 mm geotextile was embedded in between the crushed stone and lining in sample M2. The 250 mm × 250 mm dimensions were selected to fit the size of the head used for loading, while the 10 mm lining thickness corresponds to the minimum thickness of ECC that can be applied using direct spraying methods [22]. After pouring the ECC paste, the samples were then covered with cotton mats and cured by sprinkling water every day for a period of 28 days. After the curing period, a grid comprising

Table 1: Mix proportion of ECC (1 $m^3$).

| ECC premix* (kg) | Water (20°C)(kg) | Admixture-type A(kg) | Admixture-type B(kg) | Admixture-type C(kg) |
|---|---|---|---|---|
| 1.562.50 | 350.00 | 16.88 | 15.25 | 3.13 (diluted 25 times) |

*ECC premix composition: sand/cement = 0.65; fly ash/cement = 0.3; PVA fiber volume fraction = 2%.

Table 2: Description of samples and loads applied.

| Load(t) | Stress (kPa) | Sample M1 | Sample M2 | Sample S2 |
|---|---|---|---|---|
| 0 | 0 | M1-0 | M2-0 | S1-0 |
| 1 | 21 | M1-1 | M2-1 | S1-1 |
| 2 | 41 | M1-2 | M2-2 | S1-2 |
| 3 | 62 | M1-3 | M2-3 | S1-3 |
| 4 | 83 | M1-4 | M2-4 | S1-4 |

50 mm × 50 mm units was drawn on the surface of each lining creating a total of 25 nodes. The vertical lines were labeled from left to right as A to E, while the horizontal lines were labeled from top to bottom as 1 to 5 as shown in Figure 2.

An automatic leveling device was used to measure the levels on each of the 25 nodes, while a crack viewing device was used to monitor surface cracks. Initial level and crack width readings were taken after which a 220 mm × 220 mm loading head was used to apply uniform stress onto the surface of the lining. Each sample was subjected to 4 loading cycles of stress values described in Table 2. Level measurements were taken on the nodes after each loading cycle and the condition of the surface monitored for crack development. In order to avoid loss of water to the atmosphere and consequent shrinkage, the samples were kept covered with polythene sheets in an enclosed room throughout the study. In addition, to eliminate contraction and expansion of the samples due to thermal stresses, the room temperature was kept at 20°C.

The compressive and flexural strength of the ECC mix used in this study were determined by casting standard ECC prisms of dimensions 40 mm × 40 mm × 160 mm and water curing them at 20°C for 28 days after which the strength tests were carried out. All compressive strength tests adhered to the ASTM C349-02 standard, while the flexural strength tests were carried out in accordance with the ASTM C348-02 standard.

## 3. Results and Discussion

The data from the line A3–E3 marked on Figure 2 was selected for analysis in this study since it is central and hence free from the influence of the edges. No cracks were observed on any of the samples after each loading cycle. From Newton's laws of motion, the upward reactionary load generated was equal and opposite the maximum applied load of 83 kPa shown in Table 2. Therefore, since the first crack stress of ECC is 2.5 MPa [23], the stress due to the pin loads was not sufficient to cause cracking. The surface profiles of the samples after each loading cycle are shown in Figures 3, 4, and 5 which represent samples M1, M2 and S1 respectively. In these figures, the initial profile and the profiles after the 1st, 2nd, 3rd, and 4th loading cycles are represented by graphs C-0, C-1, C-2, C-3, and C-4, respectively. These graphs show variations in the surface profile of the lining in both the lateral and vertical directions. A positive level represents a compaction from the original surface, while a negative level represents a protrusion. Basically, it can be seen that there was no variation in both the lateral and vertical surface profiles on samples M1-0, M2-0, and S1-0 throughout the experiment. This behavior was expected since these samples were not loaded. Moreover, these results indicate that influences due to temperature changes and loss of water to the atmosphere were effectively curtailed. From graph C-0 from each sample, it can be seen that the initial surface profiles of the linings were not totally level. While it was desirable to achieve a level surface at the casting stage of ECC [24], the viscosity of ECC due to presence of PVA fibers [25] presented a challenge to achieving a smooth surface. The variations in the lateral and/or vertical surface profiles after each loading cycle are detailed below.

