Study on the Improvement of the Serviceability Performance of Earth Hydraulic Structures by using High Performance Fiber Reinforced Cementitious Composites

複数微細ひび割れ型繊維補強セメント複合材料による土構造水利施設の使用性の向上に関する研究

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By

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Abstract

This study investigated the effectiveness of High Performance Fiber Reinforced Cementitious Composites (HPFRCC) in improving the serviceability performance of earth hydraulic structures. The HPFRCC employed in this study was Engineered Cementitious Composites (ECC) and concrete was used as a comparison. The target application was the repair of earth dams and canals where restricting crack widths within serviceability limits is critical for ensuring water tightness and maintaining serviceability performance. Investigations were carried out to clarify effectiveness of ECC in the repair of earth embankments, durability when exposed to organic acid containing weed sap, surface deformation of canal linings and cost effectiveness. In the investigation for the repair of earth embankments, the aim was to curtail the re-emergence of weeds and consequent impairment of durability after application of a repair layer. ECC and concrete were monitored for crack development and penetration of light which supports photosynthesis and consequent growth of weeds. It was observed that while ECC developed fine surface cracks of width less than 0.1mm which prevented the penetration of adequate light to support photosynthesis and weed growth, concrete developed through cracks of unlimited width through which adequate light could penetrate. It was therefore concluded that ECC was more effective than concrete in curtailing the re-emergence of weeds on the surfaces of earth embankments. The effect of organic acids on hydration of ECC and regular was also investigated. The setting time of the fresh materials as well as compressive and flexural strength of the hardened materials were monitored. It was observed that while organic acids tend to retard the setting time of all cementitious materials by the neutralization alkali-acid reaction or through adsorption of particles on the surfaces of the hydrating cement particles, the severity of the retardation depends on the composition of the cementitious material. It was found that the retardation in the setting time of ECC was less severe than in regular concrete since the chemical additives in ECC moderated the pH of the material and enabled ECC to stiffen and gain strength within the expected period. A third investigation was undertaken to clarify the effect of the ductility of ECC under non-uniform loading on the levelness of ECC lining surfaces in canals. It was found that non-uniform loads caused undulations on the surface of ECC and hence increased roughness. The magnitude of the deformation and consequent significance of the roughness was relative to the magnitude and source of the non-uniform loading. Moreover, the inclusion of geo-textiles as separators moderated the deformation. Finally, the effect of reducing the volume of material as a cost cutting measure was investigated by monitoring the effect of thickness of ECC elements on crack distribution was monitored. It was observed that the thickness of plates has no significant effect on the crack width and crack distribution of ECC. This enables smaller thicknesses of ECC elements to be applied where structurally possible, thereby reducing the material volume and subsequently lowering overall material costs. The overall conclusion in this study was that ECC can improve the serviceability performance of earth hydraulic structures and lower the Life Cycle Costs(LCC).

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CHAPTER 1: INTRODUCTION

1.1 Thesis Statement

Earth dams and earth canals are the most common earth hydraulic structures owing to the low cost of construction and simple construction methods. However, such structures are prone to various deteriorative forces which compromise serviceability performance and hence require regular maintenance. In order to correct or prevent deterioration, repair with concrete may be necessary. However, concrete lacks both short and long term durability due to inherent deficiencies related to its material structure. Therefore, there is need to find a more durable repair material in order to improve the serviceability performance of earth hydraulic structures. Efforts to address the shortcomings of concrete have led to the development of High Performance Fiber Reinforced Cementitious Composites (HPFRCC) such as Engineered Cementitious Composite (ECC) in the last decade. The characteristics of ECC such as high strain capacity, ductility and the ability to restrict deformation to fine surface cracks may be the solution to improving the serviceability performance of earth hydraulic structures.

1.2 Motivation

Recent years have seen a rapid increase in the demand for water to meet agricultural, industrial, domestic, recreational and environmental needs on one hand and a decline in the available water resources on the other hand. Compounding the growing water crisis is the fact that out of the available water resources on earth, 97% is salty and hence not readily usable while only 3% is fresh. Moreover, of the fresh water more than 66% is frozen in glaciers and polar ice caps [1]. The remaining unfrozen water exists mainly underground with only a small fraction available above the ground in rivers, streams, dams or in the air [2]. While fresh water is a renewable resource, the supply of clean fresh water is steadily decreasing while world population continues to spiral resulting in water demand increasingly exceeding supply in many parts of the world. The reasons for the imbalance differs from place to place with insufficient rainfall being a factor in some areas while in others large volumes of water are inaccessible and freely flow into the sea due to the absence of hydraulic structures such as dams or canals to divert or store the water. Moreover, some of the available hydraulic structures are heavily deteriorated and in danger of failure due to faulty design, improper construction, poor maintenance practice, deficiencies in construction materials, extreme weather conditions or natural disasters. Earth hydraulic structures tend to suffer the most deterioration and require regular maintenance to maintain performance at the required level. The severity of the diagnosis will determine whether repair, renewal or renovation should be prescribed to recover or improve performance. However, since the costs associated with renewal and renovation are usually prohibitive and the dangers of failed structures to human life and property are tantalizing, improving the serviceability performance of the existing structures through repair may be the most viable option.

1.3 Goals/Objectives

The aim of this research is to establish whether the serviceability performance of earth hydraulic structures can be improved by using HPFRCC in repair.

1.4 Significance

As compared to concrete structures, earth dams and earth canals are prone to accelerated degradation if not properly maintained. Deficiencies of concrete have been translated to their repair structures and culminated in endless repair of repairs posing risk of failure and increasing the life cycle costs of the infrastructure. Successful improvement of serviceability performance by HPFRCC will curtail repair of repairs, enhance both long and short term durability, reduce risk of failure and reduce life cycle costs of earth hydraulic structures.

1.5 Outline of Thesis

The thesis comprises the introduction in the first chapter in which the thesis statement, motivation, objectives and significance of the study are discussed. The background and related work are discussed in the literature review in the second chapter. The third chapter details the investigations carried out, results, discussions and conclusions of the four investigations carried out in this study. Finally the overall conclusions and recommendations of the study are discussed in the fourth chapter.

CHAPTER 2: LITERATURE REVIEW

2.1 Background

Hydraulic structures are structures submerged or partially submerged in any body of water intended to disrupt the natural flow of the water by diverting, disrupting or completely stopping the flow. Examples of hydraulic structures include dams and canals constructed from concrete, earth or other materials. The use of earth as a construction material in hydraulic structures is common. In fact earth dams are the most common type of dam built to any height [3] while in small canals or where costs exceed benefits canals are usually unlined [4] or earthen. For instance as shown in Table 2.1, in Zimbabwe, earth dams account for 73% of all dams in the country. The reasons for such wide spread use are that the foundation requirements are not as rigorous as other dams, local available soil is the main construction material and neither high skill nor special plants are required. In fact most earth-moving machines can be used. As a result, the cost of construction is lower than concrete structures. However earth hydraulic structures tend to deteriorate faster than other types of dams and hence require frequent maintenance in order to maintain serviceability and functionality.

Table 2.1 Statistics of large dams in Zimbabwe [79]

Dam type	Height range(m)				Total	%
	<30	30-59	60-99	100-149		
Earth-fill	66	8	2		76	73
Rock-fill	1	2			3	2.9
Concrete gravity	6	3			9	8.7
Concrete buttress	2	1			3	2.9
Arch	6	5	1	1	13	12.5
Total	81	19	3	1	104	

During the service life of any hydraulic structure degradation occurs and the severity depends on both the constituent materials and ambient deteriorative forces. The ISO2394:1998 ‘General Principles on Reliability of Structures’ provide guidelines on performance verification based design. It is stipulated that the function and performance required from any structure should be provided for in the performance verification. Functional requirements relate to the qualitative description of the required function while performance requirements relate to the quantitative description of the functional requirements. For water supply facilities, the performance requirements relate to water supply, hydraulic and structural performances. Water supply performance relates to the supply of water by the manager and the reception of adequate water by the user. The verification items for this performance are water tightness of the supply facility and the performance of joints. Hydraulic performance relates to the transportation of water and is verified by transmissivity, hydraulic safe performance, running water and water sharing control functions. Structural performance relates to the maintenance of the structural integrity and is verified by dynamic safety, stability and durability performances. Even though a dam or canal may be structurally sound and stable enough to carry its load, loss of water tightness due to excessive cracking or deformation leads to loss of serviceability and functionality thence serviceability failure occurs. The degradation that causes serviceability loss occurs over time and is caused by either internal or external factors which can be physical, chemical or mechanical. Depending on the diagnosis of the degradation, repair may be necessary. Repair is primarily intended to recover or improve durability by improving the lifetime of a facility through suppression of the advancement of degradation and limiting partial facility damage to levels where it does not interfere with the desired functions. On the other hand, reinforcement is concerned with the recovery or improvement of structural strength of a facility through addition of concrete or fiber reinforced material.

2.2 Earth dams

Designed as an overflow section with a separate spillway, earth dams are classified by the method of construction or mechanical characteristics as rolled and hydraulic fill dams or homogeneous and non-homogeneous respectively. Failure of earth dams can be attributed to faulty design, improper construction and poor maintenance practices and is classified as hydraulic, seepage and structural failure [5]. The main cause of hydraulic failure, which accounts for over 40% of earth dam failure cases, is caused by overtopping, erosion of downstream toe, erosion of upstream surface and erosion of downstream face by gully formation. Seepage failure accounts for 35% of dam failures and is caused by sloughing on the downstream side of the dam, piping through the dam body or foundation due to excessive seepage. About 25% of earth dam failures is attributed to structural failure, which is mainly due to shear failure causing slide along the slopes due to slide in embankment or foundation, faulty construction, poor maintenance and insufficient compaction. On the other hand, natural forces such as earthquakes may cause failure due to development of cracks in the dam core which cause leakages and piping failure, setting up of slow waves due to shaking of reservoir bottom which lead to overtopping, settlement of the dam which may reduce freeboard causing failure by overtopping, sliding of natural hills causing damage to dam and its appurtenant structures, fault movement in the dam site reducing reservoir capacity and causing overtopping, shear slide of dam, liquefaction of the sand below the foundation and failure of slope pitching.

2.2.1 Maintenance problems

Certain types of grass, shrubs and trees pose persistent maintenance problem on earth dam surfaces. In most countries, most earth dams are infested with such weeds with some states in the US reporting as high as 95% [6] as having the problem. In Zimbabwe, the figure is equally high especially in the small to medium size category where maintenance is carried out by the individual owners [7]. Dam safety regulators and inspectors, engineers, and consultants are frequently confronted with challenges on the issue of removal of these weeds due to sentimental, cultural, ecological, legal, and financial issues.

2.2.2 Problems and failures associated with weeds

The penetration of weeds into earth dams and their appurtenances tend to cause serious deterioration and distress that can impede safe operation or result in failure of earth dams [6]. Trees and dense vegetation hinder effective dam inspections while tree roots can cause serious structural instability or hydraulic problems. On the other hand, trees and brush attract burrowing animals, which can also in turn cause serious structural or hydraulic problems. For instance, penetration of roots into the embankment loosens the soil and may cause cracking on the surfaces of earth dams as the roots spread through the dam body. If crack widths exceed serviceability limits, the facility loses water tightness and thence serviceability failure occurs. Moreover, uprooted trees can reduce the cross sectional area of the embankment and reduce stability while decaying roots create seepage paths which lead to a host of problems including internal seepage problems. Holes formed by blown-down tree in the downstream toe area can produce a potentially dangerous increase in hydraulic seepage gradient and internal erosion or piping problems in dikes.

In view of the foregoing, a fundamental understanding and technical knowledge of potential detrimental impacts of trees and woody vegetation growth on the safety of earthen dams and ways in which deterioration can be curbed is necessary in order to minimize failure. Most dam safety experts agree that research needs to be done on determining the relationship of plant and tree species to root penetration of artificial environments such as embankment dams, the interaction between root systems and the phreatic zone and surface as well as development and understanding of various types of physical, biological, and chemical treatment and barriers for controlling root growth. Because many existing dams exhibit dense growths of trees and woody vegetation with deep-penetrating root systems, engineering methods need to be developed for understanding, predicting, and stabilizing the effects of these root penetrations to minimize internal erosion and failure.

Fig.2.1. Dam with inspection-hindering trees in Tennessee[6]

Fig.2.2. Serious damage by uprooted tree to embankment stability at a dam in Oregon[6]

Fig.2.3. Dam failure due to root penetration in Colorado[6]

Fig.2.4. Exposed tree roots in overtopped dam[6]

Fig.2.5. Tree root induced scouring on crest and downstream face[6]

2.2.3 Maintenance Procedure

While all tree and woody vegetation growth on earth dams is undesirable and has some level of detrimental impact on the operation, performance, and safety of the dams, not all tree and woody vegetation imposes the same level of impact. As a result the treatment of vegetation on earth dams differs depending on the inspection diagnosis. For instance, ordinary grass is usually mowed while shrubs and trees are usually cut. Stumps and roots can be removed or left in the embankment. In some cases vegetative barriers such as bio-barriers or selvicides, insecticides, chemical treatment and burning can be used. The selection of the maintenance procedure depends on the ambient conditions and available resources. However each method is associated with some constraints which include financial limitations, environmental regulations, aesthetics, endangered species issues and sentimental reasons. For instance, while complete removal of the vegetation including roots would be desirable, the massive earthworks and consequent costs associated with the repair of the damaged embankment are usually prohibitive such that leaving the stumps and roots in the ground would be more viable. On the other hand, continual tree root development cannot occur in soils that are well compacted hence one method to control tree and woody vegetation growth on new and existing earth dams where remediation requires placement of additional embankment fill soil is to compact the embankment fill soils to a high degree of compaction. Increased compaction of embankment fill soils reduces the air void content and limits the amount of surface water that can infiltrate into the embankment slope. In any case, a good ground cover of grasses as required can still be established in well-compacted soils since the depth of grass root penetration is minimal and the surficial soils will typically sustain the shallow grass root penetration.

2.2.4 Physiological Requirements of Vegetation

Trees and woody vegetation, like all living things, must have oxygen, nutrients, and water (moisture) to photosynthesize, grow and survive. Without any one of these requirements, tree roots cannot continue development and tree growth cannot continue. The root system of trees and woody vegetation is in simplified terms comprised of two major components i.e. the root ball, typically directly below the trunk of the tree, and the lateral or perimeter transport root system that typically extends beyond the ‘drip line’ or vertical projection of the canopy of the tree. Contrary to popular belief, root penetration does not stabilize an embankment [6]. Rather, roots stabilize the tree and loosen the soil mass within which the tree roots are developing. While tree roots cannot survive in the inundated portion of the dam, tree root development and tree growth cannot also occur in soil masses having moisture contents less than about twelve percent for extended periods. In both cases vegetation subjected to these conditions will also wither and die.

2.3 Unlined Canals/Earthen canals

Canals are artificial channels intended for water supply or navigable transportation. While large canals are usually lined with concrete, small canals are predominantly earthen. Depending on the type of the constituent soil, volume of flow and other operational conditions, unlined canals tend to be unstable and prone to deterioration and loss of serviceability and functionality. As such, earthen canals are usually lined with tougher material to enhance stability, minimize degradation and improve serviceability performance.

2.3.1 Maintenance Problems

Like earth dams, unlined canals are also prone to exuberance of vegetation and burrowing of moles and rats and also require rigorous maintenance. Lining canals has several benefits including water conservation, stoppage of seepage flow into adjacent land or roads, reduced canal dimensions and reduced maintenance. Unlined canals often lose serviceability and functionality due to excessive water losses. For instance, canals that carry from 30 to 150 l/s can lose 10 to 15% of this flow by seepage and water consumption by weeds [4].

In active clay soils, crack development in the embankment causes slow movement of shallow water which favors development of thick aquatic weeds, which in turn encourages the drying and cracking process which may structurally weaken the banks .This obviously adds significantly to the cost of maintenance. The cracks opened in dry periods do not close fully when saturated by water flows, and losses can be up to 25% of the water diverted into the system [8]. On the other hand, cycles of swelling, heaving, shrinkage and settlement leads to progressive bank deterioration. The shear strength of clays depends on cohesion between particles and in a newly-formed compacted clay masses the inter-particle cohesion is high such that on first drying, the cracks appear and close up again on wetting, but do not regain their original inter-particle cohesion leading to a reduction in shear strength after a few drying and wetting cycles.

The banks of unlined canals are highly permeable and seepage of water through them will cause very wet or waterlogged conditions, or even pools of water on adjacent fields or roads. On the other hand, the permeability of a lined canal bank is far less than that of an unlined one and may even be zero depending on the lining material. Therefore, lining canals will significantly curtail seepage. Moreover, since the roughness resistance to flow of a lined canal is less than that of an unlined canal, for the same bed slope, the flow velocity in lined canals is higher than in unlined canals. In addition, the hard surface of the lining material is not easily eroded and hence allows a higher velocity compared to an earthen canal surface. Since the canal discharge is the product of the cross-section of a canal and the velocity of the flow, the higher velocity allowable and obtainable in lined canals enables a smaller cross -section for lined canals than unlined ones.

