

## **Evaluation of Unconfined Compression Area Correction Methods for Cementitious and Fiber Stabilized Fine Grained Soils**

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### **ABSTRACT**

Cementitious and fiber stabilized fine grained materials with high moisture contents are not routinely tested in large quantities for quantification of material properties. This paper provides needed area correction guidance using a data set containing on the order of 1,300 unconfined compression tests where approximately 10% of the specimens were reinforced with fibers. During testing, the shapes of the specimens were measured to allow calculation of the actual area. Three area correction methods are provided by ASTM standards, and these corrections are a function of the shape the specimen takes during loading. A fourth area correction method was suggested in this paper for cementitious and fiber stabilized fine grained soils as the methods in the ASTM standards did not adequately represent the shapes measured during testing. The paper also assesses the consequence of the area correction method employed for the ductile fiber reinforced specimens in terms of ultimate stress and strain.

### **INTRODUCTION**

Cementitious and fiber stabilized fine grained materials with high moisture contents are not routinely tested in large quantities for quantification of material properties. Little guidance is available for correction of area of these materials during unconfined compression (*UC*), especially at high strains. This paper provides a method for area correction using a data set containing approximately 1,300 *UC* tests, in which approximately 10% of the specimens were stabilized with fibers in addition to cementitious material. Three soils with varying organic material were included in the data set alongside twelve cementitious materials, two fibers, and three moisture content-cementitious content combinations. The data used in this paper is part of a larger database intended primarily for use in emergency construction after events such as hurricanes, but has numerous other applications (e.g. disposal of dredge spoils, mine tailings, flowable fill for underground tanks, and cementitious stabilized fill for geotextile tubes).

## EXPERIMENTAL PROGRAM

The *UC* specimens were fabricated by batching pre-prepared soil slurry at a target moisture content ( $w_{ts}(\%)$ ) in a 19 liter container. Cementitious material was added on a total soil slurry weight basis ( $C_T$ ) and the mixture was vigorously agitated with a drill and mixer bit attachment. If fibers were being tested, they were added with the cementitious material. The fibers were prepared using a modified 19 liter plastic container. A hole was drilled in the bottom of the container and a standard air pressure attachment inserted. Four metal screws were drilled into the container to separate the fibers as they were forced from the bottom with the air pressure.

The mixture was then placed into 165.1 mm long molds made of PVC pipe with a 76.2 mm diameter. A 6.35 mm porous stone was placed at each end to hold the specimen in place. Each mold was split down its side to allow extraction without damage. The end of each mold was clamped after the specimen and porous stone were added. Curing occurred underwater at room temperature. After the specimens had cured for the designated amount of time, they were extracted and tested in accordance with *ASTM D 2166-06* (2006) and *ASTM D 5102-04* (2006) as applicable; the strain rate used for testing was 0.23 cm/min.

The diameter of the specimen was measured near the top, near the middle, and near the bottom using a caliper immediately after testing prior to removal of the specimen from the load frame. The measurements were not taken in a manner to be used to correct any one specimen, rather to obtain a distribution of values for an overall assessment. The locations of the top, middle, and bottom measurements were visual and varied within a narrow range. The measurements also avoided a shear failure plane that would drastically affect the measurement.

Three soils (Table 1) were tested in conjunction with twelve cementitious materials and two types of fibers. The *F20* fiber is a 20 mm long fiber that is typically used in the concrete industry, and the *F70* fiber has a length of 70 mm and is commonly used for soil stabilization. Fibers were tested in conjunction with portland cement. Three different combinations of moisture content and cementitious content were used. Soil slurry at 100% moisture was tested with 5% and 10% cementitious material, denoted (5,100) and (10, 100), respectively, and soil slurry at 233% moisture was tested with 15% cementitious material and denoted (15, 233). Fibers were added at a rate of 0.5% of total slurry weight.

**Table 1. Soil Properties**

Soil	Origin	USCS	LL	PI	Organics (%)
1	New Orleans	CL to CH	52	35	4.2
2	New Orleans	CH to MH	101	58	25.6
3	Mobile	CH to OH	81	49	10.6

Note: Average values from multiple tests.

