2009 UPRM-ERDC Summer Research Internship Program, Geotechnical and StructuresLab, Vicksburg, MS, June 3- August 8, 2009.

Characteristics of Concrete Linked to Ballistic Resistance
Design of Testing Materials

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ABSTRACT

In order to improve soldier protection in the battlefield, the US Army Corps of Engineers (CoE) has tested the ballistic resistance of numerous materials, which can be utilized to fabricate protective barriers. A new material that has given good results is the "Ultra High Performance Concrete" (UHPC), which has compressive strengths of about ten times that of normal concrete. The present study attempts to design and create the necessary specimens to perform a ballistic resistance analysis of the CoE UHPC. The specimens created were thin panels with three different variables: fiber reinforcement and compressive strength; each variable having three levels. The selection of the panels was made by making numerous sets of UHPC mixes varying the water to cement ratio and testing their compressive strength in order to select the desired strengths. The highest level for the compressive strength variable was the CoE UHPC named Cor-Tuf, with 30,000psi.

Keywords: UHPC, ballistic resistance, concrete, compressive strength

1. INTRODUCTION

Ultra High Performance Concrete (UHPC) is a mortar or concrete material that has a compressive strength of at least 150 Mpa (21.7 ksi). It normally includes some kind of fiber reinforcement; has a high binder content with special aggregates and a very low water to cement ratio, which is possible by adding water reducing admixtures. The Army Corps of Engineers has come up with a special UHPC called Cor-Tuf. This material uses a very dense particle packing approach in order to acquire very high strengths. The constituents of the Cor-Tuf UHPC are:

- Oilwell Cement (31.6%)
- Silica Fume (12.3%)
- Silica Flour (8.8%)
- Silica Sand (30.6%)
- Steel Fibers (9.8%)
- Water with Superplasticizer (7.0%)

This material when heat cured achieves a nominal compressive strength of 30ksi. It also has a very good performance on ballistic resistance tests when compared to other concretes. The problem is that the concretes used to compare its performance have very different constituents, which makes attribution of the good performance to any given property or constituent impossible. Thus, the Corps of Engineers' Concrete and Materials Branch are in the process of creating a study that attempts to isolate the effects of cementitious matrix strength and fiber reinforcement on the ballistic resistance of concrete, using Cor-Tuf UHPC as a basis. The experiment setup to perform the study will include three levels of each variable. For the compressive strength variable 5, 17.5 and 30ksi will be the three levels, while for the fiber reinforcement variable the three levels will be No Fiber, Dramix steel fibers and Baumbach brass coated steel fibers. To obtain the mix proportions that will acquire the required strengths to create the panels for the study, information on mix strength due to constituent variation is needed. This study's objective is to obtain enough information to select the mix proportions required to create the panels that will be used in the ballistic resistance study. Also an accelerated curing process will be developed in order to be used when curing the test specimens for the ballistic study.

2. STUDY

METHODOLOGIES

A set of different mix designs were made by varying w/c ratio, binder and aggregate content. The binder and aggregate content variations were divided into three groups: High, Medium and Low cement content. The following table shows the binder, cement and aggregate percentage of weight of each group.

Table 1: Group Variations

	Cementitious Material (%)	Cement Content (%)	Aggregate (%)
High	53	38	47
Medium	47	36	53
Low	40	33	60

The variation in the groups was not significant in order to maintain the same material morphology. Also, to maintain the dense packing of the materials, the percentage of aggregates was raised by the same amount the cement percent was decreased. The aggregate and cement particles have the same size distribution, which makes them interchangeable in order to obtain the same packing.

Table 2: W/C Ratio Variations

High	Medium	Low
0.22	0.2	0.22
0.4	0.22	0.25
0.55	0.285	0.4
0.6	0.35	0.55
0.8	0.4	0.6
	0.55	0.8
	0.75	

Table 2 shows a list of the water to cement weight ratio mixes that were done. Specimens were collected in the form of cubes and cylinders to test their compressive strength at different specimens age (3, 7, 28, heat time*). A bigger quantity of specimens was collected from two of the mix designs in order to vary their curing process and obtain a new one. The accelerated curing process consisted of normal temperature curing at a 100% humidity room (called the fog room) followed by heat curing at a water filled oven. The temperature for normal curing was 70°F, while the oven was kept at 190°F. The quantity of days left at the normal curing stage varied from 3 to 7, while the days at the oven were 2 and 6. The following table and graph show the results from the curing process variations for the Cor-Tuf mix (High-0.22w/c).