Fig.2.6. Manchester Bolton and Bury Canal- The photo on the left shows the original overgrown state of the canal and to the right the canal following clearance[80]

2.3.2 Maintenance procedure

While lining a canal will not completely eliminate water losses, approximately 60 to 80% of the water that is lost in unlined irrigation canals can be saved by a hard-surface lining[4]. Minimizing water losses is very important for maintaining the conveyance efficiency. Moreover, in schemes where irrigation water is pumped, reduced water losses means less water to pump and thus a reduction in pumping costs. A surface lining such as concrete, brick or plastic on the canal prevents the growth of plants and discourages hole-making by rats or termites. Therefore the maintenance of a lined canal can be easier and quicker than that of an unlined canal. Moreover, the higher velocity that can safely be allowed in the lined canal prevents the small particles of soil carried in the water from settling out, accumulating and causing siltation. Importantly, lining a canal enhances the stability of the bed and embankments and decreases susceptibility to erosion.

The most commonly used types of lining include concrete, concrete blocks, bricks or stone masonry, sand cement, plastic and compacted clay. The choice of lining material depends primarily on local costs, availability of materials and the available equipment. Whilst the initial cost of the lining can be high, selection of a durable lining material coupled with good maintenance will ensure long term use and will offset the high initial costs. As discussed earlier, whilst concrete is ubiquitous also in lining of canals, its lack of both short and long term durability pose the same durability challenges as other concrete structures especially when the thickness of lining is very thin. Therefore, lining canals requires a high standard of construction especially in water courses which must withstand a great deal of wear and tear to avoid reduction of service life and increasing maintenance costs. Moreover, movements in the soils below the lining are transferred to the lining and depending on the properties of the lining material, brittle materials such as concrete are likely to develop through cracks and set off another repair cycle. As in earth dams, there is need to find a suitable material that can effectively control weeds and produce durable repairs so as to curtail repair cycles and lower life cycle costs.

2.4 Durability of repair materials

For repairs to be cost effective, it is necessary for the repair material to be durable. A large number of earth hydraulic structures worldwide including previously repaired ones, are currently suffering deterioration or distress and are in need of repair. As discussed earlier, repair materials include various forms of cementitious materials especially concrete. However, concrete structure repairs are often perceived to lack both early age performance and long-term durability. Early age surface cracking, spalling, or *interface de-lamination* between the repair and the concrete substrate are common after repair. The lack of durability in concrete repairs induces *repair failures* and endless "*repair of repairs*". The drying shrinkage of the 'new' repair material restrained by the 'old' substrate causes cracking in the repair material and the interface de-lamination between the repair material and the substrate may also introduce deteriorative agents which accelerate further deterioration. This results in loss of serviceability and or structural integrity of the repair system thus impairing load transfer between the repair and the substrate as

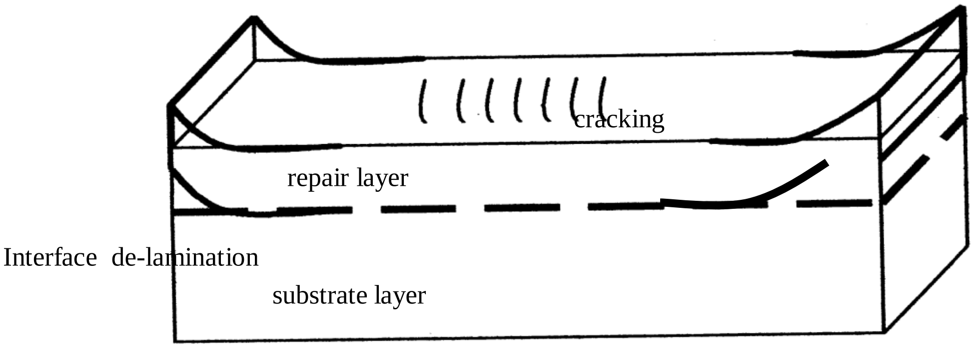


Fig.2.7. Interface de-lamination and cracking after repair

well as unsatisfactory functionality and serviceability of the structure. Service life may be shortened or life cycle costs will be increased due to the recurring repairing.

2.4.1 Fracture Toughness and Strength of a Repair material

To achieve high durability of a repaired concrete structure, both durability of the repair material and the interaction between the repair and the substrate need to be carefully evaluated. High strength concrete, for example, is believed to have good durability because of its low water/cement ratio, which makes this material stronger and less impermeable compared with normal concrete. However, despite its high compressive strength, high strength concrete tends to fracture when undergoing shrinkage due to restraint by the concrete substrate. Once cracked, the repaired system will be in danger of losing serviceability when exposed to aggressive environments despite the repair material having 'low permeability' in the absence of cracking. In general, high brittleness of repair material ultimately leads to a repaired structure with poor serviceability. In this sense, material durability should be more related to its fracture toughness i.e. material's resistance to cracking than its strength. Thus repair materials with tensile ductility for suppression of fracture such as HPFRCCs should be more suitable.

2.4.2 Compatibility of repair material and substrate layer

The compatibility between repair material and the substrate is important for the durability of the repaired system, especially compatibility in the coefficient of thermal expansion and in the Young's Modulus. A lower modulus in the repair material, in fact, could lead to lower stress build up due to restrained drying shrinkage, thus reducing the tendency to cracking in the repair material or at the interface between the repair material and the surrounding concrete.

2.4.3 Cementitious Composites

Cement pastes (PC), mortars and concretes are brittle due to the Griffith type mode of crack propagation. Modern concepts of fiber reinforcement and interface engineering have been invented to modify the brittle behavior. Short fiber reinforced composites (FRC) exhibit what is known as quasi –brittle behavior which is characterized by a more ductile post-peak softening in uni-axial tension in contrast to a plain matrix due to the gradual pull-out of fiber from a single crack plane. In recent years it has been shown that non- catastrophic failure modes exist when a brittle matrix is adequately reinforced either by continuous aligned fibers or short random fibers. This failure mode is characterized by sustained or even higher load carrying capacity after first cracking of the matrix as shown in Fig.2.8. The pseudo strain hardening behavior is associated with the appearance of a sequence of matrix cracks increasing in density until a composite peak load is reached. Conditions for the transition from quasi-brittle behavior to non-catastrophic failure mode are determined theoretically. The class of short fiber reinforced composites designed to exhibit pseudo strain –strain hardening properties based on micromechanical principles is referred to as Engineered Cementitious Composites (ECC). Table 2.2 shows a comparison of ECC with other HPFRCC and FRCs.

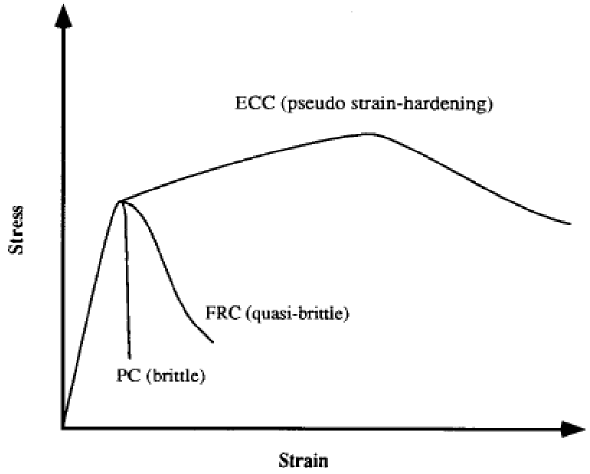


Fig.2.8 Different tensile failure modes in cementitious composites

Table 2.2 Comparison of ECC to other composite materials[9]

Properties	FRC	Common HPFRCC	ECC
Design Methodology	N/A	use high v_f	micromechanics based, minimize v_f for cost and processibility
Fiber	any type, v_f usually less than 2%; df for steel ~ 500 micrometer	mostly steel, v_f usually > 5%; df ~ 150 micrometer	tailored, polymer fibers, v_f usually less than 2%; df < 50 micrometer
Matrix	coarse aggregates	fine aggregates	controlled for matrix toughness, flaw size; fine sand
Interface	not controlled	not controlled	chemical and frictional bonds controlled for bridging properties
Mechanical Properties	strain-softening:	strain-hardening:	strain-hardening:
Tensile strain	0.1%	<1.5%	>3% (typical); 8% max
Crack width	unlimited	typically several hundred micrometers, unlimited beyond 1.5% strain	typically < 100 micrometer during strain-hardening

NB: FRC=Fiber-Reinforced Cement. HPFRCC=High-Performance Fiber Reinforced Cementitious Composites

2.4.4 Engineered Cementitious Composites (ECC)

ECC is a member of High Performance Fiber Reinforced Cement Composites (HPFRCC) materials which typically show multiple cracking and strain-hardening behaviors in tension. ECC has high ductility and toughness indicated by multiple micro-cracking behavior under uni-axial tension. ECC can relieve shrinkage induced stresses in the ECC repair layer and at the ECC/concrete interface, thereby suppressing large surface cracks and interface de-lamination. ECC looks like regular concrete, but under excessive strain the material bends because the distinctively coated matrix of fibers in the cement is allowed to slide within the cement. ECC is 500 times more resistant to cracking than concrete and 40 percent lighter in weight [10]. Ductility is high despite small volumes of fiber (< 2%).The materials in the concrete itself are designed for maximum flexibility. Under excessive strain, ECC bends because the distinctively coated matrix of fibers is allowed to slide within the cement (Fig.2.9).

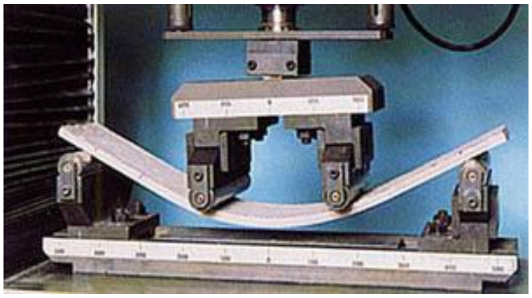


Fig.2.9.ECC bending under load[11]

2.4.4.1 Design of ECC

ECC is an easy to cast and shape mortar based composite reinforced with short random fibers, usually polymer fibers such polyvinyl alcohol (PVA). Unlike common fiber reinforced concrete, ECC is a micromechanically designed material. This means that the mechanical interactions between fiber, matrix and its interface can be taken into account by a micromechanical model which calculates these constituent properties to a composite response. As a result, guidelines for selection of fiber, matrix and interface characteristics advantageous for composite properties are made available.

2.4.4.2 Mix Proportions of ECC

The first generation of ECC has been composed of cement and silica fumes with no aggregates in the matrix. The lack of fine and coarse aggregates in the matrix results in low composite elastic modulus and high heat of hydration which may limit the widespread applications of the composites in construction industry [12].

Table 2.3 Mix Proportions of ECC [13]

mix	water by binder ratio	unit water (kg/m3)	sand by binder ratio	anti- shrinkage agent(kg/m3)	fiber volume fraction (%)	air content (%)
N	0.46	364	0.64	15	2	10
M	0.46	364	0.64	15	2	10

1) Fly ash is added by 0.3 of binder weight

2) Expansive agent replaces sand weight by 10%

In addition to the above materials, a bio-saccharide-type viscous agent is applied to provide compatibility between fluidity and fiber dispersibility and a polycarboxylic-acid –based superplasticizer. Typical fiber length is 12mm, diameter is 0.04mm, tensile strength 1690MPa and elastic modulus 40,600MPa.

2.4.4.3 Strain Hardening Behavior of ECC

One of the most significant characteristics of ECC is its tensile strain hardening behavior. With a strain capacity in the range of 3-7%, unlike common concrete, which is brittle and breaks under that amount of strain, ECC will bend under the same stress, like a piece of sheet metal. Despite the fiber content being typically less than 2% by volume, the high ductility is achieved by optimizing the microstructure of the composite employing micromechanical models.

2.4.4.4 Current Applications of ECC

Current applications include bridge decks, building dampers, retaining wall, irrigation channels, damper of RC buildings, patching on walls, dams, waterways and viaducts. In addition to tensile load bearing capacity, protection against penetration of substance through fine cracks is one of the advantages in these applications.

Fig 2.10 Earth dam repair with ECC in Tottori

2.4.4.5 Use of ECC as a repair material

In the 1990s research was commenced to validate the use of ECC as a repair material [10]. Experiments were carried out on simulated layered repair systems under controlled humidity. Measurements of time dependent surface cracking and interface de-lamination magnitude and extent confirmed that using ECC as a repair material simultaneously suppressed shrinkage induced repair surface cracking and de-lamination between the repair and the concrete substrate. It was then concluded that durability issues related to thermal expansion or contraction differences between the repair material and the concrete substrate can be addressed in a similar manner and the concept of translating ECC repair material ductility to the whole repair system durability can be widely applied to many repair applications for developing cost-effective and durable repairs.

2.4.4.6 Application to repair of earth hydraulic structures

To date research has focused on the use of ECC for the repair of concrete structures. On the other hand, regular concrete has also been the main repair material for earth hydraulic structures. In most cases, subsequent to uprooting of trees and shrubs, inspections are carried out to confirm that all major root systems have been removed. Following inspection and approval of the undercut area by the engineer, suitable backfill should be placed in the excavation and properly compacted to the dam remediation design limits. In conjunction with the undercutting and backfilling, a slope protection system such as a rigid (concrete) upstream embankment slope protection system or a concrete slab is placed directly on the upstream slope above the normal pool elevation to deter future tree and woody vegetation growth and reduce the potential for wave and surface runoff erosion. While this system is somewhat limited relative to the area of protection, the most critical aspect of this system is that it provides no filtration and/or drainage system beneath the concrete slab. However, the deficiencies of concrete repair systems such as excessive cracking discussed earlier often compromise the durability of such repair structures leading to repair failures. Moreover, continual wave action and the buildup of hydrostatic pressures beneath the concrete slab will eventually result in downward movement of the slab. While it has been proven that ECC can give more durable repair systems for concrete structures, its durability in the repair of earth hydraulic structures is yet to be elucidated. Therefore, this study was carried out to clarify if ECC can also be an effective repair material in earth dams and canals. The investigations carried out are detailed in the next chapter.

CHAPTER 3: METHODOLOGY

This study comprised 4 sets of investigations entitled:

1. Effectiveness of ECC in curtailing re-emergence of weeds on an earth embankment

2. Effect of D-galacturonic acid on hydration of cementitious materials

3. Effect of cyclic loads on the surface profile of engineered cementitious composites (ECC) linings

4. Effect of plate thickness on crack propagation characteristics of engineered cementitious composites (ECC)

A premix of ECC with mix proportions as shown in Table 3.1 was used in this study.

Table 3.1 Mix proportion of premix premix ECC (1m^3)[81]

ECC pre-mix* (kg)	water (20^{0}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%				

Ordinary mortar was used as comparison since ECC is a mortar based mix and contains no coarse aggregate. Moreover, ordinary mortar and not concrete is normally used in thin layer repair applications as targeted in this study.

3.1 EFFECTIVENESS OF ECC IN CURTAILING RE-EMERGENCE OF WEEDS ON EARTH EMBANKMENTS

3.1.1. Introduction

The establishment and control of proper vegetation is an important part of earth dam maintenance. Properly maintained vegetation can help to prevent the erosion of the embankment and aids in the control of burrowing animals. However, the intrusion of weeds in the form of trees and brushes impairs the durability of the embankment. Extensive root systems of weeds provide seepage paths for water, while trees that fall over can leave large holes on the embankment surface. Such occurrences weaken the embankment, making it susceptible to further erosion. In addition, brush obscures the embankment surface and limits close inspections. Brush also provides a haven for burrowing animals and impedes the growth of desired grass vegetation. Regular maintenance of vegetal cover is therefore necessary to recover or improve the embankment durability.

