A Study on the Effects of Plastic Shrinkage Cracking of Shotcrete Mixes Applied over a Dry Clay Base While Exposed to the Sun and Wind

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Abstract — *Thin concrete shells used as concrete liners over dry clay dikes suffer from plastic shrinkage cracking for two main reasons: the dry clay base absorbs some of the water in the concrete from below, and high heat coupled with low humidity and wind evaporate some of the water in the concrete from above. This project has the main objective of testing and determining which of three different shotcrete mixes generate the least amount of plastic shrinkage cracking when applied over a dry clay base while exposed to the sun and wind. A high w/c ratio was used to force plastic shrinkage cracking to form. Besides the control mix, a mix with polypropylene reinforcing fibers and another mix with fly ash partially substituting the Portland cement were used. The clay base in this experiment simulates a clay dike that will have a shotcrete liner applied over it to mitigate erosion and flora growth.*

Key Terms — *Fiber Reinforced Concrete, Fly Ash, Plastic Shrinkage Cracking, Shotcrete.*

INTRODUCTION

Clay dikes are an excellent impermeable barrier used for flood control and containment, but suffer deterioration due to erosion. There are many ways to counteract this problem: allowing grass and plants to grow on the dike, covering the dike with a geotextile, crushed stone, boulders, fabricated blocks, or concrete. The placing of thin concrete liners on the face of the clay dikes presents problems for the engineer that are not present in typical construction, such as steep inclines, excessive water loss during curing of the concrete and cracking.

BACKGROUND

To further understand this study, a deeper understanding of the key elements must be known.

Plastic Shrinkage Cracking

The contraction (due to drying shrinkage) of a concrete component within a structure is always subject to some degree of restraint from either the foundation, another part of the structure, or the reinforcing steel embedded in the concrete [1] [2]. The combination of shrinkage and restraint develops tensile stresses within the concrete. Due to the inherent low tensile strength of the concrete, cracking will often occur. The major factors controlling ultimate drying shrinkage of concrete include relative humidity, aggregate type, paste content, water content, and w/c ratio. The rate of moisture loss and shrinkage of a given concrete is influenced by the size of the concrete member, the relative humidity, distance from the exposed surface, and drying time. The higher the surface area to volume results in a faster drying rate.

Objectionable plastic shrinkage cracks commonly occur in the surfaces of floors and slabs when job conditions are so dry that moisture is removed from the concrete surface faster than it is replaced by bleed-water. These cracks occur before the start of curing and can occur either before or after final finishing. Plastic shrinkage cracking is most likely when environmental conditions, concrete temperature, and mixture proportions combine to cause a rapid loss of available surface moisture. Avoiding these conditions minimizes the cracking of the concrete. Other helpful practices that can counteract the excessive loss of surface moisture are using a well-dampened sub-grade, cooling the aggregates, and using cold mixing water or chipped ice as mixing water to lower the fresh concrete temperature.

Slabs-on-ground are designed and their thickness selected to prevent cracking due to external loading. Steel reinforcement may be used in slabs-on-ground to improve performance of the slab under certain conditions. These include: limiting width of shrinkage cracks; use of longer joint spacing than unreinforced slabs; and providing moment capacity and stability at cracked sections. The use of reinforcement will not prevent cracking, but will actually increase crack frequency while reducing crack widths. Properly proportioned and positioned, reinforcement will limit crack widths such that the cracks will not affect slab serviceability.

Fly Ash

Fly ash, a product from the combustion of pulverized coal, is widely used as a cementitious and pozzolanic ingredient in hydraulic cement concrete [3]. Fly ash is normally used at a rate of 15-35% by mass of total cementitious material. When fly ash is used to replace a portion of cement in a unit volume of concrete, the amount of paste (assuming the w/cm is constant) will increase. Usually, this increase in paste volume creates a concrete with greater plasticity and better cohesiveness. Using fly ash usually reduces bleeding by providing a greater surface area of solid particles and requiring a lower water content for a given workability. Improved pumpability of concrete usually results when fly ash is used. Fly ash can extend the setting time of concrete if the hydraulic cement content is reduced. Additionally, the long-term reaction of fly ash refines the pore structure of concrete to reduce the ingress of water containing chloride ions. As a result of the refined pore structure, permeability is reduced.