*3.1. ECC Lining on Crushed Stone Foundation (Sample M1).* From the graphs for the lining cast directly on crushed stone, that is, samples M1-0 to M1-4, it can be seen that while there was no significant change in the lateral profile of an individual sample with each loading cycle, a systematic pattern in the vertical displacement of the linings was observed. The surface levels generally increase with increase in cycles. Since an increase in the reduced level value indicates a compaction, the results show that the lining/crushed stone unit compressed with each loading cycle. Characteristically, it is impossible to totally eliminate voids in uniform size crushed stone despite prior vibration. As a result, the repacking of the crushed stones into existing voids in response to the applied load resulting in the compaction. Even though the loading was in the vertical direction only, the lining was free to move laterally and curve upwards since it was floating in the form. However, the graphs show insignificant variations in the lateral profile. This means that even though the crushed stone foundation beneath the lining comprised loose stones, the lining/foundation unit actually displaced vertically as a single unit. It is thought that at casting stage, due to the capability of ECC to flow under its own weight and fill in the form work in a process termed "self-compactibility" [26], the fresh ECC flowed and filled the voids within the crushed stone. Upon solidification, an ECC/crushed stone composite was created, which destroyed the ECC lining/crushed stone interface and rid the foundation surface of undulations due to the sharp edges of the stones. As a result, the scattered pin loads due to stone protrusions were eliminated and no upward reactionary pin loads and consequent undulations were generated in response to applied loading. Even though

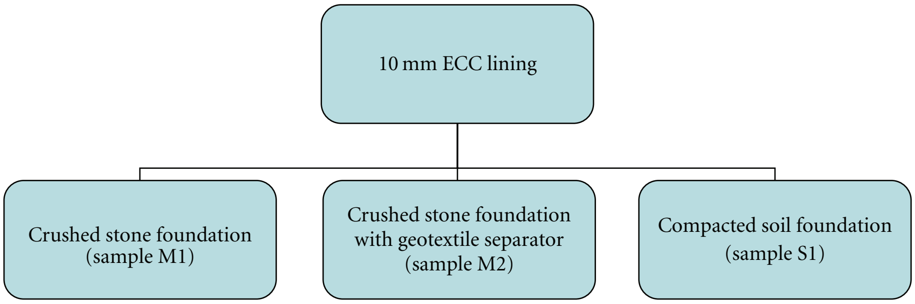


Figure 1: Description of samples used in this study.

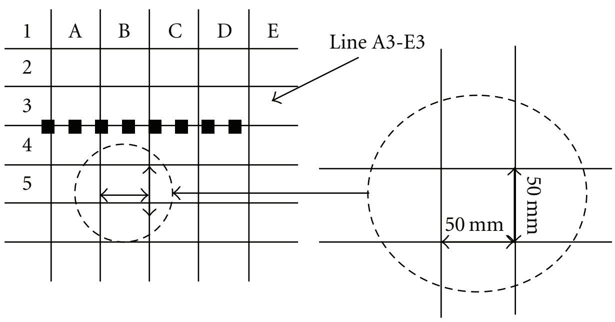


Figure 2: Gridlines on the surface of each sample.

the compressive strength of the ECC used in this study was 32 kPa, the ECC lining withstood stresses of 62 kPa and 83 kPa since infusion of the crushed stone into the ECC paste created a composite with a higher compressive strength [23]. As a result, no signs of failure were observed on the surface of the lining even for the stresses beyond the compressive strength of ECC.