Table 3: Accelerated Curing of Cor-Tuf

w/c	Group	3	7	28	2-2	2-5	3-2	3-6	4-2	4-6
0.22	H	10930	15108.33	19767	18749	15057.67	23880.5	28917	24389.5	24472

5-2	5-6	6-2	6-6	7-2	7-6
22571.33	28448	24814	25038.5	29581	30346.5

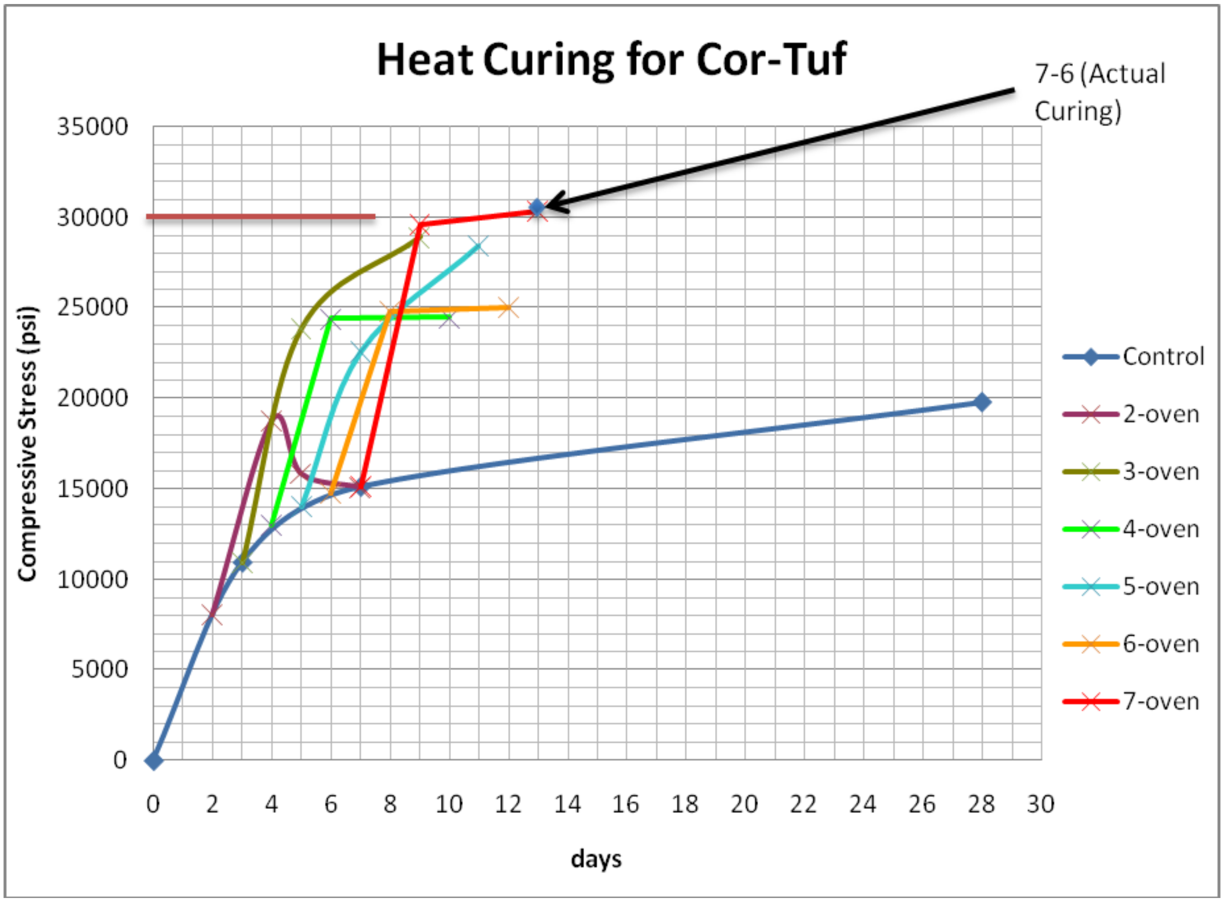

Figure 1: Accelerated Curing of Cor-Tuf

The actual curing process for the Cor-Tuf mix is the 7-6 process. With this process, this material acquires a compressive strength of about 30ksi in just 13 days, while with 28 days of normal curing it only acquires about 20ksi. The curing processes 7-2 and 3-6 both also acquire strengths very near 30ksi with only 9 days of curing, which mean 4 days less than the actual curing process. It is also important to understand that the oven curing process is much more expensive and difficult to perform than the normal curing, which makes the 7-2 process seem as a better choice in comparison to 3-6. But this is not always the case when the material is not Cor-Tuf. The next table shows the results of a curing process variation for a H-0.8w/c mix.