Fiber-Reinforced Concrete (FRC)

Fiber-reinforced concrete is a composite material made of a standard concrete mix and a dispersion of discontinuous fibers [4]. The most common reinforcements are made from steel wire and polypropylene. The use of fibers in concrete improves plastic shrinkage and settlement cracking, impact resistance, material disintegration, and ductility. Two general sizes of synthetic fibers have emerged: microsynthetic and macrosynthetic. Microsynthetic fibers are defined as fibers with diameters or equivalent diameters less than 0.012 in. Macrosynthetic fibers are those with diameters or equivalent diameters over 0.015 in. Polypropylene fibers are typically used in a range of 0.2-1.0% by volume, and sometimes higher on certain applications. Low doses of polypropylene fibers can generally be added without changing conventional concrete mixtures.

Current applications of FRC include residential, commercial, and industrial slabs on grade, slabs for composite metal deck construction, floor overlays, shotcrete for slope stabilization and pool construction, precast units, slip form curbs, and mortar applications involving sprayed and plastered Portland cement stucco.

Shotcrete

Shotcrete is the name given to a mortar or concrete mix pneumatically projected at high velocity onto a surface instead of being poured in the traditional manner [5]. Shrinkage is typically greater in shotcrete than most conventional concretes, mainly because shotcrete has less coarse aggregate and more cementitious material and water. Typical shotcrete mortar has aggregate 3/8" in diameter or less.

PROBLEM

The purpose of this study is to determine and compare the effects of plastic shrinkage cracking on various shotcrete samples poured and cured while exposed to the sun and wind while applied over a dry clay base. This study originated from the author's own field experience during a construction project consisting of building clay dikes and lining them with shotcrete to mitigate the damage caused by erosion and flora growth. On various occasions, plastic shrinkage cracking would be visible on sections of dike liner applied scarcely an hour before (Figure 1).

A direct application of the knowledge gained from this research would be for the improvement of shotcrete liners over clay dikes and slopes.

Figure 1
Shotcrete Dike Liner under Construction

METHODOLOGY

In order to study the cracks due to shrinkage, a set of tests on flat sloped fresh concrete panels subjected to outside weather conditions were performed (Figure 2).

Figure 2
Shotcrete Batches on the Roof

Three different sets of mortars were tested: control (Table 1), 30% fly ash (Table 2), and 1.5 lb/c.y. polypropylene micro fiber (Table 3). The control mix was a standard combination of Portland cement, sand, and water with a w/cm ratio of 0.94. The fly ash mix replaced 30% of the control mix's cement with fly ash, by volume. The polypropylene fiber mix used the control mix and added 1.5 pounds per cubic yard of microfiber.

To simulate the field conditions and to test the three design mixes, three wood molds were built: 30" long x 30" wide x 3" deep. To create anchorage and prevent the test slabs from shrinking into themselves and separating from the wood molds, nails were installed on the perimeter of the molds half an inch from the top. The nails were installed every two inches, projected one inch, and were bent at approximately 45 degrees (Figure 3). In these molds, two inches of dry clay were added and compacted smooth to simulate the surface of a clay dike (Figure 4). The molds were placed on the roof of a four story building to be exposed to sun and wind during the concrete pour and curing.

Temperature and wind speed measurements were taken throughout the first two hours. Each design mix was poured onto these molds to have a thickness of 1", smoothed out, and left to cure. Additionally, three test cubes per mix were made to test the compressive strength of each mix after 28 days and left to cure.