Fiber reinforced specimens tested for this paper were taken to 15% strain. Non-fiber reinforced specimens, in general, were tested to approximately 0.50% strain in excess of the strain where the maximum force ( $P_{max}$ ) occurred. Strain data

used for area correction are the anticipated values at the time dimensions of the specimens were taken as provided in this paragraph.

## TERMINOLOGY

The stress and strain at the maximum force, ( $P_{max}$ ) are referred to as  $\sigma_{max}$  and  $\varepsilon_{max}$ , respectively. For purposes of this paper,  $\varepsilon_{max}$  values were taken at the maximum force reading upon first occurrence. The ultimate stress,  $\sigma_{ult}$ , was taken to be the maximum stress attained after a given area correction was implemented, with the ultimate force,  $P_{ult}$ , and ultimate strain,  $\varepsilon_{ult}$ , occurring at  $\sigma_{ult}$ .

## AREA CORRECTIONS

*ASTM D 2166-06* (2006) and *ASTM D 5102-04* (2006) calculate strain according to Eq. 1, and stress according to Eq. 2. Differences, though, exist in area ( $A_i$ ) calculation. *D 2166* uses Eq. 3 exclusively, while *D 5102* uses Eq. 3, 4, or 5 depending on the shape of the specimen at failure. For specimens that do not deform a noticeable amount radially, Eq. 3 is used, for specimens that bulge in the middle Eq. 4 is used, and for specimens that expand in the radial direction in a uniform manner along the loading axis Eq. 5 is used. Additionally, *ASTM D 4832-02* (2006), or the standard method for testing controlled low-strength material (CLSM), provides no area correction method. Eq. 6 is an area correction developed in this paper for fiber specimens and could be used to add more conservatism to stress calculation; this equation is not part of ASTM protocol. The fiber specimens were observed to bulge around the middle and shorten in the longitudinal direction during testing, so the barrel and cylindrical area corrections were combined to develop Eq. 6.

$$\varepsilon = \frac{\Delta L}{L_o} (100) \quad (1)$$

$$\sigma = \frac{P}{A_i} \quad (2)$$

$$A_1 = A_o \quad [\text{Brittle Failure}] \quad (3)$$

$$A_2 = \frac{A_o}{(1 - (0.6\varepsilon/100))} \quad [\text{Barrel Failure}] \quad (4)$$

$$A_3 = \frac{A_o}{(1 - (\varepsilon/100))} \quad [\text{Cylindrical Failure}] \quad (5)$$

$$A_4 = \frac{A_o}{(1 - (1.6\varepsilon/100))} \quad [\text{Cylindrical plus Barrel Failure}] \quad (6)$$

Where,

$\varepsilon$  = axial strain (%)

$\Delta L$  = change in length in axial direction (cm)

$L_o$  = original length in axial direction (cm)

$P$  = applied load (kg)

$A_i$  = converted cross sectional area of specimen;  $A_1, A_2, A_3,$  or  $A_4$  (cm<sup>2</sup>)

$A_o$  = original cross sectional area of specimen (cm<sup>2</sup>)

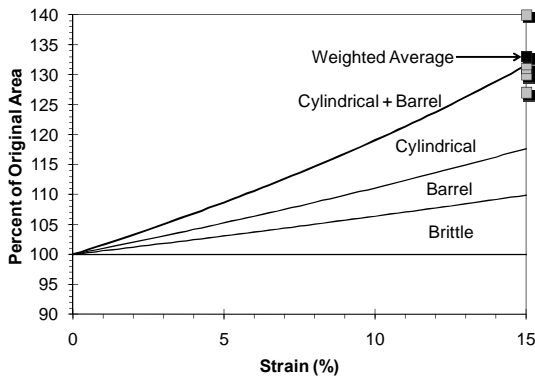
## TEST RESULTS

Table 2 provides test results of area correction data for all specimens tested. Data was grouped: 0 to < 24 hr, 24 to < 72 hr, 72 to <168 hr, and 168 hr. Data within these intervals was combined and averaged. Note the number of data points ( $n$ ) represented by each marker is shown. Table 2 was used to generate Figures 1, 2, and 3, which plot the percent original area at the middle (*Mid*) of the specimen versus strain. For example, for *Soil 1* without fibers at the 0 to <24 testing time, a percent original area value of 106 was the plotted with a strain of 3.6% as shown in Figure 1b. The weighted average area correction for all fiber reinforced specimens was shown with a darker marker in Figures 1a, 2a, and 3a.