*3.2. ECC Lining on Compacted Soil Foundation (Sample S1).* After the first loading cycle, the lateral profile of the ECC lining cast on compacted soil flattened out and maintained the same levelness with consecutive cycles. Unlike the ECC paste cast over crushed stone which flowed into the pores within the crushed stone and created an ECC/crushed stone composite, the ECC lining and compacted soil remained separate layers after solidifying. As a result, the lining could alter its lateral profile and flatten out in response to the first load. On the other hand, as in sample M1, a systematic pattern in the vertical displacement of the linings for sample S1 due to compaction of the surface was observed. However, the magnitude of the vertical displacements did not differ significantly from those of samples M1. Whilst sandy soil was expected to undergo higher compaction due to relatively lower densities to stone [27], the initial application of 90% compaction level, and the presence of voids in the crushed stone moderated the compactibility of the 2 materials. The high compaction level applied to soil decreased its porosity. In practice, such a configuration is not recommended since the material underlying the lining cannot drain away groundwater and will cause a buildup of ground water pressure and ultimate damage to the lining.

*3.3. ECC Lining on Crushed Stone Foundation with Geotextile Separator (Sample M2).* The behavior of the lining cast on crushed stone with a geotextile separator embedded in between was similar to that of sample S1 for the lower loads of 21 kPa and 41 kPa, but the pattern significantly deviated for the higher loads. In this case, the geotextile separator attached itself to the ECC paste and acted as barrier which prevented the ECC paste from flowing into the crushed stone pores. Therefore, like in the sample S1, the ECC lining and the crushed stone foundation remained separate after solidifying. Consequently, the first loading cycles only flattened out samples M2-1 and M2-2, and the lateral profile levelness was maintained with consecutive loading cycles as in samples S1-1 and S1-2. Moreover, as in samples S2-1 and S2-2, the levels in samples M2-1 and M2-2 generally decreased after application of the first loading cycle. It is thought that since both samples M2 and samples S1 remained as separate layers after solidifying, the lining separated itself from the compacted soil as it flattened out resulting in a protruded surface and consequent decreased levels. However, a marked deviation in behavior from sample S1 was observed with application of the 62 kPa loading. The ECC lining in sample M2-3 responded by deforming into an undulating profile as shown in Figure 4. Since the undulations match the surface profile of the crushed stone foundation, it is thought that the angular edges of the crushed stone exerted upward pin loads onto the geotextile attached to the ECC lining. Being flexible, the geotextile subsequently transferred the loads to the ECC lining resulting in the deformation. However, the deformations that occurred were within the elastic limits of the ECC such that total recovery occurred after each loading cycle [26] allowing recurrence of the undulations. This notion is further confirmed by the magnitude and wavelength of the undulating surface which remained almost constant for all the loading cycles. In practice, undulations increase the roughness of open channel linings. Increase in roughness is undesirable since it culminates in flow losses in accordance with the Manning's or Chezy's formulae [1]. The consequent decrease in the quantity and rate of water delivered to a desired point disrupts irrigation cycles and other water supply systems. However, since the crushed stone used in this study was only 20 mm, the amplitude of the undulations was restricted to less than 5 mm and may not significantly affect the roughness of the open channel lining. Nevertheless, it is likely that roughness will significantly