Table 1
Control Mix Design

Control	Vol. (c.f.)	Weight (lb.)
Cement	0.07	14.36
Fine Aggregate	0.53	84.83
Water	0.22	13.56
Air	0.02	2%
Total	**0.84**	**112.75**

Table 2
30% Fly Ash Mix Design

30% Fly Ash	Vol. (c.f.)	Weight (lb.)
Cement	0.05	10.02
Fly Ash	0.02	3.05
Fine Aggregate	0.53	84.83
Water	0.22	13.56
Air	0.02	2%
Total	**0.84**	**111.50**

Table 3
Reinforced Fiber Mix Design

1.5lb fiber/c.y.	Vol. (c.f.)	Weight (lb.)
Cement	0.07	14.36
Fiber	0.0	0.04
Fine Aggregate	0.53	84.83
Water	0.22	13.56
Air	0.02	2%
Total	**0.84**	**112.79**

Figure 3
Wood Mold with Perimeter Anchorage

Figure 4
Clay Base Installed

The process of measuring crack widths was taken by modifying ASTM C1579-13 [6]. To avoid possible effects of panel boundaries on crack widths, no measurements were taken within 25 mm of the mold boundaries.

RESULTS

During the pour and initial setting of the concrete samples, ambient air temperature and wind speed measurements were taken and recorded with a handheld device. The weather was fair with occasional clouds. From the data, a mean air temperature of 89.4°F was recorded with a relative humidity of 47.3% and an average wind speed of 5.4 mph and a top wind speed of 26 mph.

Cracks were quantified on all three slabs, measuring crack widths from 2.00 mm down to 0.15 mm utilizing a crack gauge at 10 mm intervals along the length of the cracks (Figure 5).

The control batch showed total crack lengths of 117 cm with an average crack width of 53 mm and the maximum crack width was 2.00mm (Figure 6).

Figure 5
Measuring Cracks with a Gauge

Figure 6
Control Batch Cracking Pattern

The fly ash batch showed an increase in total crack length but a decrease in crack width when compared to the control batch. The total crack lengths were of 224 cm with an average crack width of 0.16 mm; the maximum crack width being 0.25 mm Crack locations were marked for easier viewing (Figure 7).

Figure 7
Fly Ash Batch Cracking Pattern

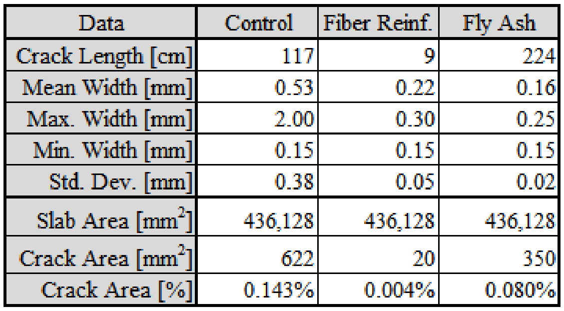
The fiber reinforced batch showed a substantial decrease in both total crack length and average crack width when compared to the control batch. The total crack lengths were of 9cm with an average crack width of 0.22 mm; the maximum crack width being 0.30 mm (Figure 8).

Figure 8
Fiber Reinforced Batch Cracking Pattern

Calculating the cracked areas as a percentage of the test slab areas found that the fly ash slab had 44% less crack area compared to the control. Similarly, the fiber reinforced slab had 97% less crack area compared to the control (Table 4).

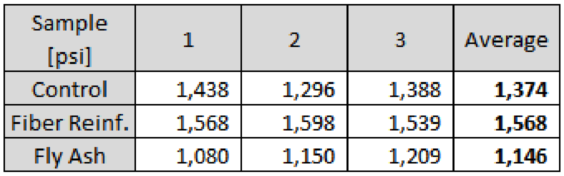
A standard 28-day compression test was performed on three 2” cube samples per batch to determine the average compressive strength of the shotcrete. The results found that the control batch had an average compressive strength of 1,374 psi, the fiber reinforced batch resisted 1,568 psi, and the fly ash batch had a resistance of 1,146 psi (Table 5, Figure 9).