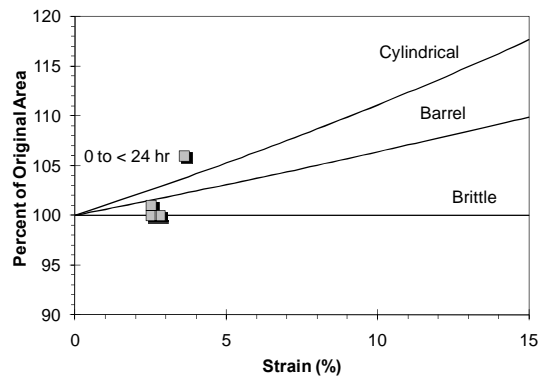
**Table 2. Area Correction Data**

Soil	Time	Fibers					No Fibers				
		$n$	$\varepsilon$	% Original Area			$n$	$\varepsilon$	% Original Area		
				Top	Mid	Bot			Top	Mid	Bot
1	0 to <24	3	15	106	127	118	10	3.6	102	106	106
	24 to <72	10	15	111	131	118	87	2.8	102	100	100
	72 to <168	11	15	110	140	124	105	2.5	104	101	100
	168	14	15	106	130	114	116	2.5	102	100	99
2	0 to <24	6	15	121	126	107	35	5.2	105	109	108
	24 to <72	11	15	111	138	114	124	3.4	102	104	102
	72 to <168	17	15	112	139	120	136	3.0	103	103	103
	168	13	15	100	107	104	140	2.7	101	103	102
3	0 to <24	8	15	108	123	112	33	8.5	106	108	111
	24 to <72	13	15	115	127	118	117	3.1	102	101	101
	72 to <168	17	15	113	125	118	133	2.7	104	102	100
	168	14	15	106	134	119	148	2.9	103	101	100

Note: *Top*, *Mid*, and *Bot* represent the area measured at the specimen top, middle, and bottom, respectively