Maintenance techniques commonly employed are grass mowing and brush cutting. Methods used in the past for the vegetation control, which are now obsolete, include chemical spraying and burning [14]. Complete removal of stumps and roots of weeds is necessary to curtail their re-emergence. The stumps can be removed either by pulling or with machines that grind them down. This exercise severely distorts the embankment surface. In order to restore the surface, it is therefore necessary to undertake massive earthworks to dispose waste soil and import suitable fill of required strength and imperviousness to water. Procurement of the disposal site and fill source is an intricacy that has resulted in the failure of commencement of several scheduled dam repair works [15]. There is need therefore, to employ a more viable technique.One such technique involves the cutting of weeds on the surface and covering them with a suitable repair material that can curtail their re-emergence. Weeds, like all other plants proliferate through the process of photosynthesis. Photosynthesis is the process by which plants naturally synthesize carbohydrates and grow. Light is a key factor for this process to occur [16]. Photosynthetically active radiation measured as photosynthetic photon flux density (PPFD), is required to convert atmospheric CO_2 and water into essential organic compounds by the plants. Concurrently, they produce CO_2 during respiration. Generally, photosynthesis cannot occur under low light intensity but as the intensity increases, the process also increases up to a compensation point that permits it to compensate for the plant's respiratory needs. After the compensation point, a plant can gain carbon and thus grow [17]. Therefore, preventing the process of photosynthesis from occurring consequently curtails the re-emergence of weeds on the surface of an earth embankment. Selection of a suitable repair material is critical for the effectiveness of this technique. Such a material must prevent photosynthesis from occurring and still maintain the structural integrity of the embankment. It must also be tenacious to excessive deformation due to the inevitable differential settlement of the earth embankment Any cracks produced by the repair material must be small enough to restrict access of light, a key element for the photosynthesis of the weeds. In this way, the process can be prevented. The use of stabilized muddy sediments as fill soil is one technique currently being developed [15].However, the rigorous process of acquiring the sediments from below the dam complicates this technique. Asphaltic concrete is a flexible material that can resist deformation due to differential settlement [18], but its low strength allows certain plants such as bamboo and puffball fungus to shoot through [19]. Plain cement materials such as cement pastes, mortars and concretes are commonly used for construction. The brittleness of these materials due to the production of a Griffith type [29] crack of unlimited width diminishes their capacity to perform desired structural functions. The cited brittleness under severe loading of concrete for instance, deterioration under normal service load and lack of sustainability of its reinforced structures [20] compromises both its early age performance and long-term durability. Therefore, as a repair material, it produces structures with poor durability susceptible to aggressive environments and prone to endless, uneconomical cycle of repairs [21]. For its water retaining structures, the British Code BS 8007(1987) [ref. 10.19] states that a maximum crack width of 0.2mm is deemed adequate for water tightness and a more stringent 0.1mm is necessary where aesthetic appearance is of particular importance. It is believed that cracks less than 0.2mm heal autogenously as water percolates through the cracks and dissolves calcium salts in the cement preventing leakage. The concrete repair layer must therefore meet this standard to maintain water tightness. Ordinary mortar, formed by a mixture of cement, water and fine aggregate sand has high workability and hence is easy to handle on site. However, like other plain cement materials, it is brittle, and exhibits deficiencies similar to those of concrete. In addition, it has low strength, inferior extensibility and undergoes significant drying shrinkage. Consequently, mortar easily develops shrinkage cracks [33]. The compression strength of a repair material is not the only measure of its ability to achieve durability of a repair structure. While compression strength is significant in structural repairs, other factors such as shrinkage, tensile strength and the adhesive bond strength to the substrate are significant for the failure of the repair and consequent reduction of its durability [35]. Efforts to address the brittle behavior of plain cement materials have led to modern concepts of fiber reinforcement and interface engineering [22].Engineered Cementitious Composites (ECC), a member of the High Performance Fiber Reinforced Cement Composites (HPFRCC) group, is a fiber reinforced cement based composite material that is excellent at crack dispersion. It is also formed mainly from cement and sand with fiber and certain chemicals as additional materials. ECC is systematically engineered to achieve high ductility under tensile and shear load. It can achieve maximum ductility in excess of 3% under uni-axial loading with only 2% volume of fiber content. It has a strain capacity 500times that of normal concrete or other fiber reinforced concrete [31]. It produces multiple fine cracks less than 0.1mm. The tight crack width of ECC is important to the serviceability of ECC structures as the tensile ductility is to the structural safety at ultimate limit state [17].In addition to tensile load bearing capacity, protection against penetration of substances by the fine cracks is another advantage of ECC [22]. The fine cracks can alter corrosion mechanism of rebars within the HPFRCC from macro-cell corrosion with a fast rate to micro-cell corrosion with a slow rate. In Japan, the fine cracking mode of ECC which limits permeation of water, has led to its application in the repair of dams and irrigation surfaces among other uses [23]. In this study, the effectiveness of ECC in restricting the penetration of light to weed stumps to prevent photosynthesis and curtail the re-emergence of weeds was investigated. Ordinary mortar, a plain cement material was used as a comparison.

3.1.2. Experimental Program

Two sets of experiments were carried out, one in the laboratory and the other in the field. In the laboratory, crack width, crack density and luminance (*the amount of light that passes through or is emitted from a particular area*) through ECC and mortar plates were measured. In the field, ECC and mortar plates were cast over freshly mowed bamboo stumps and embedded with strain sensors. The re-emergence of shoots was monitored by measuring the strain within the plates for 6 months. The height of shoots from bamboo stumps with no plate cover was concurrently measured.

3.1.2.1 Materials

The materials used in the experiments were ECC and ordinary mortar. The target weed was *Sasa Senanensis,* which is a bamboo variety. Bamboo was selected due to its high growth speed [24] and production of significant shooting forces [25]. All species of the bamboo tribe have C-3 photosynthesis [26] and hence do not need full sunlight to photosynthesize as opposed to C-4 plants which photosynthesize more efficiently under full sunlight. Therefore, *Sasa Senanensis* is indicative of plants with lower light and consequently lower PPFD requirements.

The mix proportions of ECC are shown in Table 3.1. ECC premix powder was used in this experiment. The major components of the ECC premix powder were cement, sand and poly-vinyl alcohol (PVA) fiber (2% by volume) of length 12mm, diameter 0.04mm, tensile strength 1690MPa and modulus of elasticity 40,600MPa. At a room temperature of 20^0C, the premix ECC powder was added to an electric mixer. Water and 3 admixtures, type A (superplastisizer*)*, type B (anti-shrinkage agent) and type C (expansive agent for air content adjustment) were mixed together and added to the premix powder at once. The mixer was covered and run for 2 minutes to avoid losses of the mix components. While the mixer was running, its cover was removed and mixing was continued until 10minutes elapsed. The ECC paste was then transferred into a tray. The homogeneity of the mix was corroborated by further hand mixing.

Ordinary mortar was cast by mixing water, cement and sand to the following ratios: water/cement =0.5 and sand/cement = 3. The procedure was done in accordance with the ASTM C305-99 standard.

3.1.2.2 Testing Procedure

a. Measurement of luminance

ECC and mortar plates of dimensions 400mm x 400mm x10mm ECC were cast and water cured for 28days at 20^0C.The plate dimensions were selected to fit the limits of the bending machine used for generation of cracks .The 10mm thickness was selected to match the minimum possible thickness for placing ECC layers using the direct spraying method [27]. Three sets of ECC plates were prepared. Each set comprised 3 plates. The first set was the control and hence was kept intact. Using the 'Third-Point Loading' test [34] configuration, the second set was loaded to ultimate failure to determine the average ultimate failure load. Using 80% of the determined average ultimate failure load (Fig.3.1.1), cracks were generated on the third set. The plates were turned over to generate cracks on both sides. Two sets of mortar plates were prepared, each set also comprising 3 plates. The control set was left intact while the plates in the second set were loaded until a through crack developed. The loading configuration was the same as for the ECC plates.

Luminance was then measured on the set of ECC plates with cracks and the set with no cracks. A 1mm wide crack was made on each mortar plate by pushing the 2 broken pieces of mortar together and adjusting them until readings from a device for measuring the width of cracks on the surface of concrete structural walls Crack Viewer FCV-30 showed an average width of 1mm. The 1mm crack width was selected as the worst case scenario for ordinary concrete or mortar. Luminance was again measured on the set of mortar plates with a 1mm wide crack and the set with no cracks. The test was implemented in a dark room, with all external light sources eliminated. Each test plate was placed on a platform and illuminated by 2 tungsten bulbs, each with wattage of 150W (Fig.3.1.2).Luminance readings were read from the light meter placed below the plate. Three readings were taken on each plate to determine its average luminance. The average luminance from the 3 plates in each set was then used to obtain the average luminance for the set.

Fig.3.1.1. Generation of cracks using a bending machine

Fig.3.1.2. Illumination of an ECC plate by 2 tungsten bulbs, each with wattage of 150W

b. Determination of crack density

A 100mm wide strip at the center of both the top and bottom sides of each ECC test plate was marked. The marked strip was thinly painted using fluorescent paint to accentuate the cracks on the plate. In a dark room, each plate was illuminated under black light. The fluorescent paint in the cracks glowed yellow under the light. Using a digital camera, pictures were taken at 3 positions on the strip. Images from the camera were viewed using a computer aided drafting software application AutoCAD (Fig.3.1.3a). The quantity of cracks along 3 positions on the 100mm wide strip was physically counted from the images to determine the average density of the cracks. This average was then multiplied by 10 to obtain the average quantity of cracks per unit meter. However, since a single through crack was produced in each mortar plate, this method was not applicable in determining the crack density in mortar. Instead, visual inspection was used to determine the number of cracks on each plate.

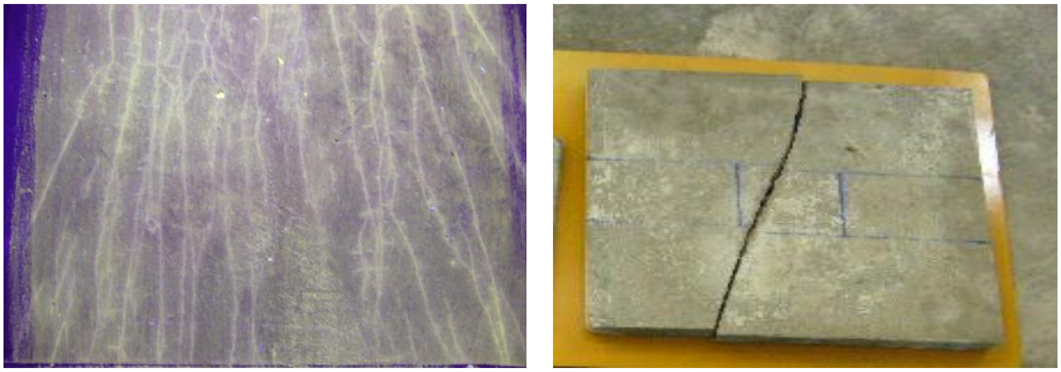

(a) (b)

Fig.3.1.3.(a)10mm ECC plate with multiple fine cracks (b)10mm mortar plate with 1 through crack

c. Measurement of crack width

Crack width measurements were carried out on 3 cracks on each of the 3 ECC plates used in this test to determine the average crack width. The crack width was measured using the Crack Viewer FCV-30. The device was connected to a computer and the device sensor was placed on the surface of the test plate. The crack width data and images obtained for each crack was recorded directly from the laptop screen (Fig.3.1.4). Again for mortar, a through crack of unlimited width was produced and so this method was not applicable.

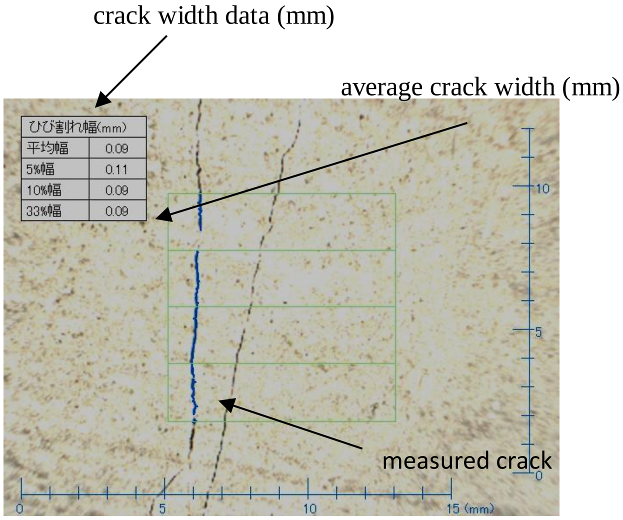

ひび割れ幅(mm)	
平均幅	0.09
5%幅	0.11
10%幅	0.09
33%幅	0.09

Fig.3.1.4. Image and data from the Crack Viewer FCV-30 for a 10mm ECC plate

d. Measurement of strain

The *Sasa Senanensis* was mowed and stumps leveled to the ground. Fresh ECC and mortar was cast over the bamboo stumps into plates of dimensions 1000mm x 500mm x 10mm.The surface dimensions were selected to allow a significant number of bamboo stumps to be covered (average 15 stumps). The plates were embedded with 3 strain sensors along the middle strip (250mm from the 1000mm edge, Fig.3.1.5) .The right and left sensors were embedded 50mm from the 500mm edge. The 3rd sensor was embedded 495mm from the 500mm edge. All sensors were embedded 2mm below the surface of the plates as shown in section A-A in Fig.3.1.6. Steel anchors were used to fix the plates to the ground. Strain readings were collected from the sensors periodically for 6 months using a digital strain meter TC-31K.Visual inspections were concurrently carried out on the plates.

Two controls were established. The first control was in the form of ECC and mortar plates cast over bare soil with no bamboo stumps underneath. The second control was established by measuring the height of shoots from 3 bamboo stumps with no plates covering them. The shoots were labeled B-1, B-2 and B-3. A measuring tape was used for this test. The height readings were collected concurrently with strain readings.

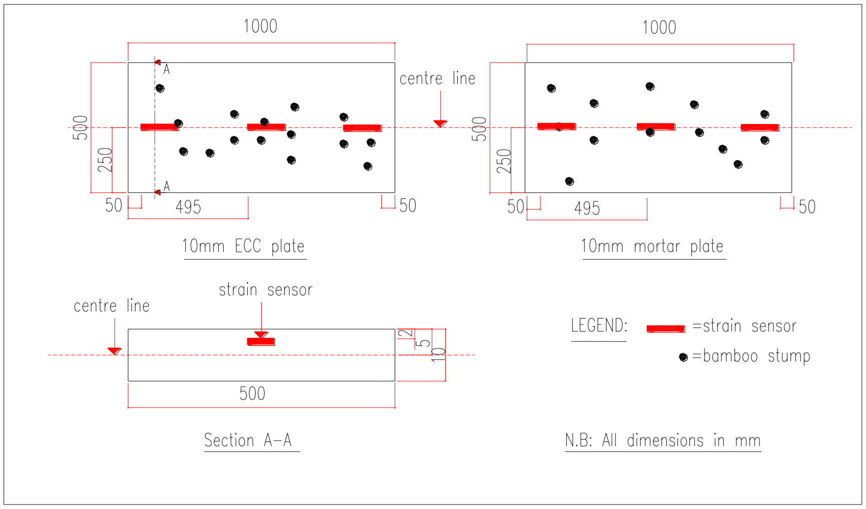


Fig.3.1.5. Schematic diagram of ECC and mortar plates showing bamboo stumps and strain sensor positions

3.1.3. Results

3.1.3.1 Luminance, crack width and crack density

The luminance of the dark room was 0. The average luminance through ECC and mortar plates is shown in Table 3.2. The ECC plates produced multiple fine cracks but the mortar plates produced a single though crack of unlimited width shown in Fig.3.1.3. The average crack width and average crack density for ECC plates is shown in Table 3.3. An image of a measured crack and corresponding data from the Crack Viewer FCV-30 is shown in Fig.3.1.4.

Table 3.2 Average luminance through 10mm ECC and mortar plates

	no cracks		with cracks	
	(lx)	(μmol m^{-2} s^{-1})*	(lx)	(μmol m^{-2} s^{-1})*
ECC	0.36	7.20×10^{-3}	1.46	2.92×10^{-2}
mortar	0.21	4.20×10^{-3}	27.00	5.40×10^{-1}

*To convert lx to μmol m^{-2} s^{-1} divide lx value by 50[15]

Table 3.3 Average crack density and crack width for 10mm ECC plates

bottom density (cracks /100mm)	top density (cracks /100mm)	average density (cracks/ 100mm)	average density (cracks/ m)	average crack width mm
12.75	12.50	12.63	126.30	0.09

3.1.3.2 Bamboo shoots growth and strain variations in ECC and mortar plates

The bamboo shoots emerged from the soil around the ECC and mortar plates 21 days after casting .The variation in height of the shoots B-1, B-2 and B-3 from the control stumps is shown in Fig.3.1.6. Neither shoots nor visible cracks were observed on top of the plates. The variation of strain with time for the ECC and mortar plates is shown in Fig.3.1.7. Each graph represents results from the 3 strain gauges on a particular plate. The location of the gauges within the plates is schematically shown in Fig.3.1.5. Graphs 1 and 3 represent the results from plates 1 and 3 which are the ECC test and control plates respectively. Graphs 2 and 4 represent the results from plates 2 and 4 which are the mortar test and control plates respectively. Each line on the graph represents readings from a particular strain sensor in a plate. The left, middle and right sensors are denoted as sensor 1, 2 and 3 respectively. The strain sensor is therefore denoted by 2 digits *x-y*. The left digit(x) represents the plate number and the right digit(y) represents the position of the sensor thus, line 1-2 represents readings from the strain sensor on position # 2 of plate # 1.