Table 4
Calculated Crack Data for the Various Shotcrete Test Batches



Data	Control	Fiber Reinf.	Fly Ash
Crack Length [cm]	117	9	224
Mean Width [mm]	0.53	0.22	0.16
Max. Width [mm]	2.00	0.30	0.25
Min. Width [mm]	0.15	0.15	0.15
Std. Dev. [mm]	0.38	0.05	0.02
Slab Area [mm^2]	436,128	436,128	436,128
Crack Area [mm^2]	622	20	350
Crack Area [%]	0.143%	0.004%	0.080%

Table 5
28-day Compression Test Results



Sample [psi]	1	2	3	Average
Control	1,438	1,296	1,388	**1,374**
Fiber Reinf.	1,568	1,598	1,539	**1,568**
Fly Ash	1,080	1,150	1,209	**1,146**

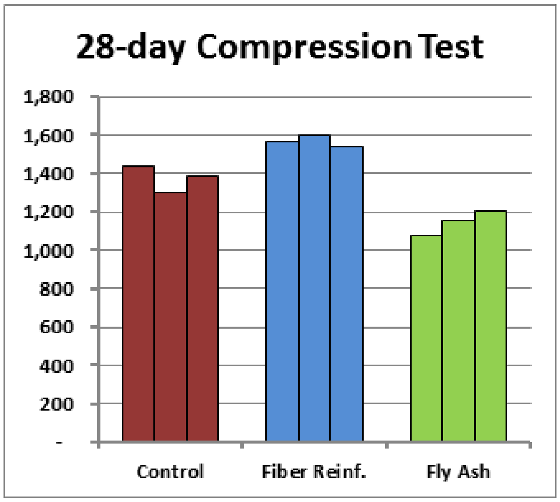


Figure 9
28-day Compression Test Results

CONCLUSIONS

From the data obtained, various conclusions can be reached. In terms of workability, the fly ash mix was the easiest to handle and smooth out in the mold. This is due to the increased amount of paste, having replaced 30% by weight of the Portland cement with the less dense fly ash. The fiber reinforced mix was the hardest to handle, the fibers confining the fresh concrete. While the ease of the manual handling of the different mixes has its value, the fact that the primary placement method is by the shotcrete method minimizes its benefits compared to the other parameters of behavior.

Once cured, all mixes could be measured for total crack lengths and crack widths. The usage of fiber reinforcement greatly improved the mix's resistance to plastic shrinkage cracking, generating only 8% of the crack length, 41% of the mean crack width, and 3% of the total crack area generated by the control mix. The fly ash mix, on the other hand generated 191% of the crack length but 29% of the mean crack width and 56% of the total crack area generated by the control mix.

The fiber reinforced mix performed better than the control, having less crack length and width. The fly ash mix had mixed results, having an increase in crack length but much less crack width.

The 28-day compression test results concur with what the literature predicted. The batch with 1.5 lb/c.y. of fiber reinforcing obtained 114% of the control batch's compressive resistance. The batch with 30% of the cement replaced with fly ash only obtained 83% of the control's compressive resistance. This was expected, as concrete with fly gains compressive resistance at a slower pace. However, concrete with fly ash has certain desirable qualities when compared to a standard concrete mix, such as easier workability, lower setting temperature and lower permeability.

FUTURE WORK

Taking into account that the principal reason for this study is to find a better mix design to protect a clay dike from erosion and flora, a possible next step would be to repeat this experiment with various shotcrete mixes, varying the amount of fiber reinforcing to determine the cracking characteristics of each and ultimately, which is the most cost effective. Another experiment could be to expose the different slabs to grass and other seeds, to determine the minimum crack width required for plants to successfully grow in them, thus posing a long term danger to the dike liner if no maintenance is performed. With this information, the correct shotcrete mix can be chosen, taking in consideration both minimizing crack formation and cost.

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