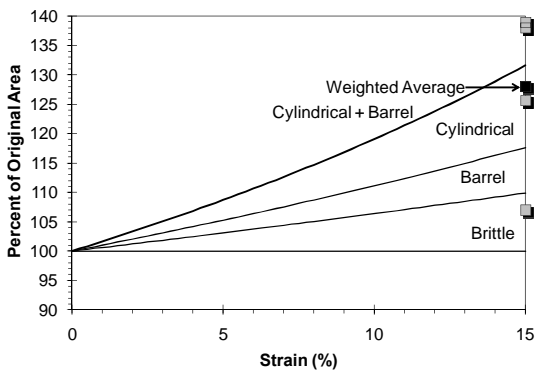


(a) *Specimens With Fibers*

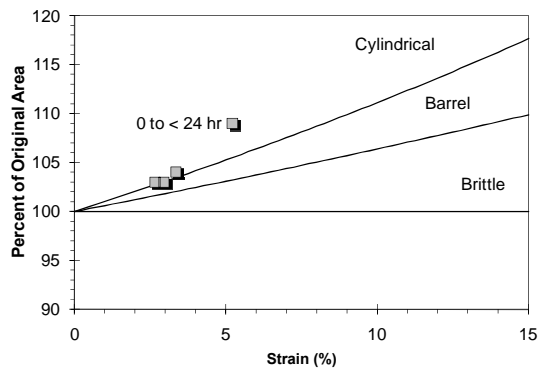


(b) *Specimens Without Fibers*

**Figure 1. Soil 1 Area Correction Results**

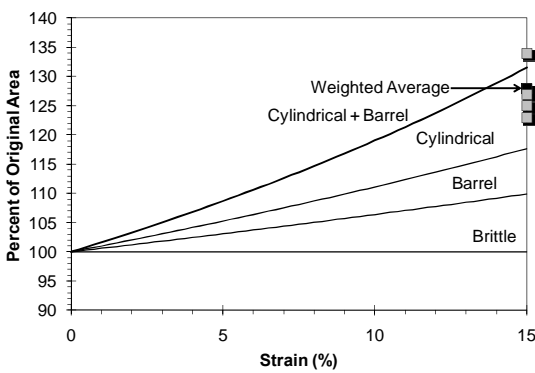


(a) *Specimens With Fibers*

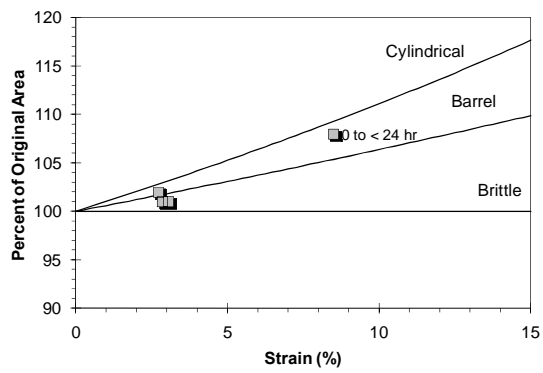


(b) *Specimens Without Fibers*

**Figure 2. Soil 2 Area Correction Results**



(a) *Specimens With Fibers*



(b) *Specimens Without Fibers*

**Figure 3. Soil 3 Area Correction Results**

In order to make a decision on the method of area correction to use for the specimens, the visual appearance of the specimens was considered along with Figures 1, 2, and 3. The weighted average of *Soil 1* fiber specimens exceeded the cylindrical plus barrel correction, and the weighted average of *Soil 2* and *Soil 3* fell very close to this correction. If *ASTM D 5102* is to be followed, the cylindrical correction should be used. However, the cylindrical plus barrel correction is supported by the data and is recommended by the authors for all fiber reinforced specimens.

As shown in Figure 1b, the *Soil 1* specimens without fibers tested before 24 hours exhibited cylindrical failure, and all other samples exhibited no radial expansion during testing and failed according to the brittle failure mode. *Soil 2* specimens without fibers demonstrated cylindrical failure at all testing times as seen in Figure 2b. Furthermore, *Soil 2* specimens did not visually appear to maintain their shape as well as *Soil 1* and *Soil 3* specimens. *Soil 2* at 100% moisture content with no cement exhibited a shear strength of approximately  $0.02 \text{ kg/cm}^2$ , and did not appear to benefit from cement as much as *Soil 1* and *Soil 3*. As seen in Figure 3b, the data points for *Soil 3* area correction all fall near the plot of barrel correction. *Soil 3* specimens tested before 24 hours did exhibit some radial expansion during testing, and a barrel or cylindrical failure mode could have been chosen. Cylindrical failure was chosen to maintain conservatism since cylindrical failure produces a lower value of stress for analysis. For *Soil 3* specimens tested after 24 hours, barrel failure also could have been selected, but a brittle failure was assumed since the specimens did not appear to change shape and typically exhibited a shear failure as evidenced by a 45 degree crack running from the top to the bottom of the specimens that was observed during testing. The following is a summary of all area correction recommendations:

- Fiber Reinforced Specimens
  - All soil types: Use cylindrical plus barrel (Eq. 6) for all specimens.
- Non-Fiber Reinforced Specimens
  - *Soil 1*: For specimens tested before 24 hours use cylindrical correction (Eq. 5); for specimens tested after 24 hours use brittle correction (Eq. 3).
  - *Soil 2*: Use cylindrical correction for all specimens (Eq. 5).
  - *Soil 3*: For specimens tested before 24 hours use cylindrical correction (Eq. 5); for specimens tested after 24 hours, use brittle correction (Eq. 3).

## CONSEQUENCE OF AREA CORRECTION

The consequence of employing cylindrical plus barrel area correction (Eq. 6) relative to the cylindrical area correction (Eq. 5) for fiber reinforced specimens was investigated. Equations 7 and 8 show the percent difference calculation displayed in Figure 4. Figure 4 demonstrates the increase in area that occurs as a result of employing the cylindrical plus barrel correction ( $A_4$ ) in lieu of no area correction ( $A_1$ ) or the ASTM cylindrical correction ( $A_3$ ). As shown, for the same value of  $P_{ult}$ , the area and, therefore, the calculated stress, are over 30 percent different from uncorrected specimens at 15 percent strain and over 10 percent different from specimens corrected with the cylindrical approach at 15 percent strain.