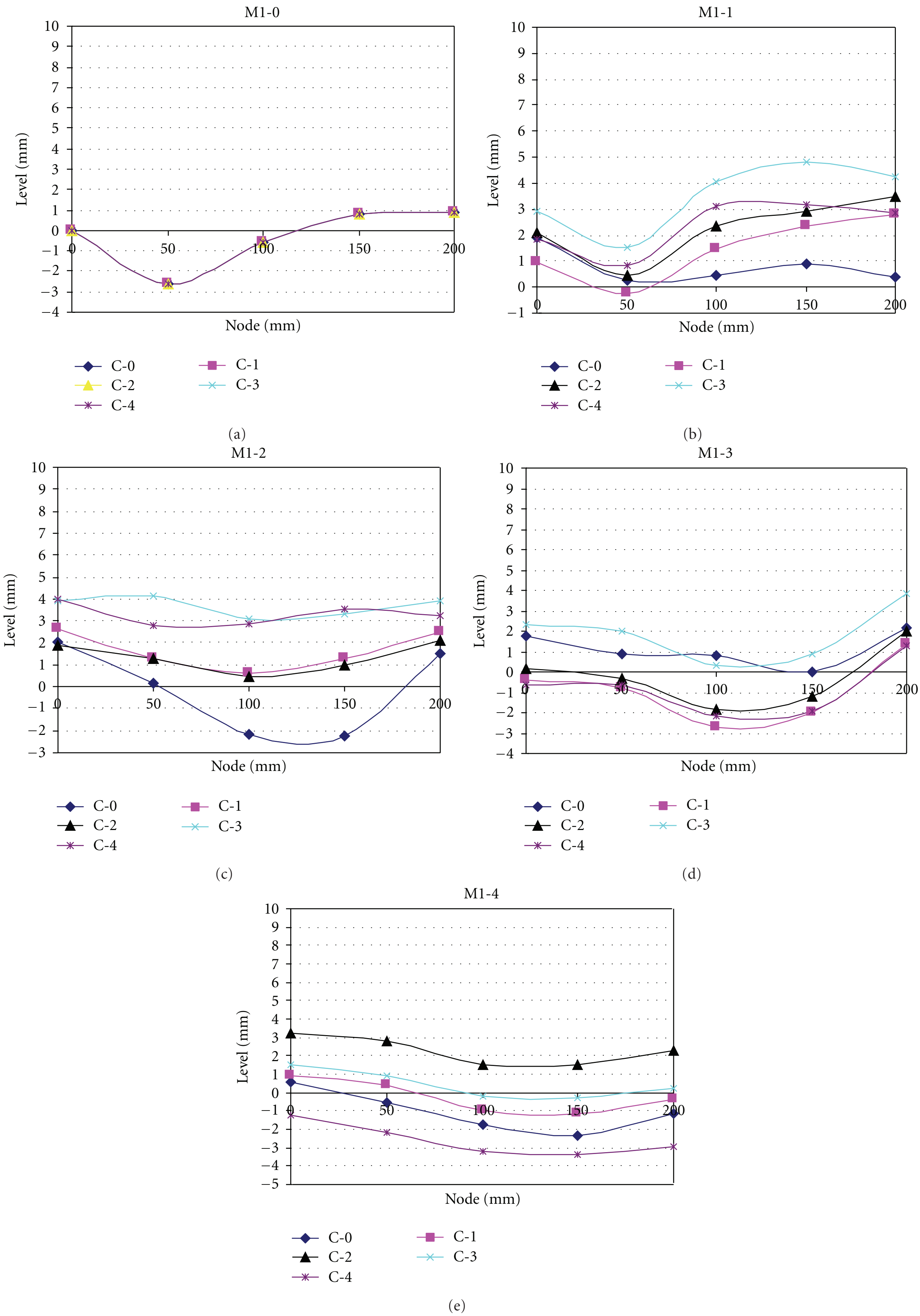


Figure 3: Surface profile along line A3-E3 of ECC lining cast on crushed stone (sample M1).