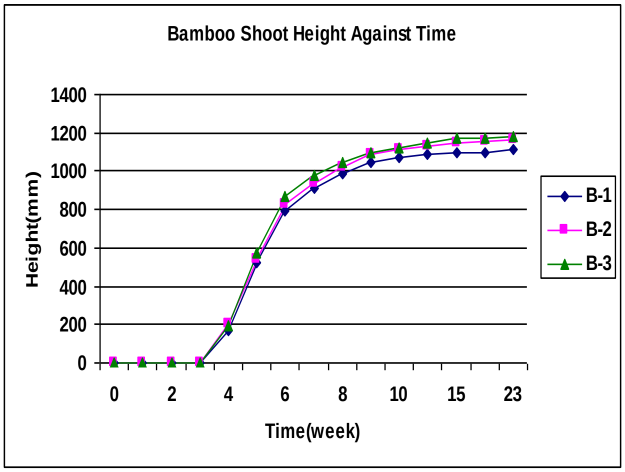
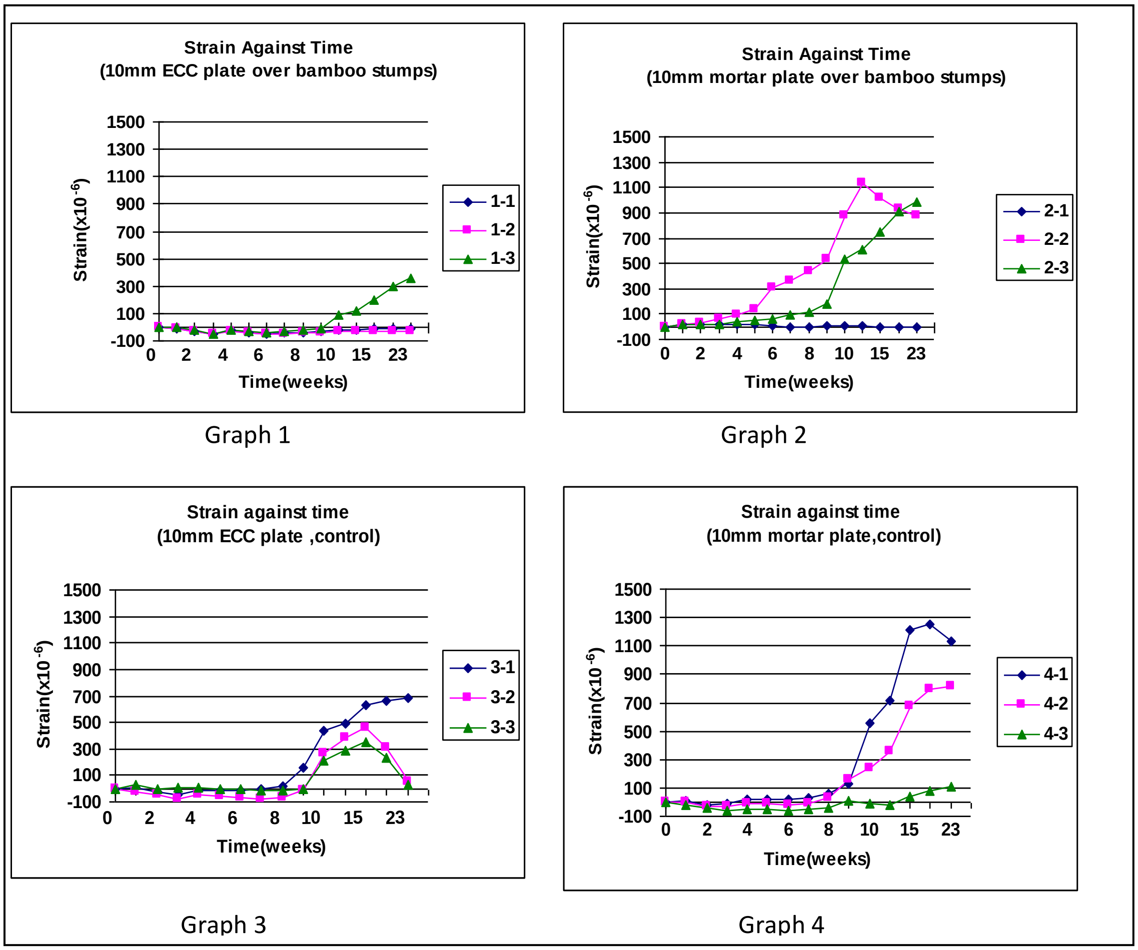


Fig.3.1.6 Variation of height of bamboo shoots B-1, B-2 and B-3 with

3.1.4. Discussion

3.1.4.1 Luminance through ECC and mortar plates



Graph 1

Graph 2

Graph 3

Graph 4

Fig.3.1.7. Graphs of Strain (x10^{-6}) against time (weeks) for 10mm ECC and mortar plates

It was determined that an average luminance of 0.0072µmol m^{-2} s^{-1} and 0.0042µmol m^{-2} s^{-1} penetrated the ECC and mortar plates with no cracks respectively. This means the luminance through the mortar plate with no cracks was 58% less than luminance through the corresponding ECC plate. The density of the mortar and ECC plates measured just before the experiment was 2482kg/m^3 and 1926kg/m^3 respectively. This means that the particles in the mortar plate before crack generation were more tightly packed than the particles in the ECC plate and hence allowed less light to penetrate as reflected by lower measured luminance. On the other hand, an average luminance of 0.0292µmol m^{-2} s^{-1} penetrated the ECC plate with cracks while 0.54µmol m^{-2} s^{-1} penetrated the mortar plate with a single 1mm crack. This means 18 times more light penetrated the mortar plate with a single 1mm through crack than the ECC plate with multiple fine cracks (*126.3cracks/m, 0.09mm diameter*). Inferring to the crack propagation patterns of ECC and mortar, the localized fracture due to Griffith crack propagation characteristic of mortar resulted in a through crack which allowed significant light to penetrate through, whereas the characteristic strain-hardening after the first cracking of the ECC resulted in multiple micro-cracking on the surface of the plate which were more restrictive to the penetration of light [31].

From Table 3.2, it was deduced that before the generation of cracks, both plates prevented the penetration of significant amounts of light. However, after the generation of cracks, 4 times more light penetrated the ECC plates with cracks than without while 129 times more light penetrated the mortar plates with a single 1mm through crack than with no cracks. This shows that the single through crack of the mortar plate greatly depleted its capacity to prevent the penetration of light and comparatively, the effect of fine ECC cracks was less severe .This observation confirms the deficiencies associated with plain cement materials as repair materials pitted against the advantages of ECC cited in the introduction to this paper . The brittleness of the mortar under severe loading caused the through crack which enabled significant amounts of light to pass through. This characteristic then exposed any underlying structures to the aggressive environment [21]. However, ECC, due to its high strain capacity produced multiple fine cracks with 0.09mm average diameter on the surface. These cracks managed to significantly restrict the penetration of light.

3.1.4.2 Crack width and crack density of ECC and mortar plates

The 10mm mortar plates produced a single through crack but the 10mm ECC plates produced multiple fine cracks of average width 0.09mm. This shows that the mortar, which is brittle produced the common form of localized fracture due to Griffith crack propagation [29] whereas the cracks in ECC were bridged by the PVA fibers in the material and hence the resulting small widths [30]. The characteristic strain-hardening after the first cracking of the ECC resulted in the multiple micro-cracking. This tight crack width by ECC 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. In contrast, mortar, like ordinary concrete and fiber reinforced concrete relies on steel reinforcement for crack width control [20].

3.1.4.3 Strain Variations in ECC and mortar plates

In general, a decrease in strain indicates the occurrence of contraction in a material while an increase in strain indicates the occurrence of expansion. As shown in the graphs in Fig.3.8, all the ECC and mortar test and control plates experienced initial contraction from the time of casting up to the 4th week after which the plates gradually expanded until the 15th week. Thereafter, contraction resumed. Therefore, there are no significant differences in strain variations within the ECC and mortar test and control plates throughout the test period. Given that strain varies in response to external forces, the absence of a clear distinction in the strain variations in the plates indicates that there was no major difference in the underlying forces. Since both the test and control plates were subjected to the same conditions except the presence of the bamboo stumps underneath the test plates, it was expected that if the bamboo stumps produced shoots, elastic forces exerted by the bamboo shoots would cause additional elastic strain to the test plates. No corresponding elastic strain was expected on the control plates (*no bamboo stumps underneath*). If enough light penetrated the overlying plates the bamboo stumps were expected to shoot, photosynthesize and grow. Since the test plates were anchored to the ground, the forces of the bamboo shoots would then cumulatively exert stresses on the plate causing deformation in the form of bending of the plate. The bending would then causes relative displacement between particles in the material body within the plate in the form of elastic strain. This process was expected to commence at the time the bamboo shoots started appearing on the bamboo stumps with no covering (*second control*) i.e. 21days after casting (Fig.3.1.6). Any increase in strain from this point onwards on the plates over bamboo stumps only and no corresponding strain increase on control plates could thus be attributed to the force from the bamboo shoots. However from the graphs in Fig.3.1.7, no significant difference in strain between the plates over bamboo and control plates was observed from the aforementioned 21 days and throughout the growing period of the control bamboo shoots affirming that the bamboo stumps below the ECC and mortar plates did not shoot.

This observation concurs with the results from the luminance experiment. Since the ECC and mortar plates used for the strain measurement test were cast in situ and no cracks were generated, the properties of these plates thus match the properties of the ECC and mortar plates with no cracks used in the luminance experiment. From table 3.2, the luminance of the ECC and mortar plates with no cracks was 0.0072µmol m^{-2} s^{-1} and 0.0042µmol m^{-2} s^{-1} respectively. The minimum PPFD for *Sasa Senanensis* is 3.4molm^{-2}day^{-1}[3] i.e. 0.039µmol m^{-2} s^{-1}. This means that *Sasa Senanensis* requires at least 0.039µmol m^{-2} s^{-1} of PPFD to photosynthesize. Since the minimum value of PPFD required for the photosynthesis of the *Sasa Senanensis* is more than the average amount of light that penetrated both the ECC and mortar plates with no cracks, the bamboo stumps could therefore not photosynthesize. Consequently no elastic forces could be generated by bamboo shoots to cause significant variations in the strain of the test plates.

On the other hand, 0.0292µmolm^{-2} s^{-1} of light penetrated the ECC plate with cracks while 0.54 µmol m^{-2} s^{-1} penetrated the mortar plate with a single 1mm crack. This means that the luminance through the ECC plate with cracks was also less than the minimum PPFD required for the photosynthesis of *Sasa Senanensis*. Consequently, the 10mm ECC plate with cracks can also prevent the photosynthesis of *Sasa Senanensis* .However, the luminance though the mortar plate with a single 1mm crack was more than the minimum PPFD required for the photosynthesis of *Sasa Senanensis*. Therefore, the mortar plate with a single 1mm crack can allow enough light for the photosynthesis to occur. In addition, the mortar characteristic through crack produced by mortar makes it susceptible to further lateral and vertical movements in response to the differential settlement of earth embankments. Such movements can cause further expansion of the crack which in turn increases its light penetration capacity. The bamboo shoots can then grow further and continue to expand the crack. Once the crack width exceeds serviceability limits, durability failure ensues.

In view of the foregoing discussion, other factors characteristic of cementitious materials can be attributed to the variations in strain in the ECC and mortar plates. After casting, the ECC and mortar plates underwent autogeneous shrinkage until the 4th week. In addition to plastic shrinkage which occurs when the cement paste in the cementitious material is still in its plastic state, volume change, in the form of either shrinkage or swelling continues to occur after setting of the material has taken place. The withdrawal of the hitherto unhydrated cement results in autogeneous shrinkage which occurs in the interior of the material mass. Since the contraction of the cement paste is restrained by the rigid skeleton of the already hydrated cement paste, the magnitude of autogeneous shrinkage is very small, typically about 40×10^{-6} at age 1 month [19]. This typical value of shrinkage at age 1 month is comparable to the values of strain in ECC and mortar at the same age (Fig.3.1.7). It was observed that the values of the shrinkage strain of the ECC and mortar plates are almost the same. According to Japanese Industrial Standards for Construction Materials and Building, JIS A 6203B, the shrinkage strain of ECC is almost the same as that of concrete. After the 4th week, the thermal strain, which is directly proportional to variations in temperature, caused the increase in strain in all the plates. The plates were cast at the beginning of April (spring) when temperatures were relatively low .The average temperature recorded on the plates using a thermocouple was 21^{0}C in the 1st 4 weeks. The temperatures increased rapidly after 4 weeks (at the onset of summer) with average temperatures of 38^{0}C being recorded .After 15 weeks temperatures began to decrease again (average 30^{0}C) as fall approached. This trend in temperature is matched by the trend in the graphs in Fig.8 i.e. the increase in strain from the 4th week until the 15th week followed by a decrease thereafter.

3.1.5. Conclusion

The following conclusions can be drawn from this study:

1. The 10mm ECC plate is effective in curtailing the re-emergence of *Sasa Senanensis* before and after the production of cracks by preventing the penetration of sufficient light for its photosynthesis.
2. The 10mm mortar plate is effective in curtailing the re-emergence of *Sasa Senanensis* before the production of cracks only. After the production of the typical single through crack, the mortar allows sufficient light for the photosynthesis and subsequent re-emergence of the bamboo.
3. Since *Sasa Senanensis* is a C-3 photosynthesis plant (*lower light requirements for photosynthesis*), the ECC and mortar plates with no cracks and the ECC plate with cracks can also curtail the re-emergence of all C-4 photosynthesis plants which need full sunlight (*higher light requirements*) to photosynthesize.
4. The high strain capacity of ECC results in the production of fine surface cracks which minimize the penetration of light through the ECC plate thereby eliminating the possibility of photosynthesis of underlying weeds.
5. The fiber-bridging property across an ECC matrix crack gives the material ductility. Excessive deformation due to any differential settlement of an earth embankment that causes expansion of any existing cracks is therefore minimal. The restricted crack width and location of the cracks on the surface of the ECC plate entails that the ECC cracks are not capable of hosting other flying seeds which have a potential to sprout, grow and expand the hosting crack. The possibility of any underlying weed stumps accessing sufficient light for photosynthesis in future is therefore eliminated.
6. The production of the typical Griffith type through crack in mortar or concrete makes the crack susceptible to further expansion due to differential settlement of earth embankments. The expanded crack increases the quantity of light available for weeds to photosynthesize and re-emerge. The expanded crack can also host flying seeds from other weeds .These weeds can also sprout and grow which leads to further expansion of the crack and ultimate loss of serviceability integrity of the structure.
7. Since the ECC cracks are resilient to further expansion due to the growth of weeds, the loss of serviceability integrity of an embankment repaired by an ECC layer is unlikely. ECC is therefore an effective and durable repair material on earth embankment surfaces.

3.2. EFFECT OF D-GALACTURONIC ACID ON HYDRATION OF CEMENTITIOUS MATERIALS

3.2.1. Introduction

Plain cement materials such as cement pastes, mortars and concretes are commonly used for construction. The mix basically consists of cement, water, fine aggregate, coarse aggregate and other admixtures in varying proportions. However, these materials have inherent deficiencies such as brittleness under severe loading, deterioration under normal service load and lack of sustainability of reinforced structures [20], which compromise both early age performance and long-term durability. The brittleness of plain cement materials emanate from the typical production of a localized single 'Griffith type' crack [29] This single crack which is of unlimited width is prone to expansion and can become a conduit for the ingress of aggressive and deteriorative substances. Efforts to address the brittle behavior of plain cement materials have led to modern concepts of fiber reinforcement and interface engineering [22].

Engineered Cementitious Composites (ECC), a member of the High Performance Fiber Reinforced Cement Composites (HPFRCC) group, is a fiber reinforced cement based composite material that is excellent at crack dispersion. It is systematically engineered to achieve high ductility under tensile and shear load. ECC can achieve maximum ductility in excess of 3% under uni-axial loading with only 2% volume of fiber content. It has a strain capacity 500 times that of normal concrete or other fiber reinforced concrete [31] and produces multiple fine cracks less than 0.1mm as opposed to the through crack produced by plain cement materials. The tight crack width of ECC is important to the serviceability of ECC structures as the tensile ductility is to the structural safety at ultimate limit state. In addition to tensile load bearing capacity, the fine surface cracks of ECC curtail the penetration of deteriorative substances [22] and can alter corrosion mechanism of rebars within the HPFRCC from macro-cell corrosion with a fast rate to micro-cell corrosion with a slow rate [23].

Durability is as critical in repair and retrofit applications as in new structures. Currently plain cement materials are ubiquitous in such applications due to their low initial cost, but the inevitable cycle of repairs associated with these materials makes the use of the enhanced ECC a more economically viable alternative. Whilst plain cement materials have been in use since the 19th century [36], ECC was only developed in the early 1990s [37] and currently its widespread use is being limited by the high cost of the material and the general tendency by engineers to use traditional materials with known characteristics. It has been clarified by other researchers that ECC exhibits exceptional behavior under cyclic temperature loads, carbonation exposure, fatigue loading and long term mechanical performance [38] among other parameters as compared to regular plain cement material. Moreover, ECC can relieve shrinkage induced stresses within the ECC repair layer thereby suppressing the development of large through cracks and interface de-lamination between the substrate and repair layer [21] and [39] elucidated that ECC is more effective than ordinary mortar in curtailing the re-emergence of weeds on the surfaces of repaired earth embankments. However, there is need to continue to make a comparison of the behavior of ECC alongside plain cement materials to further validate the replacement of plain cement materials with ECC.

The ECC mix, which is basically without coarse aggregate, typically contains much higher cement content than regular concrete, fiber reinforcement and several chemical additives. Portland cement, the chief ingredient and binder in both plain cement material and ECC is a hydraulic material which sets and develops strength by forming hydrates through hydration, a chemical reaction in which Portland cement combines with water and stiffens before hardening into a solid mass in the two successive processes of setting and hardening. Although Portland cement has been used for well over 175 years and its behavior is understood from an empirical perspective, chemically, it is still a complex substance whose mechanisms and interactions have yet to be fully defined [40]. Certain chemical additives such as NaCl, gypsum and sugars can accelerate, retard or modify the hydration process respectively [32][41]. As such unintended modifications to the hydration process of cementitious materials which may impair overall durability of structures are inevitable if such structures get into contact with deteriorative chemicals. Essentially, in the absence of adequate protective measures, cementitious material structures should not be set up in potentially deteriorative environments. Nevertheless, it is imperative to minimize such phenomena by implementing appropriate protective measures on existing and intended structures. While some organic acids are known to deteriorate plain cement materials, the relative tenacity of ECC, in light of its myriad of chemical additives, is yet to be fully understood.