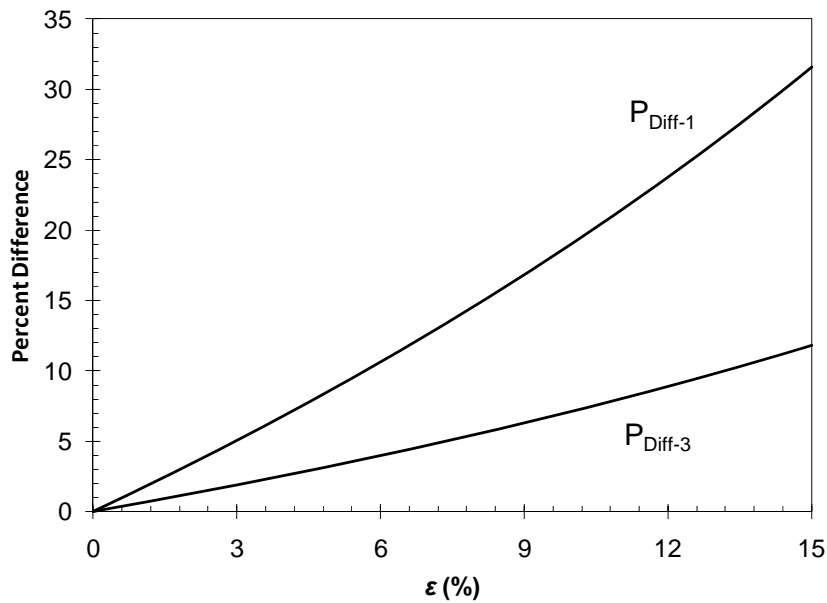
$$P_{Diff-1} = \frac{(A_4 - A_1)}{A_1} 100 \quad (7)$$

$$P_{Diff-3} = \frac{(A_4 - A_3)}{A_3} 100 \quad (8)$$

Where

$P_{Diff-1}$  = Percent Difference between  $A_4$  and  $A_1$

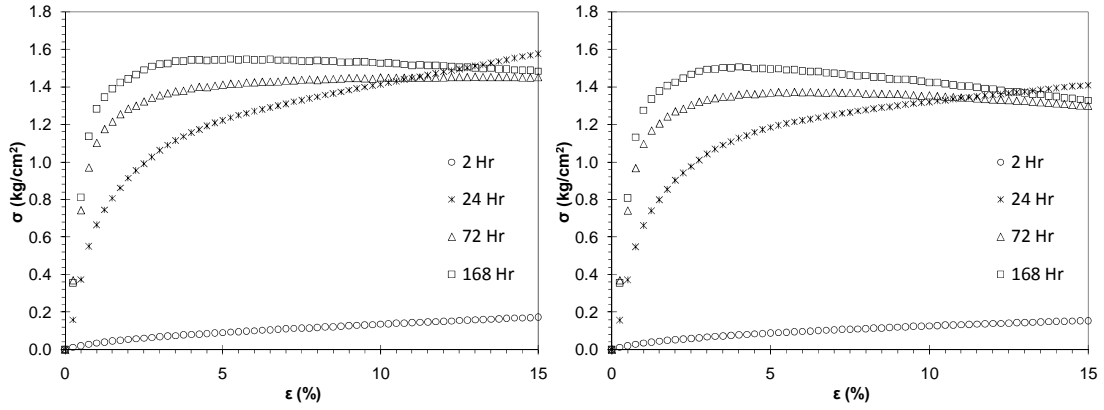
$P_{Diff-3}$  = Percent Difference between  $A_4$  and  $A_3$



**Figure 4. Area Percent Difference Plot**

Figures 5, 6, and 7 display the stress-strain curves for *Soil 3* cementitious and fiber reinforced specimens with the ASTM cylindrical correction and the cylindrical plus barrel correction. *Soil 1* and *Soil 2* stress-strain plots have been omitted, but these plots showed results similar to Figures 5, 6, and 7. The stress-strain plots for the two corrections for all soil types were used to generate Table 3.