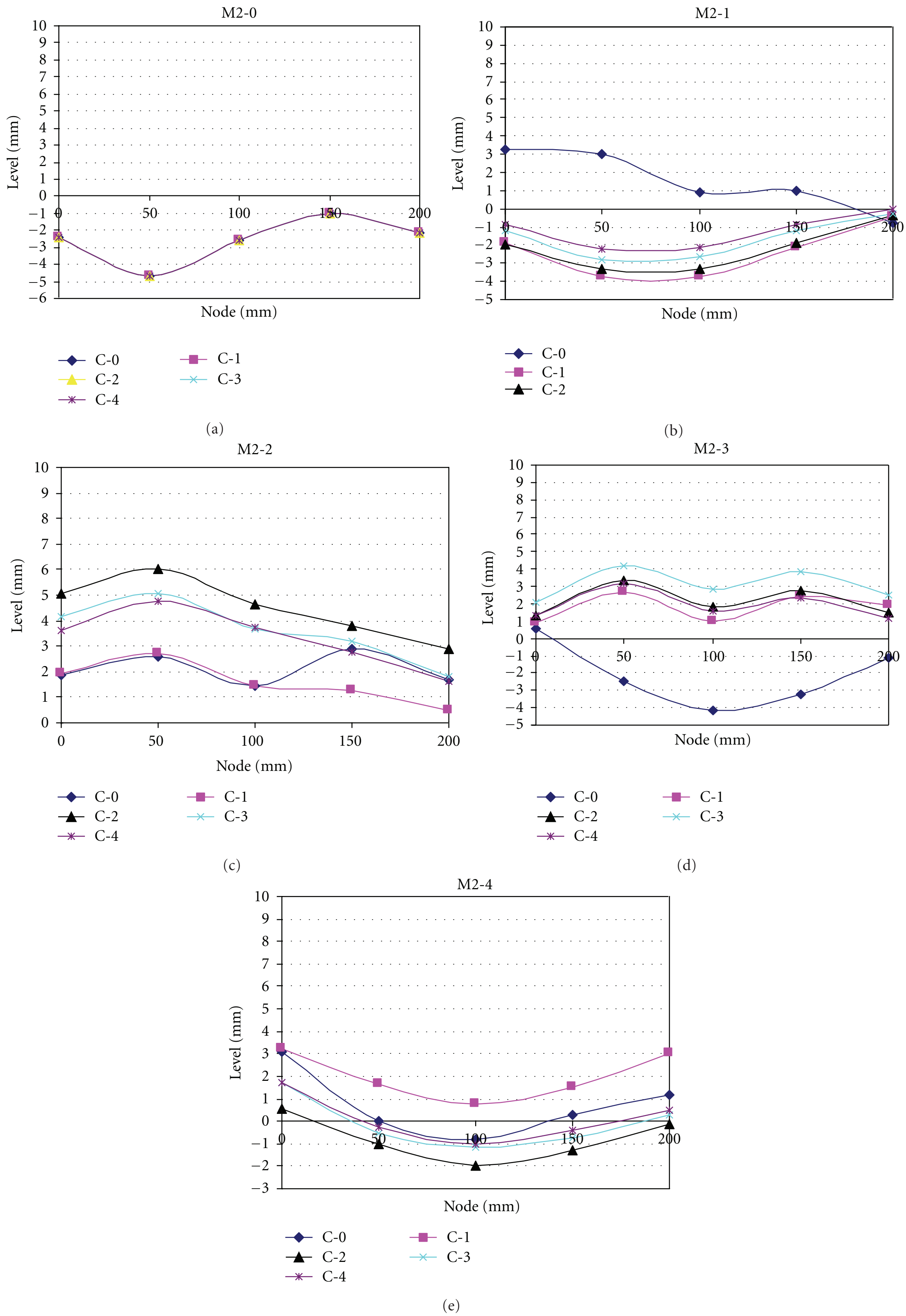


Figure 4: Surface profile along line A3-E3 of ECC lining cast on crushed stone with a geotextile embedded (sample M2).