Table 4: Accelerated Curing of H-0.8

w/c	Group	3	7	28	3-2	3-6	4-2	4-6	5-2	5-6
0.8	H	2258	2551.667	5645.5	5618.333	7113.5	4061.5	8143	6125.333	7497

6-2	6-6	7-2	7-6
6841	6965.75	5238	7022

For this mix the best curing process would be 4-6 which acquires a strength 55% higher than 7-2. If the cost and difficulty of the oven process and the total days of curing is taken into consideration, probably a good curing process for this mix would be 6-2. The 3-6 process although not the best, still obtains a good strength and is compatible with the Cor-Tuf mix strength requirements. This means that no matter the w/c ratio of the mix, the 3-6 process would probably obtain an efficient strength. For this reason the 3-6 process was selected as the heat time* in which the specimens collected were tested. The next graph shows the results of the strengths for the High cement group at 3 days, 7 days, 28 days and 3-6 curing process.

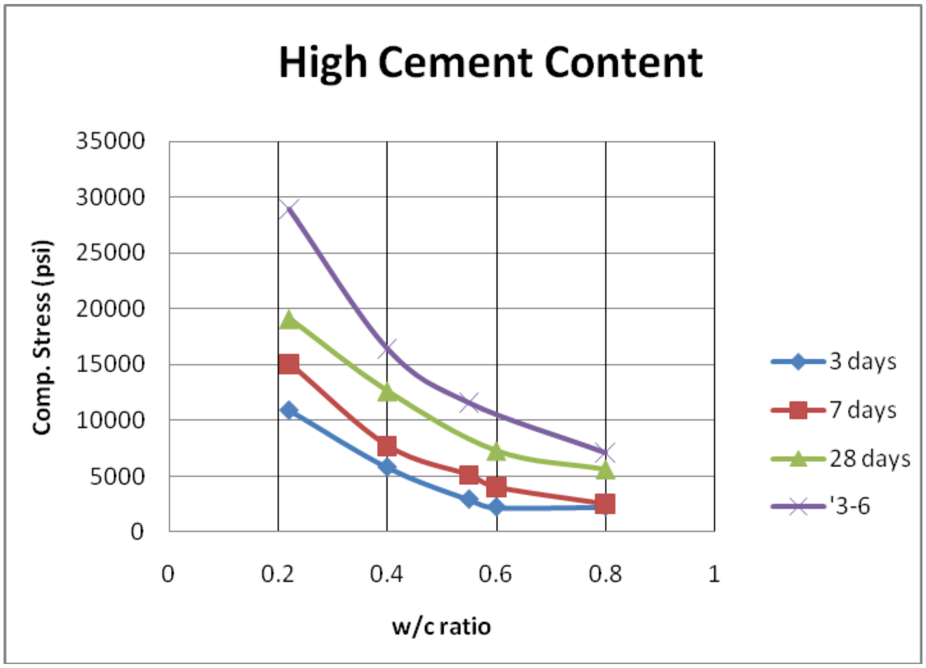

Figure 2: High Cement Compressive Strength vs. w/c ratio

This graph shows how the accelerated curing not only completes the curing in less time, but also acquires a higher strength that would not be possible with normal temperature curing. The highest value in the graph corresponds to the Cor-Tuf mix cured with the 3-6 process, which is approximately 29ksi. The Medium and Low groups show a similar behavior, but the heat time curve doesn't show such an increase in strength as the High group.