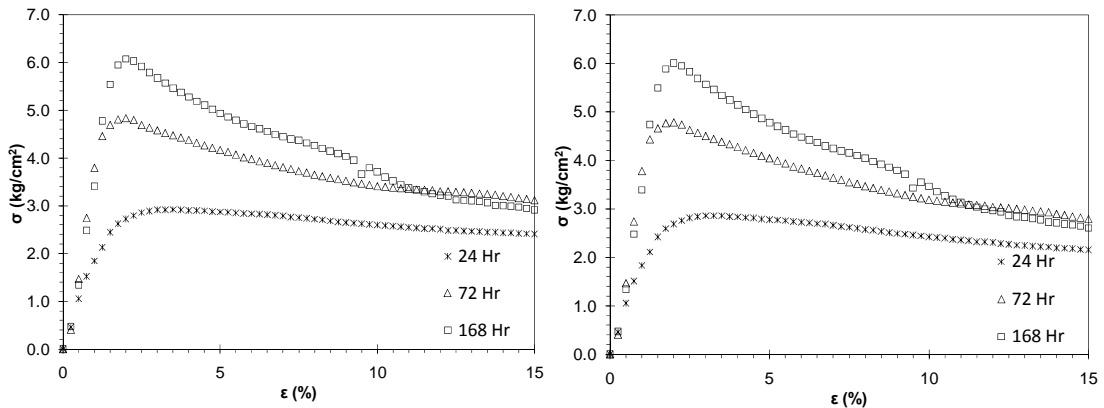
Table 3 demonstrates the consequence of area correction as it pertains to  $\sigma_{ult}$  and  $\epsilon_{ult}$ . For the (5, 100) mixes, there is a moderate decrease in  $\sigma_{ult}$  for all soil types, but a considerable reduction in  $\epsilon_{ult}$  is evident in some cases for *Soil 2* and *Soil 3*. The (10, 100) and (15, 233) mixes also showed a moderate decrease in  $\sigma_{ult}$  for each soil type, but essentially no change in  $\epsilon_{ult}$  was observed. Overall, the ultimate stress ( $\sigma_{ult}$ ) was reduced 1 to 12 percent as a result of the newly developed area correction method.



(a) Cylindrical

(b) Cylindrical plus Barrel

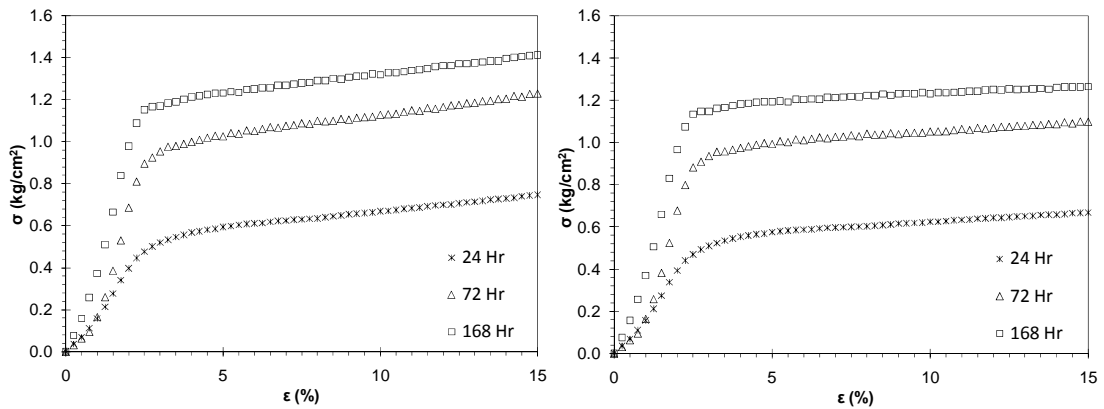
**Figure 5. Stress Strain Plots for (5, 100) F20 Specimens for Soil 3**