Weeds are a common phenomenon on both new construction sites and existing facilities such as earth dams, irrigation channels, storm-water drains and retaining walls. While it may be desirable to uproot all weeds before construction or during maintenance, reinforcement or repair of these facilities, the cost associated with such exercises is usually prohibitive. Alternatively, weeds are usually stumped to the ground level and the desired new, repair or retrofit structure overlain. However, certain weeds, such as bamboo, release substantial amounts of sap when lacerated. The sap is virtually a complex chemical comprising mainly water, with sugars, organic acids, hormones, nutrients and mineral elements dissolved in it [42]. In structures with thick layers of material, the interaction between the cementitious material and the sap can be insignificant. However, for both structural and aesthetic reasons, repair and retrofit elements are often in the form of thin layers and hence in such applications, the interaction of the repair layer and the chemicals in the sap cannot be ignored. Therefore, it was the objective of this study to investigate the impact of a certain organic acid on the hydration of ECC and ordinary mortar. Since the hydration process is sensitive to the concentration, temperature and mix proportions of reactants among other environmental factors, typical ECC and ordinary mortar mixes as designed in practice were used in this study.

3.2.2. Experimental Program

The effect of D-galacturonic acid on the setting and hardening of cementitious materials was investigated. Firstly, the sap from bamboo was tested for the presence of D-galacturonic acid and subsequently, the effect of the acid on the setting and hardening of ECC and plain cement materials was monitored. The Vicat test was used to monitor setting while the compressive and flexural tests were used to monitor hardening. In the field, ECC and ordinary mortar plates were cast over freshly lacerated bamboo stumps with sap oozing out. The effect of the bamboo sap on the stiffening of the plates was monitored for 28days by visual inspection.

D-galacturonic acid was selected because it is the principal component of pectin (40-60%), a polysaccharide widely found in plants [43] [44]. Bamboo was used as the source of sap because it is the fastest growing plant in the world which thrives in diverse climates, has wide spatial distribution [45] [46] and releases substantial amounts of sap when lacerated.

3.2.2.1 Materials

The cementitious materials used in this study were ECC and ordinary mortar. Bamboo sap was used to confirm the presence of D-galacturonic acid in plants but the concentrated manufactured form of the acid was used in the experiments. Since the micromechanics design of ECC is complex, for laboratory purposes, a premix with simple mixing instructions from the manufacturer is more practical [47]. Therefore, the ECC used in this study comprised a premix ECC powder and chemical additives mixed to instructions by the manufacturer. To simulate practical conditions, the mix proportions commonly used in practice were selected for the ordinary mortar.

The ECC mix proportions are shown in Table 3.1. The components of the ECC premix powder were cement, sand, PVA fiber and fly ash. The fiber was 12mm in length and 0.04mm in diameter with a tensile strength of 1690MPa and a modulus of elasticity of 40,600MPa. The premix ECC powder was added to an electric mixer at a room temperature of 20^0C. Water and the 3 admixtures, type A (poly carboxylic acid based superplasticizer*)*, type B (CSA type anti-shrinkage agent) and type C (poly oxi-alkaline based expansive agent for air content adjustment) were mixed together and added to the premix powder at once. The mixer was covered and run for 2 minutes to avoid losses of the mix components. 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 and uniform distribution of the fresh mix was corroborated by further hand mixing and any lumps discarded.

The ordinary mortar was prepared by mixing sand, Portland cement and water to the following ratios: water/cement=0.5 and sand/cement=3. The ASTM C305-99 was adhered to for the preparation.

Bamboo sap was extracted by soaking chopped pieces of bamboo reeds in pure water for 4 weeks. A 1mg/ml solution of D-galacturonic acid was prepared by dissolving the acid powder in pure water at a ratio of 1mg of acid to 1ml of water. The 1mg/ml acid solution was further dissolved in pure water to produce 5 different aqueous solutions. The aqueous solutions were made by pipetting a particular volume of the acid into a 100ml volumetric flask and making up to the 100ml mark with pure water using the proportions shown in Table 3.4.

Table 3.4 Production of the D-galacturonic acid aqueous solutions in a 100ml volumetric flask

sample	volume of 1mg/ml D-galacturonic acid solution (ml)	concentration of D-galacturonic acid aqueous solution (μg/ml)	pH
1.	0	0(pure water)	7
2.	2	20	6.9
3.	4	40	6.8
4.	6	60	6.7
5.	8	80	6.6

3.2.2.2 ***Testing Procedure***

a.Chemical composition analysis of bamboo sap

The presence of D-galacturonic acid in the bamboo sap was ascertained chromatographically using the ‘Carbazole method’ [48] which is a standard test for the presence of uronic acids.

b. Setting time

Five ECC and ordinary mortar pastes were prepared by replacing the water component of the paste with the D-galacturonic acid aqueous solutions of concentrations shown in Table 3.5. Measurements of pH were taken on the D-galacturonic acid aqueous solutions and D-galacturonic acid aqueous solutions / ECC or ordinary mortar pastes soon after mixing. The final setting time was then monitored using the ‘Vicat’ apparatus. The test was carried out to the ASTM C 807-03a standard.

c. Flexural and compressive strength

Standard ECC and ordinary mortar prisms of dimensions 40 mm x 40 mm x 160 mm were cast. Soon after de-moulding, 25% of the samples were cured in the 80 μg/ml D-galacturonic acid aqueous solution and 75% were cured in pure water. The curing temperature was 20^0C in both cases. The concentration of 80 μg/ml D-galacturonic acid corresponded with the highest concentration used in the setting time experiment. The samples were labeled as shown in Fig.3.2.1. Compressive and flexural strength tests were carried out on sample A and a third of sample B at the age of 2, 7, 14, 21and 28 days. After 28 days, 50% of the remaining prisms from sample B were soaked in D-galacturonic acid to make sample C. Compressive and flexural strength tests were continued on the hardened samples B and C fortnightly for a period of 56days. 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.

d. Effect of bamboo sap on the stiffening ECC and ordinary mortar plates

Bamboo reeds were stumped to the ground level. Fresh ECC and ordinary mortar were cast into plates of 1000 mm x 500 mm x 10 mm dimensions over the stumps with sap oozing out. The dimensions 1000 mm x 500 mm were selected to enable a sizeable number of bamboo stumps to be covered, while the 10mm thickness was selected as the minimum thickness that can be practically applied on site using common application methods. Two controls were established in the form of plates of the same dimensions cast over bare ground (control 1) and bamboo stumps which were left uncovered throughout the experiment (control 2). The test plates and controls were visually inspected periodically from the time of casting up to 28 days.

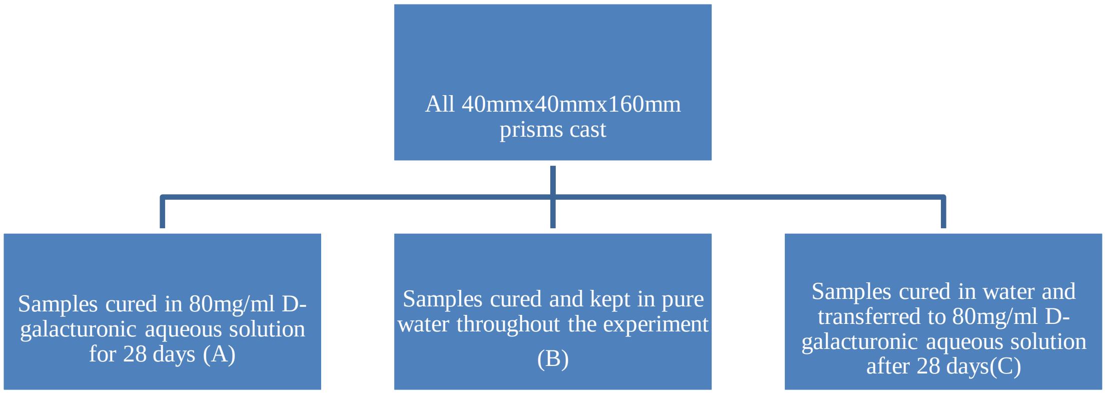


Fig. 3.2.1. Details of the ECC and mortar samples used in the experiment

3.2.3. Results

The pH of the D-galacturonic acid aqueous solutions and the D-galacturonic acid aqueous solution/ECC or ordinary mortar pastes are shown in Table 3.4 and Table 3.5 respectively. The effect of the acid aqueous solutions on the final setting time of ECC and ordinary mortar is shown in Table 3.5. The rate at which the acid increased the setting time is shown in Fig.3.2.2.The flexural and compressive strength of the mortar samples during the standard curing period (28 days) are shown in Fig.3.2.3 and Fig.3.2.4 while the flexural and compressive strength of the hardened samples soaked in D-galacturonic acid after 28days of pure water curing are shown in Fig.3.2.5 and Fig.3.2.6.

The ECC and mortar plates cast on bare ground (control plates) stiffened and dried up completely within 24 hours as expected. However, unstiffened circular patches were concurrently observed on the ECC and mortar plates cast over bamboo stumps (Fig.3. 2.7). The circular unstiffened patches corresponded to the positions of the underlying bamboo stumps. In addition, excess fluid was observed on the mortar patches. At the age of 2 days after casting, the ECC patches had stiffened like the rest of the plate. On the other hand, the unstiffened wet patches persisted on the mortar plates for a period of more than 14 days during which the fluid gradually decreased in intensity and changed in coloration from colorless to yellowish (Fig.3.2.8). On the 21st day after casting, the yellowish fluid finally dried up but no mass mortar was formed. Instead, disaggregated sand and cement-like material remained on the previously moist patches (Fig.3.2.9) of the worst affected section. As time progressed, the disaggregated material was eroded by the rain and circular holes remained in the mortar through which the underlying bamboo stump could be observed (Fig.3.2.10).

Table 3.5 pH of ECC and ordinary mortar soon after mixing with D-galacturonic acid aqueous solution

sample	concentration of D-galacturonic acid aqueous solution (μg/ml) in mix	ECC	ordinary mortar
1.	0(pure water)	11.83	12.85
2.	20	11.69	12.55
3.	40	11.53	11.74
4.	60	11.46	11.20
5.	80	11.38	10.44

Table 3.6 Effect of D-galacturonic acid on the final setting time of ECC and ordinary mortar

	concentration of D-galacturonic acid aqueous solution (μg/ml)	final setting time (min)	
		ECC	ordinary mortar
1.	0	510	285
2.	20	530	310
3.	40	545	525
4.	60	564	590
5.	80	575	880

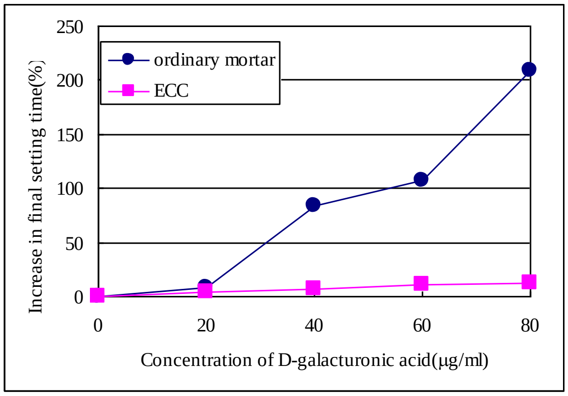


Fig.3.2.2. Rate of increase in final setting time of ECC and ordinary mortar due to D-galacturonic acid

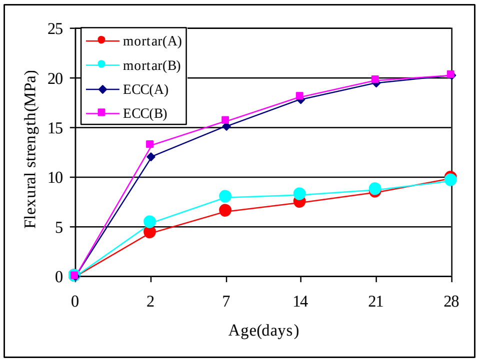


Fig.3.2.3. Flexural strength of ECC and mortar cured in acid (A) and water (B)

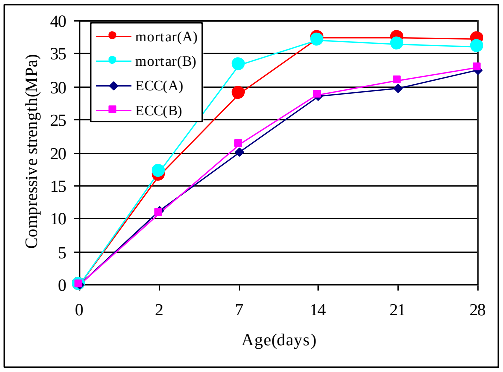


Fig.3.2.4. Compressive strength of ECC and mortar cured in acid(A) and water(B)

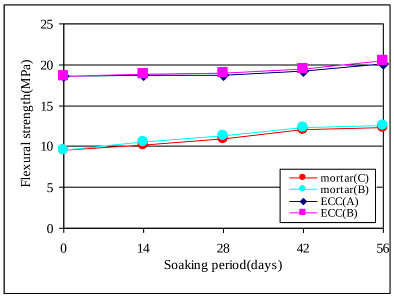


Fig.3.2.5. Flexural strength of hardened ECC and mortar soaked in acid(C) and water(B)

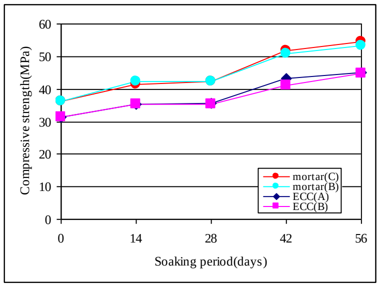
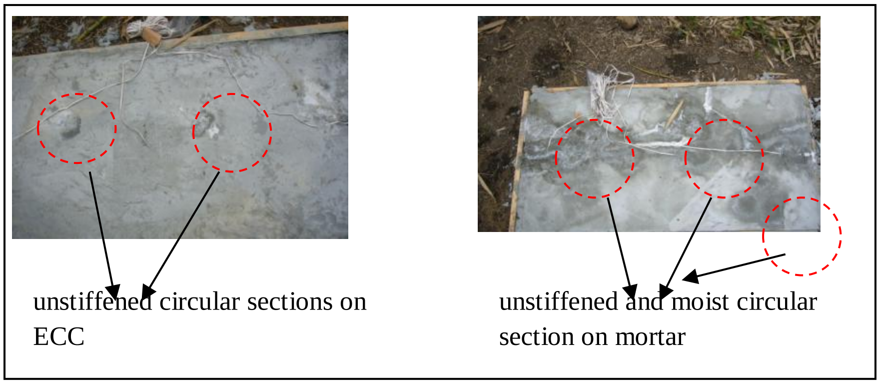


Fig.3.2.6. Compressive strength of hardened ECC and mortar soaked in acid(C) and water(B)



unstiffened circular sections on ECC

unstiffened and moist circular section on mortar

Fig.3.2.7.ECC and ordinary mortar plates 24 hours after casting

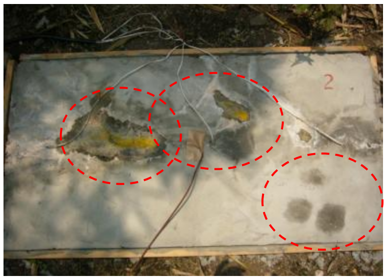


Fig.3.2.8.Yellowish fluid on top of the mortar plate 14 days after casting

Fig.3.2.9. Disaggregated sand and cement on previously unstiffened patch on mortar 21 days after casting

Fig.3.2.10. Circular hole on mortar plate

3.2.4. Discussion

a. Effect on setting time

The circular unstiffened patches on the ECC and mortar plates can be attributed to D-galacturonic acid contained in the sap from the bamboo stumps underlying the plates due to the shape and positioning. On the other hand, as shown in Table 3.6, the setting time of both ECC and ordinary mortar increased with increase in the concentration of the D-galacturonic acid. While the setting time of ECC was higher than that of the ordinary mortar at lower concentrations of the acid, the setting time of the ordinary mortar eclipsed that of ECC as the concentration of the acid increased. Hence, at the highest concentration of D-galacturonic acid used in this experiment, 80µg/ml, the rate of increase in the setting time of ECC and the ordinary mortar was 13% and 208% respectively. This shows that the setting retardation effect of the acid was more severe on the ordinary mortar than on ECC as concentration of the acid increased as was also confirmed in the field where the unstiffened patches on ECC lasted only 2 days relative to more than 14 days observed on the mortar plates. However, as shown in Fig.3.2.2, at lower concentrations of D-galacturonic acid, the setting time of ECC was higher than that of the ordinary mortar. This is due to the influence of the polycarboxylic acid based superplasticizer present in the ECC mix. Whilst it has been proved that shrinkage reducing agents have a negligible effect on setting time [49], most superplasticizers generally tend to decrease setting time [50]. However, the polycarboxylic acid based superplasticizer in the ECC mix is known to retard setting time if it is used in low dosage [51] as in this study.