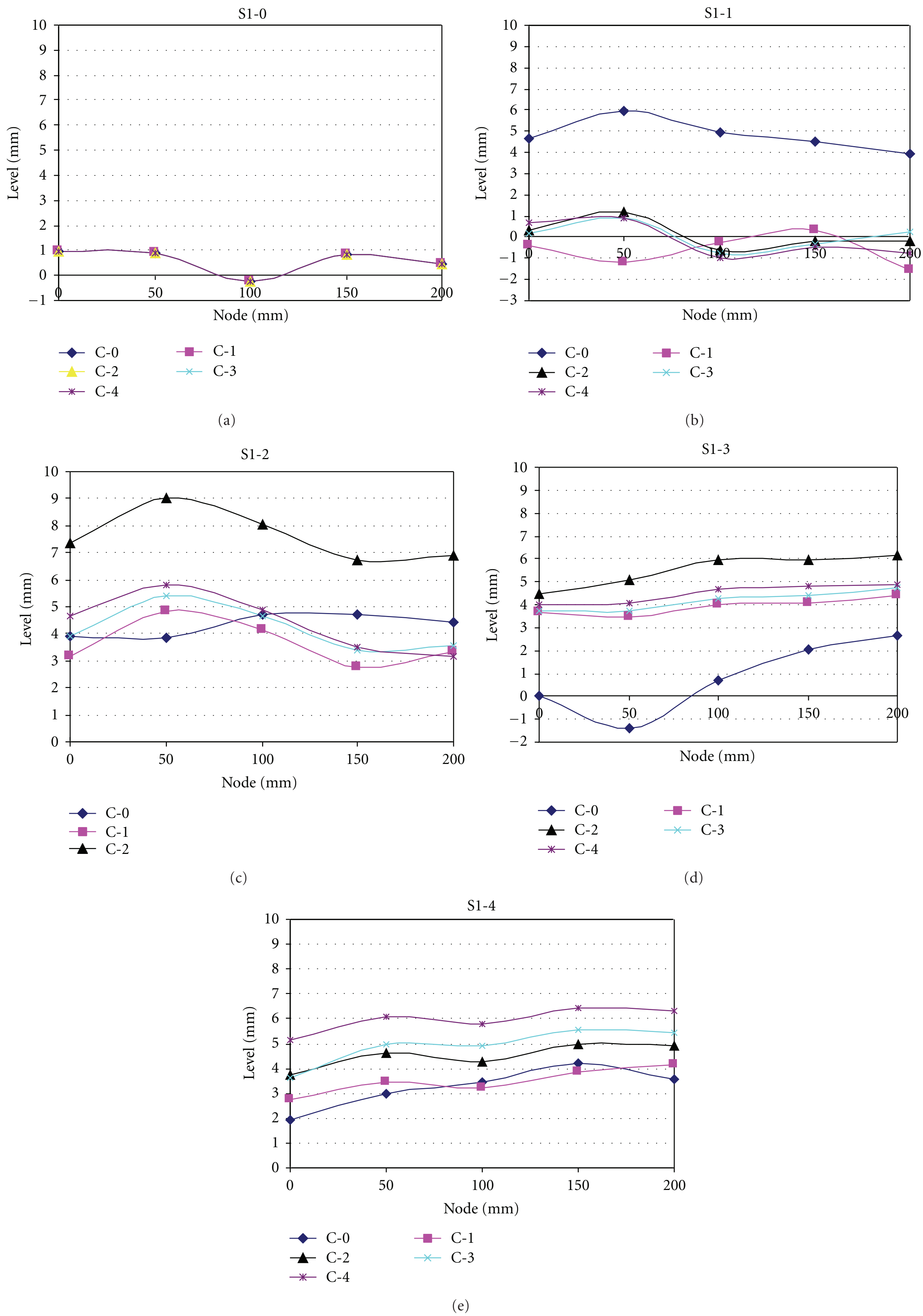


Figure 5: Surface profile along line A3-E3 of ECC lining cast on compacted soil (sample S1).

increase if larger sizes of crushed stone are used in the subsurface drain with ECC as the open channel lining due to the high strain capacity and ductility of ECC [28] which gives the material flexibility to stretch to high magnitudes. Despite the occurrence of undulations on M2-3, no cracks were observed since the magnitude of the generated upward reactionary loads of 62 kPa was not high enough to cause cracking of sample M2-3. Moreover, it is believed that the geotextile that can also act as reinforcement absorbed some of the loads.