(a) Cylindrical

(b) Cylindrical plus Barrel

**Figure 6. Stress Strain Plots for (10, 100) F20 Specimens for Soil 3**



(a) Cylindrical

(b) Cylindrical plus Barrel

**Figure 7. Stress Strain Plots for (15, 233) F20 Specimens for Soil 3**

**Table 3. Consequence of Area Correction**

Soil	Fiber	( $C_T$ , $w_{is}(\%)$ )	Time (hr)	$\sigma_{ult}$ (kg/cm <sup>2</sup> )	$\epsilon_{ult}$ (%)	
1	F70	(5,100)	168	1.12 (1.10)	3.00 (2.75)	
			24	1.05 (0.94)	15.00 (15.00)	
			72	1.26 (1.13)	14.75 (14.75)	
	F20	(10,100)	24	3.02 (2.96)	3.25 (3.00)	
			72	4.70 (4.64)	2.00 (2.00)	
			168	5.87 (5.79)	2.25 (2.25)	
	F20	(15,233)	24	0.22 (0.20)	14.50 (14.50)	
			72	0.47 (0.42)	14.50 (14.25)	
			168	0.63 (0.56)	15.00 (14.50)	
	2	F70	(5,100)	2	0.48 (0.45)	7.50 (5.25)
				72	1.55 (1.41)	14.75 (9.50)
		F20	(5,100)	2	0.92 (0.82)	15.00 (13.50)
24				1.47 (1.35)	13.00 (7.75)	
72				1.53 (1.44)	13.50 (6.50)	
168				1.64 (1.53)	12.50 (7.50)	
F20		(10,100)	24	4.52 (4.42)	3.75 (3.75)	
			72	5.70 (5.58)	3.50 (3.50)	
			168	6.02 (5.91)	3.00 (3.00)	
F20		(15,233)	24	1.72 (1.54)	15.00 (15.00)	
			72	3.05 (2.73)	15.00 (15.00)	
			168	3.36 (3.00)	15.00 (14.75)	
3	F70	(5,100)	2	0.14 (0.13)	14.00 (15.00)	
			24	0.97 (0.89)	13.75 (5.50)	
	F20	(5,100)	2	0.17 (0.15)	14.00 (13.25)	
			24	1.58 (1.41)	15.00 (14.75)	
			72	1.45 (1.37)	8.75 (4.75)	
			168	1.55 (1.51)	5.25 (4.00)	
	F20	(10,100)	24	2.92 (2.86)	3.25 (3.00)	
			72	4.84 (4.78)	2.00 (2.00)	
			168	6.08 (6.00)	2.00 (2.00)	
	F20	(15,233)	24	0.75 (0.67)	15.00 (14.75)	
			72	1.23 (1.10)	14.75 (14.75)	
			168	1.41 (1.26)	14.50 (14.00)	

Note:  $C_T$  and  $w_{is}(\%)$  refer to cementitious content and moisture content, respectively.

Note: Values outside and inside parentheses represent Eq. 5 and Eq. 6 corrections, respectively.

The ductility of the specimens must be considered when evaluating the change in  $\epsilon_{ult}$  and  $\sigma_{ult}$ . Stress in the specimens that were very ductile, such as the (5, 100) and (15, 233) specimens, increased to the yield point and then remained essentially constant to 15% strain as shown in Figures 5 and 7. In some instances, the stress was reduced enough by the cylindrical plus barrel correction at higher strain to decrease  $\epsilon_{ult}$  noticeably, such as the 72 hour test in Figure 5. However, the magnitude of stress did not decrease notably after  $\epsilon_{ult}$  was reached in this case, indicating the ductility of

the specimens. Also, the change in  $\sigma_{ult}$  is larger if  $\sigma_{ult}$  occurs at a higher strain due to greater change in area, as shown previously in Figure 4.

## CONCLUSIONS

A method for employing conventional *UC* area corrections for a large data set was explained in this paper for materials with high moisture contents that were stabilized with either cementitious material or cementitious material and fibers. The visual appearance of the specimens during testing was considered, and the change in area was measured in order to select an area correction method. The correction of area was important since shear strength was the data set's primary variable of interest.

Actual stresses at higher strains in *UC* specimens stabilized with cementitious material and fibers may be lower by 1 to 12 percent than that shown in stress-strain plots using the maximum area correction from conventional area correction methods. Area correction is more significant at higher strains, and by any standard is an approximation. Area correction does not consider the location of failure and assumes symmetry of shape during loading. The cylindrical plus barrel area correction proposed in this paper creates a more conservative estimate of maximum stress, and could be useful for similar materials that are stabilized with cementitious material and fibers. The consequence of implementing the cylindrical plus barrel correction was also explored, particularly as it relates to the magnitude of ultimate stress and strain.

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