The impact of D-galacturonic acid on the setting time of ordinary mortar and ECC can be further explained as follows. D-galacturonic acid is an uronic acid or ‘sugar -acid’ which exhibits both carbonylic and carboxylic acid functions. Therefore, as a typical sugar, D-galacturonic acid retarded the hydration process in both materials by adsorbing particles onto the surfaces of the hydrating cement particles on both Ca (OH)2 nucleus and CSH gel [41], an action which according to Milestone [52] ‘contaminates’ the material. Moreover, from Table 3.5 the pH of both ECC and ordinary mortar was more than 7 which shows that the materials are alkali. Therefore, the encounter of the acidic D-galacturonic acid and the alkaline ECC and ordinary mortar resulted in a typical acid-alkali neutralization reaction which characteristically produced water and a salt. The water produced in the neutralization reaction increased fluidity of the ECC and ordinary mortar subsequently also retarding the setting process. However, Fig.3.2.2 shows that the rate at which the acid retards the setting process in the ordinary mortar is much higher than in ECC. It is known that the severity of the neutralization reaction depends on the pH of the reactants. In the neutralization reaction, an equivalent amount of acid reacts with an equivalent amount of alkali to form an equivalent amount of salt and water. While the reaction between a strong alkali and a strong acid yields a neutral salt (pH 7), the salt formed with other combinations like ‘strong acid - weak alkali’ and ‘weak acid - strong base’ are not neutral. They produce salts, which are either acidic or basic in nature with a pH not equal to 7 [53]. Subsequently, the quantity of the salt and water produced in this reaction varies accordingly. At 0% concentration of the acid, the pH of the ordinary mortar and ECC were 12.85 and 11.83 respectively making the ordinary a stronger alkali than ECC. Therefore, as the concentration of the D-galacturonic acid increased, so did the neutralization reaction in the ordinary mortar, consequently producing a larger quantity of salt and water than the ECC. This larger quantity of water then resulted in the setting time of the ordinary mortar being much higher than that of ECC. The water production due to the reaction explains the extra fluidity observed on top of the mortar plates. However, since the extent of this reaction was much less severe in ECC than in mortar, no extra water was observed on the ECC unstiffened patches. The water produced by the neutralization reaction on the affected ECC patches did not exceed the appropriate water content limits of the mix. The excess water on the mortar patches exceeded the appropriate limits for the mortar mix subsequently negating the setting process, resulting in the non- stiffening of the affected portions. While the hardened ECC curtailed the production of sap from the bamboo stumps, the unstiffened mortar patches allowed the bamboo sap to continue to freely ooze out with ease as observed on the uncovered control stumps. Moreover, after exhaustion of water production by the neutralization reaction, the fluid on top of the mortar plate assumed the same yellowish coloration of bamboo sap [54] as on the control stumps and gradually dwindled and dried up in tandem with the control. The ultimate disaggregation of the mortar into the original constituents i.e. sand and cement greatly weakened the mortar plate and exposed it to erosive forces as was observed in this study when the sand and cement was eventually washed away by rain leaving behind circular holes (Fig.3.2.10).

By virtue of being cementitious materials, both the ECC and ordinary mortar underwent the hydration process. However, as expected there were variations in the extent to which the setting and hardening processes of these materials were modified by the D-galacturonic acid due to the differences in the mix components. While matching the water/cement ratio of ordinary mortar to that of ECC and inclusion of a superplasticizer may reduce the setting retardation effect of the D-galacturonic acid on the ordinary mortar, such a design would increase the material cost of the material and obliterate the cost advantage that ordinary mortar currently holds over ECC. Since superplasticizers and high cement content are the major source of ECC’s exorbitant cost [55], it is necessary to continue to research on ways of reducing the cost of emerging high performance materials with desirable properties such as ECC. Moreover, in practice, with the exception of hot climates where high temperatures tend to accelerate the stiffening of cementitious material, the use of superplasticizers is optional in most plain cement materials cast in moderate climates. However, in ECC, as in other fiber reinforced cementitious composites, the processing and workability of the fiber containing mix is intricate and to obtain a mix with desirable flow properties at constant particle concentrations the electrosteric dispersion and stabilization technique is employed. This technique involves the optimal combination of superplasticizer which acts as an electrostatic dispersant, with a water-soluble polymer viscous agent which acts both as a steric stabilizer and viscosity-enhancing agent [56]. Therefore, it is imperative to add a superplasticizer to the ECC mix as much as the high cement content is a requirement of the micromechanics design of the ECC mix.

b.Effect on strength

Due to the presence of fibers, the flexural strength of all ECC samples was higher than the mortar samples for all the conditions tested while the compressive strength of the mortar is higher than that of ECC due to the higher sand content in mortar. However, for each material, there were some notable variations in both flexural and compressive strength of the samples curing or soaked in the acid and the samples in water. The attainment of strength of both ECC and mortar was slightly affected by the presence of D-galacturonic acid in the curing water. As shown in Fig.3.2.3 and Fig.3.2.4, the flexural and compressive strength of the mortar prisms curing in water was initially higher than that of mortar curing in water containing D-galacturonic acid. However, the 28day-strength of the mortar cured in acid was slightly higher than that cured in water. At early ages of the curing process the hydration of the mortar was retarded by the acid to a slightly larger extent than the ECC. Hence, the delay in strength development of this mortar resulted in a denser and more uniform structure which attained slightly higher 28-day strength than the mortar cured in pure water (Jumardurdiyeva 2005). Apart from the slight increase in the flexural strength of ECC curing in water over that curing in the acid-containing water at the age of 2 days, there was no significant variation in both the flexural and compressive strength of ECC over the 28 days of curing in either medium. According to Neville (1996), the speed of setting and the rapidity of hardening (strength gain) are independent of one another. Moreover, the curing process commenced 24 hours after casting when the setting of the plates had already expired and strength development was commencing. In addition, due to the slow rate of penetration of deteriorative agents, the impact of the acid on the 40mm thick prisms was much reduced and decreased with increase in age of the plates. Consequently, as shown in Fig.5 and Fig.3.2.6, D- galacturonic acid did not have any significant effect on both the flexural and compressive strength of both hardened ECC and mortar after 28 days of water curing. At the age of 28 days when the hardened samples were soaked in the acid, significant hydration had already transpired. While in general, strong acids with a pH value below 5.5 can severely decompose cementitious materials [32], the pH of the D-galacturonic acid aqueous solution used for soaking the mortar samples was only 6.6 and hence not strong enough to inflict significant deterioration.

Whilst there was no significant impact on the flexural and compressive strength of both materials due to D-galacturonic acid, the impact on the setting of mortar cannot be ignored. The increase in the setting time of ordinary mortar impairs early age performance of the related structure and exposes the affected sections to erosive agents such as water. Even though other parts of the structure may set and harden at the expected rates, the eroded sections become conduits for more deteriorative agents and impinge on the long term durability of the structure [39]. Since ECC is able to maintain its flexural superiority over ordinary mortar despite the encounter with the acid and can significantly resist retardation of the setting process, ECC remains a superior material over ordinary mortar in repair and retrofit applications where the flexibility and ductility of ECC is desirable and ECC structures set up in areas susceptible to organic acids intrusion will have better early performance and consequently higher long term durability than ordinary mortar structures.

3.3.5. Conclusion

1. D- galacturonic acid is an ‘acid -sugar’ with both carbonylic and carboxylic functions. As such, it can retard the setting time of cementitious materials by the neutralization alkali-acid reaction as well as by retardation of the hydration process through adsorption of particles on the surfaces of the hydrating cement particles.

2. The retardation in the setting time of ECC was less severe than in ordinary mortar due to the impact of the acidity of its chemical additives on the pH of the material.

3. The tenacity of ECC towards setting retardation by the D-galacturonic acid allows the hydration process to cause the necessary stiffening and gain of strength of the material within the expected period. This ensures both short and long term durability of the overall structure.

4. In environments susceptible to the acid exposure, the retardation of the setting time of ordinary mortar by the D-galacturonic acid creates points of weaknesses within the overall structure which are vulnerable to deteriorative agents. This phenomenon depreciates both the short and long term durability of the overall structure.

5. D-galacturonic acid has an insignificant effect on the attainment of flexural and compressive strength of ECC during curing but it has an appreciable effect on the strength attainment of mortar.

6. There is no significant effect of D-galacturonic acid on the strength of both ECC and mortar after the standard curing period of 28days, a period in which significant hydration will have transpired in cementitious materials.

7. ECC is able to maintain its flexural superiority over ordinary mortar despite the presence of D-galacturonic acid.

8. The severity of the effect on the hydration process by D-galacturonic acid depends on the material composition of the structure in question, pH of the reactants and the stage in the hydration process at which the encounter occurs. Moreover since the content of D-galacturonic acid varies from plant to plant, it is recommended to ascertain the actual composition in a plant or weed whose sap is likely to get into contact with fresh or hardened cementitious materials. Where necessary, curtailment of the production of the detrimental sap by an appropriate treatment method before construction should be undertaken.

3.3 EFFECT OF CYCLIC LOADS ON THE SURFACE PROFILE OF ECC LINING

3.3.1. 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 [57] 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 [58]. 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 [59].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 sub-surface drain may be inserted in the foundation of the open channel to separate groundwater from surface water and avoid the build-up of water pressure which can damage the channel lining [60]. Types of sub-surface drains include porous concrete, crushed stone and river gravel [62]. In line with Newton’s laws of motion [61], interactive loads are expected at the lining/sub-surface 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 [63] 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 sub-surface 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 [64] and often culminate in high or infinite cost to economies and human life [65] 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 sub-surface drain. While the surface of a porous concrete sub-surface 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 sub-surface 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 [66], 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.

While plain concrete is the most commonly used lining material owing to its low cost and easy handling [67], the material has inherent deficiencies related to its material structure which diminish both its early age performance and long term durability [68].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 [69]. 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. On the other hand, deteriorations also increase 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 [12]. 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 uni-axial loading[67][31]. While concrete has been in use since the 19th century [36], ECC was only developed in the 1990s [37] 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.

3.3.2. Experimental program

ECC lining surfaces were monitored for variations in roughness and crack development. Three sub-surface conditions were investigated i.e. 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.

3.3.2.1 Materials

ECC premix powder was used for the lining material while sandy soil, 20mm angular crushed stone and a geo-textile separator (*Tts-101 Toa filter*) were used for the foundation. The premix comprised cement, sand, fly ash and PVA fiber 12mm in length, 0.04mm in diameter, 1690MPa in tensile strength and 40,600MPa in modulus of elasticity. The proportions of the mix components are shown in Table 3.1. 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 anti-shrinkage agent) and type C (poly oxi-alkaline based expansive agent for air content adjustment) to an electric mixer. The room temperature was kept at 20^{o}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.

3.3.2.2 Testing Procedure

Samples M1, M2 and S1 were prepared in 250mm x 250mm x 50mm forms as detailed in Fig.3.3.1. Each sample comprised 5 units detailed in Table 3.3.1 according to subjected loading. A 40mm foundation was prepared on the base of each form. The crushed stone in samples M1 and M2 was vibrated for 2minutes 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 [70]. The ECC paste was poured over the foundation to form a 10mm thick lining. A 250mm x 250mm geo-textile was embedded in between the crushed stone and lining in sample M2. The 250mm x 250mm dimensions were selected to fit the size of the head used for loading while the 10mm lining thickness corresponds to the minimum thickness of ECC that can be applied using direct spraying methods [27]. 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 50mm x 50mm 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 Fig.3.3. 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 220mm x 220mm 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 3.7. 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^{o}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 x 40 mm x 160 mm and water curing them at 20^{o}C for 28days 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.

Table 3.7 Description of samples and loads applied

load(t)	stress (kPa)	sample M1	sample M2	sample S1
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

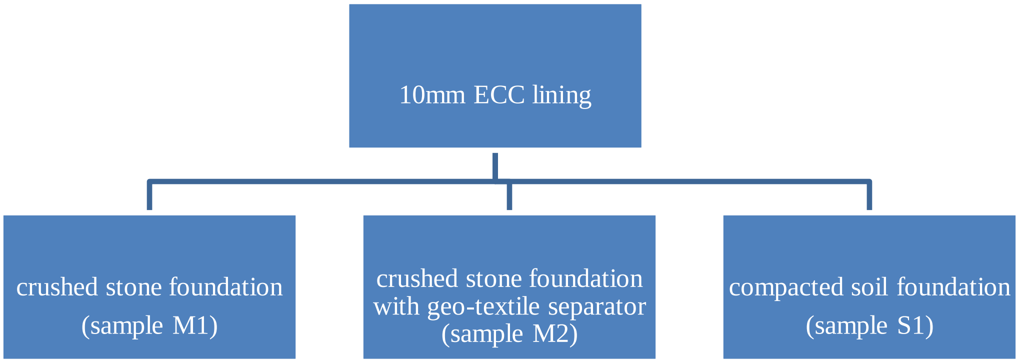


Fig.3.3.1. Description of samples used in this study

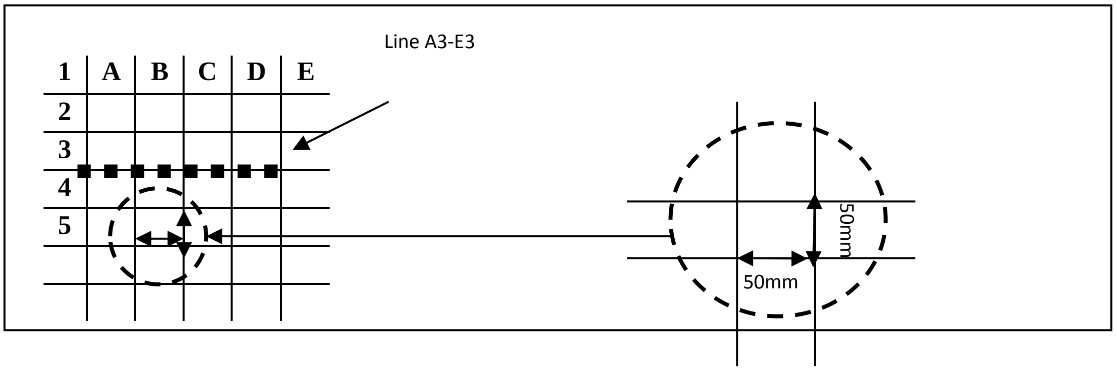


Fig.3.3.2. Gridlines on the surface of each sample

3.3.3. Results and Discussion

The data from the line A3 –E3 marked on Fig.3.3.2 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 83kPa shown in Table 3.7. Therefore, since the first crack stress of ECC is 2.5MPa [71], 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 Fig.3.3.3, Fig.3.3.4 and Fig.3.3.5 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 [72], the viscosity of ECC due to presence of PVA fibers [73] 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:

a.ECC lining on crushed stone foundation (sample M1)

From the graphs for the lining cast directly on crushed stone i.e. 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'[74] , 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 the compressive strength of the ECC used in this study was 32kPa, the ECC lining withstood stresses of 62kPa and 83kPa since infusion of the crushed stone into the ECC paste created a composite with a higher compressive strength [74]. 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.

b.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 [34], 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 build-up of ground water pressure and ultimate damage to the lining.

c.ECC lining on crushed stone foundation with geo-textile separator (sample M2)

The behavior of the lining cast on crushed stone with a geo-textile separator embedded in between was similar to that of sample S1 for the lower loads of 21kPa and 41kPa but the pattern significantly deviated for the higher loads. In this case, the geo-textile 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 62kPa loading. The ECC lining in sample M2-3 responded by deforming into an undulating profile as shown in Fig.3.3.4. 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 geo-textile attached to the ECC lining. Being flexible, the geo-textile 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 [74] 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 [76]. 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 20mm, the amplitude of the undulations was restricted to less than 5mm and may not significantly affect the roughness of the open channel lining. Nevertheless, it is likely that roughness will significantly 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 [76] 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 62kPa was not high enough to cause cracking of sample M2-3. Moreover, it is believed that the geo-textile that can also act as reinforcement absorbed some of the loads.

Finally, at applied loading of 83kPa 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.