Finally, at applied loading of 83 kPa, which was much higher than the strength of the ECC, the lining lost its ductility and neither undulations nor lateral profile variations were observed on sample M2-4. Rather, the lining underwent increased compaction as the cycles increased due to repacking of the crushed stone as observed in samples M1 and S1.

## 4. Conclusions

(1) Cyclic loads affect the vertical profile of the ECC lining cast on both crushed stone and compacted soil by compacting the surface. The level of compaction depends on the compactibility of the foundation components.

(2) The effect of cyclic loads on the lateral profile of the ECC lining depends on the composition of the underlying subsurface drain. Cyclic loads do not affect the lateral profile of the ECC lining cast directly on a crushed stone drain. ECC paste can flow and solidify in the crushed stone voids, resulting in an ECC/crushed stone composite with a higher compressive strength than the originally designed ECC lining. However, the solidification clogs the voids in the crushed stone and diminishes its function as a drain culminating in damage to the lining due to a buildup of ground water pressure.

(3) The inclusion of a geotextile separator between the crushed stone subsurface drain and the ECC lining has a significant impact on the response of the ECC lining to cyclic loads. The geotextile effectively separates the subsurface drain from the lining and allows the lining to deform freely. By preventing the ECC paste from clogging the crushed stone pores and diminishing the capacity of the subsurface drain the geotextile prevents the buildup of ground water pressure. In addition, the geotextile also prevents the occurrence of cracks on the ECC lining by moderating the upward pin loads from the crushed stones in the foundation.

(4) Cyclic loads do not affect the lateral profile of the ECC lining cast on compacted soil foundation. The lining and the subsurface also remain as separate layers after solidification allowing it to displace freely. However, the absence of a freely draining material below the ECC lining will cause damage to the lining due to build up of ground water pressure.

(5) Whether it is used with or without a geotextile, the ductility of ECC enables it to respond to excessive loads by stretching-like metal rather than breaking-like concrete. Being flexible, ECC can assume the shape of the underlying foundation material and develop undulations. While undulations due to small sizes of crushed stone cannot significantly increase surface roughness of a water channel, larger undulations can cause significant increases which consequently increase Manning's roughness coefficient and decrease the velocity of flow across a surface.

(6) The characteristic high strain capacity of ECC enables it to restrict the crack widths in linings to less than 0.1 mm and satisfy serviceability limits in water storage facilities where according to British Code BS 8007(1987) [10, 19] a maximum crack width of 0.2 mm is deemed necessary for maintaining water tightness.

## References

[1] V. T. Chow, *Open-Channel Hydraulics*, McGraw-Hill, New York, NY, USA, 1959.

[2] K. Subramanya, *Flow in Open Channels*, Tata McGraw-Hill, New York, NY, USA, 3rd edition, 2009.

[3] M. H. Chaudry, *Open Channel Flow*, Springer, New York, NY, USA, 2nd edition, 2007.

[4] H. F. French, *Farm Drainage*, Orange Judd and Company, New York, NY, USA, 1859.

[5] L. C. P. M. Stuyt, J. Dierickx, and B. J. Martinez, *Materials for Subsurface Land Drainage Systems*, FAO Irrigation and Drainage, 2006.

[6] M. E. Browne, *Schaum's Outline of Theory and Problems of Physics for Engineering and Science*, McGraw-Hill, New York, NY, USA, 1999.

[7] ISO 2394, *General Principles on Reliability for Structures*, 3rd edition, 1988.

[8] A. Mark and P. E. Marek, *Hydraulic Design Manual: Conduit Strength and Durability*, Texas Department of Transportation (TxDOT): Design Division (DES), 2009.

[9] B. Gharabaghi, W. T. Dickinson, R. P. Rudra, W. J. Snodgrass, and B. G. Krishnappan, "Performance analysis of reinforced vegetative channel lining systems," *Computers and Structures*, vol. 72, no. 1, pp. 149–164, 1999.

[10] D. T. Souders and C. W. Hirt, *Modeling Roughness Effects in Open Channel Flow. Flow Science Technical Note (FSI-02-TN60)*, Flow Science, 2002.