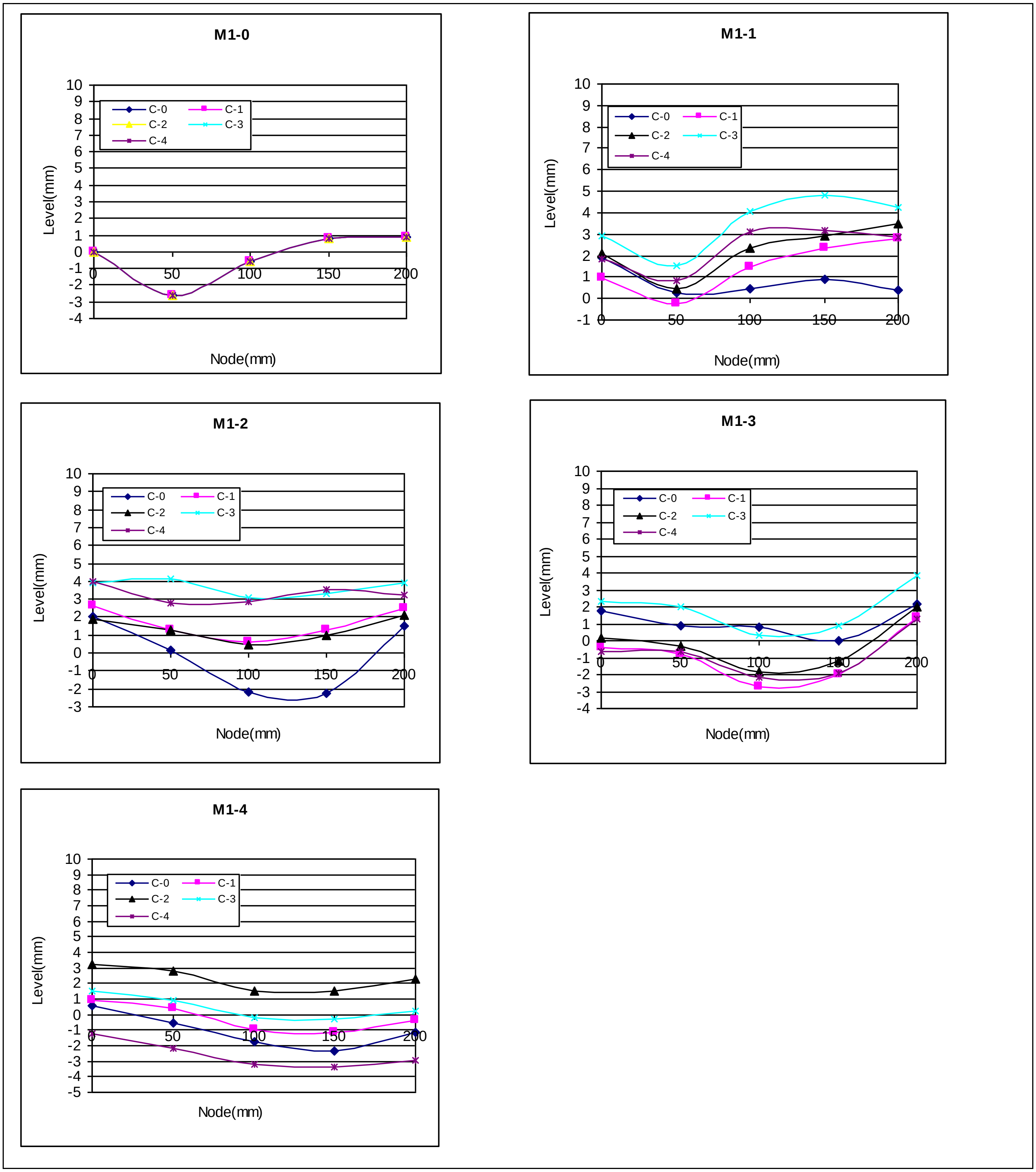


Fig. 3.3.3. Surface profile along line A3-E3 of ECC lining cast on crushed stone (sample M1)

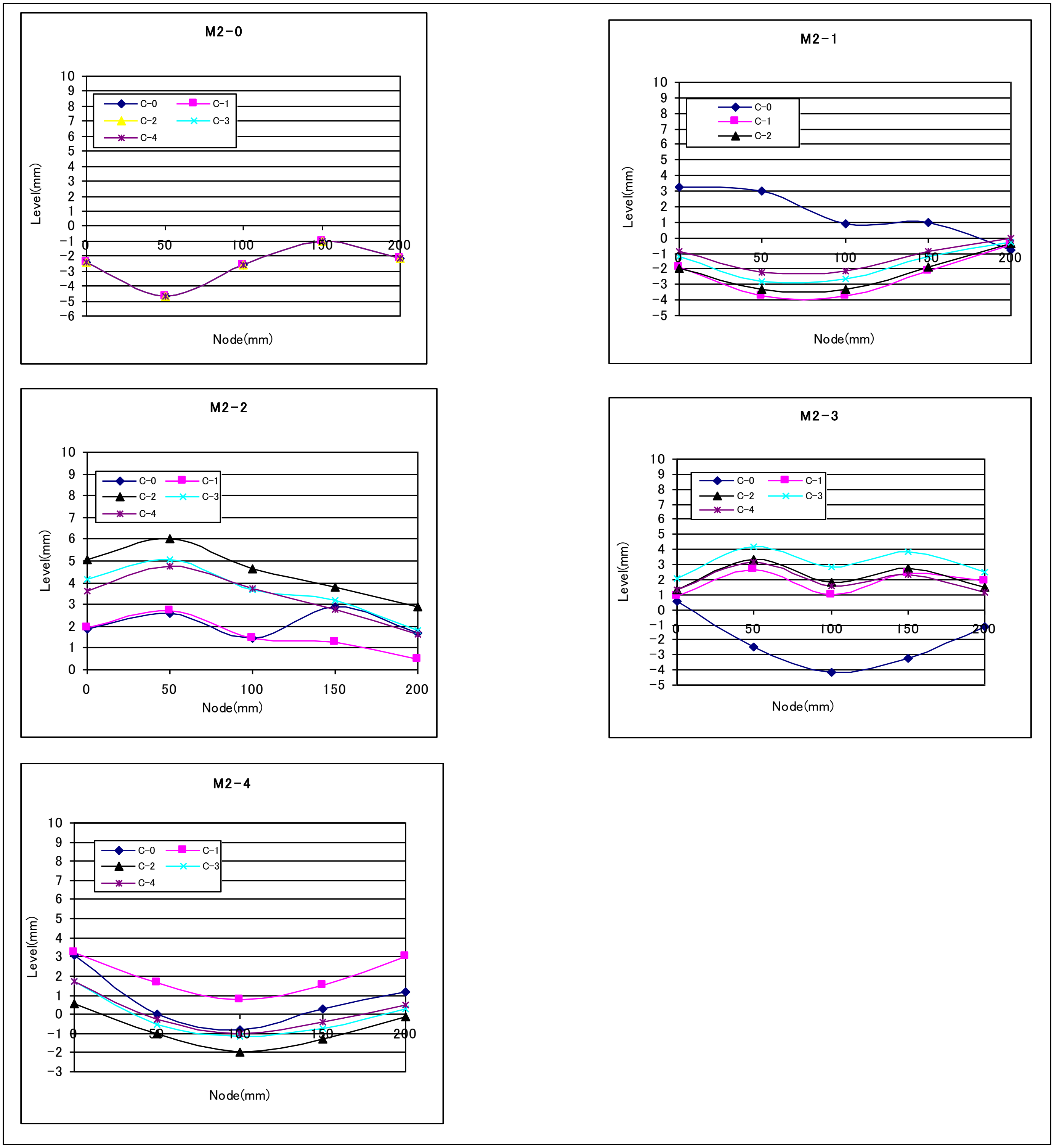


Fig.3.3.4. Surface profile along line A3-E3 of ECC lining cast on crushed stone with a geo-textile embedded (sample M2)

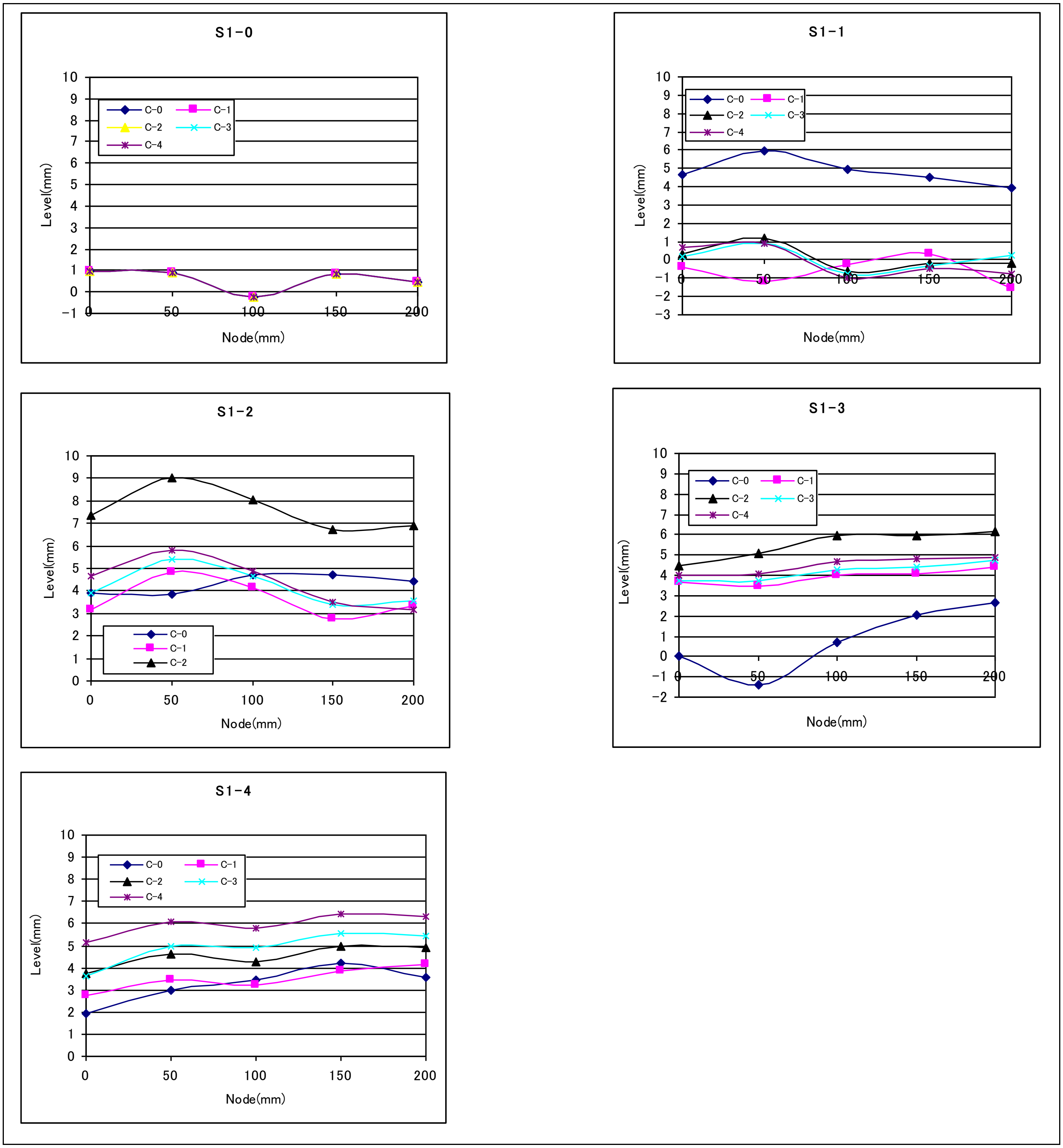


Fig.3.3.5. Surface profile along line A3-E3 of ECC lining cast on compacted soil (sample S1)

3.3.4. Conclusion

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 build-up of ground water pressure.
3. The inclusion of a geo-textile 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 geo-textile 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 geo-textile prevents the build-up of ground water pressure. In addition, the geo-textile 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 geo-textile, 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 0.1mm and satisfy serviceability limits in water storage facilities where according to British Code BS 8007(1987) [ref. 10.19] a maximum crack width of 0.2mm is deemed necessary for maintaining water tightness.

3.4. EFFECT OF PLATE THICKNESS ON CRACK PROPAGATION CHARACTERISTICS OF ECC

3.4.1. Introduction

Plain cement materials such as cement pastes, mortars and concretes are commonly used for construction. In spite of their ubiquity, these materials have several inherent deficiencies such as brittleness originating from their material structure [77] which diminish both early age performance and long-term durability. Modern concepts of fiber reinforcement and interface engineering emanated from efforts to address the deficiencies of these materials [82] producing High Performance Fiber Reinforced Cement Composites (HPFRCC) such as Engineered Cementitious Composites (ECC) in the 1990s [47]. ECC is a ductile fiber reinforced cement based composite material that has been found to be excellent at crack dispersion. Formed primarily from cement and sand with fiber and certain chemicals as additives, ECC is systematically engineered to achieve high ductility under tensile and shear load. It can achieve maximum ductility in excess of 3% under uniaxial loading with only 2% volume of fiber content [10]. Moreover, due to its strain hardening capacity, ECC develops fine cracks of less than 0.1mm width, which are limited to the surface in contrast to the through cracks developed by plain cement materials [31].

Durability concerns of plain cement materials also exist in retrofit or repair works especially on the substrate/repair layer interface. In some cases, the drying shrinkage of the new material restrained by the old material leads to cracking and interface de-lamination introducing water and other deteriorative agents into the repaired system thereby invoking fresh deterioration and necessitating a new and certainly uneconomical repair cycle. However, it has been verified experimentally, that when an adequate bond is provided, the high ductility of ECC can relieve shrinkage induced stresses in the ECC repair layer and at the ECC/concrete interface, suppressing the development of large through cracks and interface de-lamination [68]. Therefore, in retrofit and repair applications, based on properties only, ECC is a more suitable material than traditional plain cement materials. However, in practice, the use of ECC is currently limited to less than 10 countries worldwide. This is mainly due to its elevated cost emanating from its requirement of special fibers, very high cement content and a high performance super-plasticizer [55]. Certainly, cost and sustainability of ECC are two aspects that need to be addressed to make the use of ECC widely acceptable. While optimization of the composite to minimize the fiber content is critical to cost reduction, optimization of the overall dimensions of ECC elements can reduce the volume of material required thereby reducing the overall material cost.

In repair and retrofit applications, there is usually little flexibility regarding the length and width of the original structure but thickness tends to be adjustable depending on the structural requirements. Even though it is possible to apply ECC layers of thickness as low as 10mm using the direct spraying method [27], the selection of the optimum thickness for a particular element depends on the structural requirements such as expected crack widths since design codes specify crack width limits based on functional use of the structure. For instance, the British Code BS 8007(1987) [ref. 10.19] states that a maximum crack width of 0.2mm is deemed adequate for water tightness in water retaining structures, and a more stringent 0.1mm is necessary where aesthetic appearance is of particular importance. Hence, it is imperative for a repair layer to meet this standard to be deemed adequate. Inevitably, variations in material content, dimensions and external loads in turn vary the size and distribution of cracks developed by any material. It is therefore the objective of this study to elucidate the impact of variations in thickness, on the size and distribution of cracks propagated by ECC.

3.4.2. Experimental Program

Repair and retrofit structures are usually applied in layers or plate-like elements and hence in this study, plates were used as the target elements. ECC plates of varying thickness were cast and cracks artificially generated followed by the determination of crack width and crack density.

3.4.2.1 Materials

ECC premix powder was used in this experiment. The major components of the ECC premix powder were cement, sand and water soluble poly-vinyl alcohol (PVA) fiber of length 12mm, diameter 0.04mm, tensile strength 1690MPa and modulus of elasticity 40,600MPa. The mix proportions of ECC are shown in Table 3.1. At a room temperature of 20^{o}C, the premix ECC powder was added to an electric mixer. Water and 3 admixtures: Type A (super-plasticizer), Type B (anti-shrinkage agent) and Type C (expansive agent for air content adjustment) were mixed together and added to the premix powder. The mixer was covered and run for 2 minutes to avoid losses of the mix components. While the mixer was running, its cover was removed and mixing was continued until 10 minutes elapsed. The ECC paste was then transferred into a tray. The homogeneity of the mix was further corroborated by hand mixing.

3.4.2.2 Experimental Procedure

a. Determination of Crack Distribution

ECC plates of dimensions 400mm x 400mm and thicknesses of 10mm, 20mm, 30mm were cast and cured in water for 28days at 20^{o}C. The dimensions 400mm x 400mm were selected to fit the limits of the device used for generation of cracks. The upper dimension of 30mm was selected since it is the common thickness used in ECC repair applications while the lower dimension of 10mm coincides with the minimum ECC thickness that can be placed using the direct spraying technique. Three sets of ECC plates were prepared for each thickness, each set comprising 3 plates. Using the ‘Third-Point Loading’ test configuration [76], on a bending machine, the first set was loaded to ultimate failure to determine the average ultimate failure load for each thickness. Using 80% of the determined average ultimate failure load, cracks were generated on the second set. The third set was kept intact as the control. A 100mm wide strip was marked on the central portion of the set of plates with cracks. A thin film of fluorescent paint was used to accentuate the cracks and in a dark room, each plate was illuminated under black light, which caused the fluorescent paint-packed cracks to glow yellow. Using a digital camera, pictures were taken at 3 positions on the strip. Images from the camera were viewed using the computer-aided drafting software, AutoCAD 2002. The number of cracks along the 100mm wide strip was then physically counted from the images and multiplied by 10 to obtain the average number of cracks per unit meter.

b. Determination of Crack Width

Crack widths were measured using a crack width-measuring device, the Crack Viewer FCV-30. The average crack width was determined by taking measurements on 3 cracks from each of the 10mm, 20mm and 30mm plates used for determination of crack distribution. Images and data of each crack were recorded as shown in Fig.3.4.1.

3.4. 3. Results and Discussion

Table 3.8 Average crack density and crack width

thickness (mm)	average density (cracks/m)	average crack width (mm)
10	125	0.07
20	115	0.08
30	135	0.08

During mixing of the material, it was observed that the ECC fresh mix had very high workability, which enabled easy placing. The behavior of the 10mm, 20mm and 30mm plates under load was similar to ductile material i.e. gradual bending into a visible curve in contrast to instant rupture of plain cementitious materials. Moreover, multiple fine surface cracks were observed on the surface of the plates. As shown in Table 3.8, the average crack widths for the 10mm, 20mm and 30mm plates were 0.7mm, 0.8mm and 0.8mm respectively while the average crack densities were 125 cracks/m , 115 cracks/m and 135 cracks/m.

The crack widths and crack densities obtained in this research agree with data obtained by previous researchers. For instance, the multiple fine surface cracks observed on the ECC plates are typical and the values of crack widths of 0.8mm to 0.9mm agree with findings by Li [22] and Kanda [27]. The unique property of ECC relative to other fiber reinforced composites is its ductility and confinement of crack widths to less than 0.1mm.The high workability of ECC is due to the moderate amount of short discontinuous fibers which allows flexibility in construction execution, including self-consolidation casting [73], a property that is very useful in repair and retrofit applications. The bending behavior in response to loading is typical ductile behavior characteristic of ECC enabling failure of ECC structures to be less catastrophic than plain cement structures which are brittle.

The matrix of fibres evenly distributed within ECC slide within the cement forming matrix cracks when loaded whose density increase until composite peak load resulting in the bending of ECC under excessive strain. From Table 3.8, there was no significant variation in crack patterns, crack density and crack width for the 10mm, 20mm and 30mm thicknesses. Ultimate failure of all the plates was gradual and was preceded by bending in typical ductile behavior. The multiple micro cracking observed at the crack generation load (80% of ultimate failure load) is due to the characteristic strain hardening after the first cracking of the ECC. The fibers, which are evenly, distributed within the material bridge the cracks thereby restricting the crack width. This tight crack width by ECC is self-controlled and a material characteristic independent of rebar reinforcement ratio [20] or plate thickness. The restriction of crack width to an average size of 0.8mm obtained in this study is important in water storage facilities applications where a maximum crack width of 0.2mm and 0.1mm are deemed necessary for water tightness and aesthetic appearance respectively. Since the reduction in thickness of the plates does not significantly affect crack width or crack density, ECC layers of small thickness can be applied in repair and retrofit works where minimal distortion of the dimensions and aesthetic appearance of the original structure is crucial.

So far, researchers have focused on the crack dispersion properties and structural aspects of ECC and there is very little focus on the issue of cost reduction which to date has limited the use of an otherwise excellent repair material. While previous researchers (Kunieda [31]; Swift [78]) have elucidated the effectiveness of ECC as a repair material, the optimization of the dimensions of ECC elements as a cost reduction measure has not been investigated. While technically it is possible to apply 10mm thick ECC layers, in practice most applications are 30mm thick. This research investigated the reduction in thickness of ECC repair layer as a material volume reduction and consequent cost cutting measure and proved that it is possible to decrease the thickness of an ECC repair layer and still obtain its unique and desirable properties of ductility and multiple surface fine cracks of widths less than 0.1mm. In terms of volume of material, a 10mm reduction in thickness results in a 33% reduction of volume per unit area, which is significant in the reduction of cost of material. This is important in addressing the current limitation in the use of ECC due to the high cost of the material.

3.4.4. Conclusion

1. The thickness of plates has no significant effect on the crack width and crack distribution on ECC. This enables smaller thicknesses of ECC elements to be applied where structurally possible, thereby reducing the material volume and subsequently lowering overall material costs.
2. ECC can restrict crack widths to less than 0.1mm despite reduction in thickness from 30mm to 10mm making ECC suitable for use in water storage facilities.
3. The ability of ECC to maintain small widths despite reduction in thickness is important for repair and retrofit applications where adherence to the structural integrity and minimal distortion to aesthetic appearances of the original structure are crucial.
4. Reduction in thickness of ECC results is significant reduction in the volume and material cost which addresses the issue of the high cost currently associated with the material. Moreover, the ductility and production of fine surface cracks as opposed to the brittleness and production of through cracks by plain cementitious material makes ECC a more durable repair or retrofit material since it curtails the cycle of repairs imminent with the use of other plain cement materials thereby also increasing economic viability.

CHAPTER 4: OVERALL CONCLUSIONS AND RECOMMENDATIONS

1. ECC was found to be more effective than regular concrete in curtailing the re-emergence of weeds on the surfaces of earth embankments due to its production of fine surface cracks of less than 0.1mm in width. On the other hand, through cracks of unlimited width produced by concrete are susceptible to further expansion by lateral or vertical movements due to differential settlement of earth embankments culminating in loss of serviceability. In contrast the use of ECC in the repair of earth dams or lining of canals improves the serviceability performance.

2. While organic acids are known to retard the setting time of all cementitious materials, retardation effect on ECC was found to be less severe than in ordinary mortar hence ECC could stiffen and gain of strength within the expected period. However, the retardation of the setting time of ordinary mortar by the organic acid created points of weaknesses vulnerable to deteriorative agents and impairing both short and long term durability of related structures. Despite the severity effect of hydration modification on ECC being less than on mortar, higher concentrations of the acid in certain weeds increase the risk even in ECC. It is therefore recommended to eliminate sources of organic acids before casting thin layers of all cementitious materials in applications such as the repair of earth dams and lining of canals.

3. Due to its ductility ECC was found to be apt to deformation by non-uniform loads which caused undulations on the surface of ECC linings. In canal surfaces such a phenomenon increases roughness. However the significance of the roughness depends on the magnitude and source of the non-uniform loading. In cases where large size crushed stone is used in the sub-surface drain, the magnitude of deformation is expected to be large consequently increasing roughness. It is therefore recommended to use separators such as geotextiles which have been found in this study to moderate the formation of undulations.

4. The thickness of ECC was found to have no significant effect on the width and distribution of cracks produced by the material. This means reduction of thicknesses of ECC elements where structurally possible can significantly reduce the volume of material subsequently lowering overall material costs. This is important since to date the use of ECC is being limited by its exorbitant cost and there is need to continue to find ways to decrease the cost to make its use more widely acceptable.

Finally, this study clarified that ECC is a more durable material than traditional concrete such as mortar in earth hydraulic structures applications. This means the use of ECC in repair can improve the serviceability performance of earth hydraulic structures. Moreover, despite the relatively high initial cost of the material, ECC curtails the cycle of repairs imminent with traditional concretes thereby decreasing its Life Cycle Costs (LCC). Therefore, in the long term ECC is a more economically viable material.

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SUMMARY OF THESIS

This study investigated the effectiveness of High Performance Fiber Reinforced Cementitious Composites (HPFRCC) in improving the serviceability performance of earth hydraulic structures through repairing with a thin layer of the cementitious material. The HPFRCC employed in this study was Engineered Cementitious Composites (ECC) and regular concrete was used as a comparison. The target application was the repair of earth hydraulic structures such as earth dams and earthen or unlined canals. Earth dams and unlined canals are prone to deterioration due to exuberance of weeds and other deteriorative forces and hence require regular maintenance. Moreover, restricting crack widths within serviceability limits is critical for ensuring water tightness and maintaining serviceability performance. The costs associated with complete removal of weeds may be prohibitive and other engineering solutions are necessary to control deterioration. In some cases, repair of earth structures by cementitious materials may be necessary to improve durability and strength. The effectiveness of this solution hinges on the durability of the repair material. The use of materials with poor durability results in repair structures with poor durability which may constantly require repairs. Such a cycle of repairs increases life cycle costs and hence need to be controlled. Whilst regular concrete has been ubiquitous in construction for over 175 years, inherent deficiencies related to its brittle behavior and production of through cracks of unlimited widths adversely affects both the short and long term durability of related concrete structures. On the other hand, ECC has high strain capacity is ductile and hence can restrict deformation to surface fine cracks of widths less than 0.1mm.While it has been elucidated that ECC is more effective than concrete in repair of concrete structures, applications in earth hydraulic structures is yet to be clarified.

Therefore, investigations were carried out in this study to clarify the effectiveness of ECC in the repair of earth embankments, durability when exposed to organic acid containing weed sap, surface deformation of canal linings and cost effectiveness. In the investigation for the repair of earth embankments, the aim was to curtail the re-emergence of weeds and consequent impairment of durability after application of a repair layer. ECC and concrete were monitored for crack development and penetration of light which supports photosynthesis and consequent growth of weeds. It was observed that while ECC developed fine surface cracks of width less than 0.1mm which prevented the penetration of adequate light to support the photosynthesis and consequent growth of weeds, concrete developed through cracks of unlimited width through which adequate light to support growth of weeds could penetrate. It was therefore concluded that ECC was more effective than regular concrete in curtailing the re-emergence of weeds on the surfaces of earth embankments. Moreover, the through crack produced by concrete is susceptible to further expansion due to differential settlement of earth embankments and therefore can also host flying seeds from other weeds which can sprout and grow. This leads to further expansion of the crack and loss of serviceability integrity of the entire water supply facility.

The hydration process in cementitious materials is prone to modification by external substances and since exposure of fresh construction material to organic acids from the sap of lacerated weeds is inevitable during maintenance or construction, an investigation to assess the durability of ECC and concrete in corrosive environments was carried out. In this investigation, the effect of organic acids on hydration of the cementitious materials was carried out. The setting time of the fresh materials as well as compressive and flexural strength of the hardened materials were monitored. It was observed that while organic acids tend to retard the setting time of all cementitious materials by the neutralization alkali-acid reaction or through adsorption of

particles on the surfaces of the hydrating cement particles, the severity of the retardation depends on the composition of the cementitious material. It was found that the retardation in the setting time of ECC was less severe than in regular concrete since the chemical additives in ECC moderated the pH of the material and enabled ECC to stiffen and gain strength within the expected period. However, the retardation of the setting time of concrete by the organic acid impinges the short term durability and resistance to deteriorative agents thus weakening and also depreciating long term durability.

It is known that surface roughness of canals affects the velocity and quantity of flow and hence it is desired that a lined canal surface remains smooth throughout its lifetime. An investigation was undertaken to clarify the effect of the ductility of ECC under non-uniform loading on the levelness of ECC lining surfaces. It was found that non-uniform loads caused undulations on the surface of ECC and hence increased roughness. The magnitude of the deformation and consequent significance of the roughness was relative to the magnitude and source of the non-uniform loading. Moreover, the inclusion of geo-textiles as separators moderated the deformation.

Since the use of high cost of the ECC material is currently limiting its widespread applications, the effect of reducing the volume of material as a cost cutting measure was investigated. In this investigation, the effect of thickness of ECC elements on crack distribution was monitored. It was observed that the thickness of plates has no significant effect on the crack width and crack distribution of ECC. This enables smaller thicknesses of ECC elements to be applied where structurally possible, thereby reducing the material volume and subsequently lowering overall material costs. The ductility of ECC, production of fine surface cracks as opposed to the brittleness and production of through cracks by plain cementitious material and ability to restrict crack widths to less than 0.1mm despite reduction in thickness from 30mm to 10mm makes ECC a more durable and econominally viable repair material than traditional concrete.

Through this study it was clarified that ECC is a more durable repair material than traditional concretes in earth hydraulic structures applications. This means the use of ECC in repair works can minimize the cycle of repairs and improve the serviceability performance of earth hydraulic structures. Moreover, despite the relatively high initial cost of the material, improvement of the serviceability performance and curtailment of the cycle of repairs imminent with traditional concretes decreases the Life Cycle Costs (LCC) of earth hydraulic structures.

学位論文の要旨

本研究では，土構造の水利施設の使用性の向上を図ることを目的として，水利施設の表面にセメント系材料である複数微細ひび割れ型繊維補強セメント複合材料（以下，HPFRCC）を薄層で施工することの効果を検討した。本研究で使用した HPFRCC は，高靭性セメント複合材料である ECC（Engineered Cementitious Composites）であり，ECC の効果は普通コンクリートの結果と比較して明らかにしている。対象とした土構造の水利施設は，ため池及び土水路である。

土構造の水利施設は，表面に繁茂している雑草木などにより変状を起こすことから，定期的な維持管理を必要とする。また，水利施設の変状として重要な項目となるひび割れについては，水密性の確保の面からもその幅を制限する必要がある。水利施設に変状を生じさせる原因となる雑草木については，その完全な除去が経費の面から限度があるため，工学的手法による解決を考える必要がある。

土構造物の補修・補強対策としては，セメント系材料などを用いた表面被覆を挙げることができるが，その効果は材料の耐久性により異なる。耐久性の低い材料による補修・補強は，再劣化による対策工事の繰り返しを生むだけであり，Life Cycle Cost を増加させないためにも控える必要がある。

コンクリートは 175 年以上に渡り建設材料として使われているが，脆性挙動でありひび割れ幅の制御ができない等の普通コンクリートの特徴は，構造物の短・長期的な耐久性に影響を及ぼす。一方，セメント系材料でありながら高靭性であり変形追従性に優れ，平均ひび割れ幅が 0.1mm 以下である ECC は，普通コンクリートよりも土構造の水利施設に適していると考えられる。

本研究では，ECC を表面被覆材として土構造の水利施設の使用性を改善することを目的として，土構造の堤体の補修効果，植物由来の有機酸における耐久性，土水路における表面変状及び費用対効果について明らかにする。

土構造の堤体の補修効果は，ECC で表面被覆した後の雑草木の再出現状況と施工後の ECC の耐久性により評価した。雑草木の成長により起こるひび割れの進展と光合成に必要な光の透過量を ECC と普通コンクリートの両者で測定したところ，ECC の表面ひび割れは 0.1mm 以下の微細であるために光合成に必要な光の透過が抑制され，ひび割れ幅を制御することができないコンクリートでは光合成に必要な光が透過した。また，屋外での実証試験からは，ECC は普通コンクリートよりも土構造の堤体表面における雑草木の再出現の削減に効果的であるという結論を得た。加えて，普通コンクリートでは，発生したひび割れの中に飛来種子が根付き雑草が繁茂するが，ECC に発生するひび割れは微細であるために表面に飛来種子による雑草繁茂がないことも確認した。一方，雑草木を切断する時に溶出する有機酸が ECC の水和反応に悪影響を及ぼすことが明らかになったために，植物由来の有機酸における ECC と普通コンクリートの耐久性について評価した。その結果，ECC と普通コンクリートの両者とも水和反応が抑制され，凝結時間が著しく延びるだけでなく強度が著しく低下することが明らかになったが，その程度は ECC の方が軽いことを試験により明らかにした。

水利施設の一つである水路においては，表面粗度が流速や流量に影響を及ぼすことから，表面状態が水路の供用寿命を通じて滑らかであり続けることが望まれる。そこで，土水路の ECC ライニングによる水路の使用性の改善を目的として，不等分布荷重が作用した場合の ECC の延性の効果を検討した。

その結果，ECC の表面における不等分布荷重の作用は粗度の増加を引き起こすだけでなく，粗度の程度は不等分布荷重の大きさと作用位置に関係すること，ジオテキスタイルを挿入することで粗度が修正されることを明らかにした。

ECC は材料価格が高いために広範囲には適用できないが，必要となる材料量を減らすことができれば，総合的には経費を減少させることができる。そこで，ECC 板の厚さとひび割れ分布の関係について検討することで，水利施設の使用性を確保するための板厚について検討した。その結果，板厚は ECC におけるひび割れ幅とひび割れ分布において重要ではなく，ECC は構造的に可能な限り薄くすることができ，それにより材料量を減らすことができ，全体の材料費を減少させることができることを明らかにした。脆性でありひび割れが貫通する普通コンクリートに比べて，延性であり微細ひび割れである ECC では，10～30mm の厚さにおいてひび割れ幅が 0.1mm を下回り，補修効果を経済的に得ることができる。

本研究では，土構造の水利施設における耐久的な補修を図る上で，ECC は普通コンクリートよりも効果があることを明らかにした。補修工事における ECC の使用は，土構造の水利施設の使用性を改善することができるだけでなく，経費の面においては，初期経費が高くなるものの，普通コンクリートで起こるような補修の繰り返しを最小限に止めることができ，総合的には Life Cycle Cost を減少させることができる。

APPENDIX - List of Publications

Published/Accepted Papers

1. Cleopatra Panganayi, Hidehiko Ogata, Kunio Hattori, “Effectiveness Of ECC In Curtailing Re-Emergence Of Weeds On An Earth Embankment”, (Elsevier) Construction and Building Materials, Vol. 24, Issue 4, p. 545-551, April 2010 – **Section 3.1**

2. Cleopatra Panganayi, Hidehiko Ogata, Kunio Hattori, “Effect of D-galacturonic Acid on Hydration of Cementitious Materials”, American Society of Civil Engineers (ASCE) Journal of Materials in Civil Engineering, (accepted April 22nd, 2011-in production) – **Section 3.2**

3. Cleopatra Panganayi, Hidehiko Ogata, Kunio Hattori, “Effect of plate thickness on crack propagation characteristics of Engineered Cementitious Composites (ECC)”, (Science Alert) Asian Journal of Applied Sciences, Vol. 4, Issue 5 p. 542-547, April 2011 – **Section 3.4**

Conference Proceedings

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