[11] J. S. Lee, I. Y. Choi, H. U. Lee, and H. H. Lee, "Damage identification of a tunnel liner based on deformation data," *Tunnelling and Underground Space Technology*, vol. 20, no. 1, pp. 73–80, 2005.

[12] Zhu Yuanlin and D. L. Carbee, "Strain rate effect on the tensile strength of frozen silt," in *Proceedings of the 4th International Symposium on Ground Freezing*, pp. 153–157, Sapporo, Japan, August 1985.

[13] B. D. Alkire and J. A. Morrison, "Comparative response of soils to freeze-thaw and repeated loading," in *Proceedings of the 3rd International Symposium on Ground Freezing*, pp. 89–96, New Hampshire, Hanover, NH, USA, June 1982.

[14] M. D. Lepech and V. C. Li, "Large-scale processing of engineered cementitious composites," *ACI Materials Journal*, vol. 105, no. 4, pp. 358–366, 2008.

[15] V. C. Li, "Engineered cementitious composites," in *Proceedings of the International Conference on Construction Materials (ConMat '05)*, pp. 22–24, Vancouver, Canada, 2005.

[16] M. Li and V. C. Li, "Behavior of ECC/concrete layer repair system under drying shrinkage," *Journal of Restoration of Buildings and Monuments*, vol. 12, no. 2, pp. 143–160, 2006.

[17] V. C. Li, D. K. Mishra, and H. C. Wu, "Matrix design for pseudo-strain-hardening fibre reinforced cementitious composites," *Materials and Structures*, vol. 28, no. 10, pp. 586–595, 1995.

[18] M. Kunieda, K. Rokugo, and S. Miyazato, *Structural Applications of HPFRCC in Japan. Measuring, Monitoring and Modeling Concrete Properties*, Springer, Amsterdam, The Netherlands, 1977.

[19] A. J. Francis, *The Cement Industry 1796–1914: A History*, 1977.

[20] V. C. Li, "From micromechanics to structural engineering—the design of cementitious composites for civil engineering applications," *JSCE*, vol. 10, no. 2, pp. 37–48, 1993.

[21] Minerals Council of Australia, *Minesite Water Management Handbook*, 1st edition, 1997.

[22] T. Kanda, T. Saito, N. Sakata, and M. Hiraishi, "Fundamental properties of direct sprayed ECC," in *Proceedings of the JCI International Workshop on Ductile Fiber Reinforced Cementitious Composites (DFRCC '02)*, pp. 133–142, Takayama, Japan, 2002.

[23] V. C. Li, "Engineered Cementitious Composites(ECC)- Tailored composites through micromechanical modeling," in *Fiber Reinforced Concrete: Present and the Future*, N. Banthia, A. Bentur, and A. Mufti, Eds., Canadian Society of Civil Engineers, 1998.

[24] T. Kamada and V. C. Li, "Effects of surface preparation on the fracture behavior of ECC/concrete repair system," *Cement and Concrete Composites*, vol. 22, no. 6, pp. 423–431, 2000.

[25] S. K. Saxena, *Polyvinyl Alcohol (PVA). Chemical and Technical Assessment (CTA)*, FAO 61st JECFA, 2004.

[26] H. J. Kong, S. G. Bike, and V. C. Li, "Development of a self-consolidating engineered cementitious composite employing electrosteric dispersion/stabilization," *Cement and Concrete Composites*, vol. 25, no. 3, pp. 301–309, 2003.

[27] A. M. Neville, *Properties of Concrete*, John Wiley & Sons, New York, NY, USA, 4th edition, 1996.

[28] G. Fischer and V. C. Li, "Deformation behavior of fiber-reinforced polymer reinforced engineered cementitious composite (ECC) flexural members under reversed cyclic loading conditions," *ACI Structural Journal*, vol. 100, no. 1, pp. 25–35, 2003.