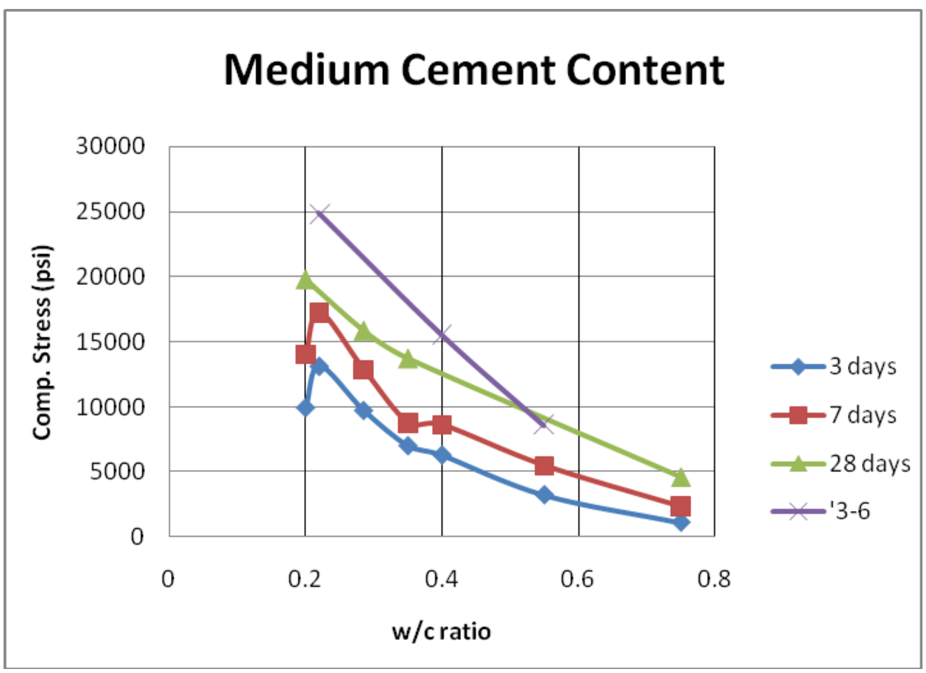

Figure 3: Medium Cement Compressive Strength vs. w/c ratio

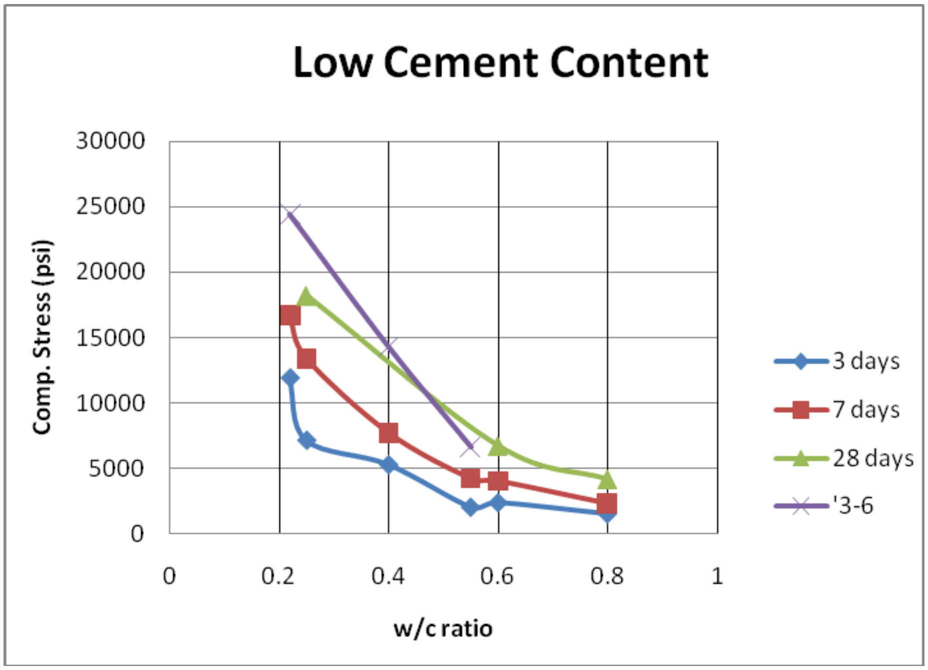

Figure 4: Low Cement Compressive Strength vs. w/c ratio

The Medium and Low groups acquire a maximum strength of approximately 25ksi with the 3-6 curing process. For normal curing the three groups acquire approximately the same strengths. This can be shown in the next graph which compares the three groups at normal curing.

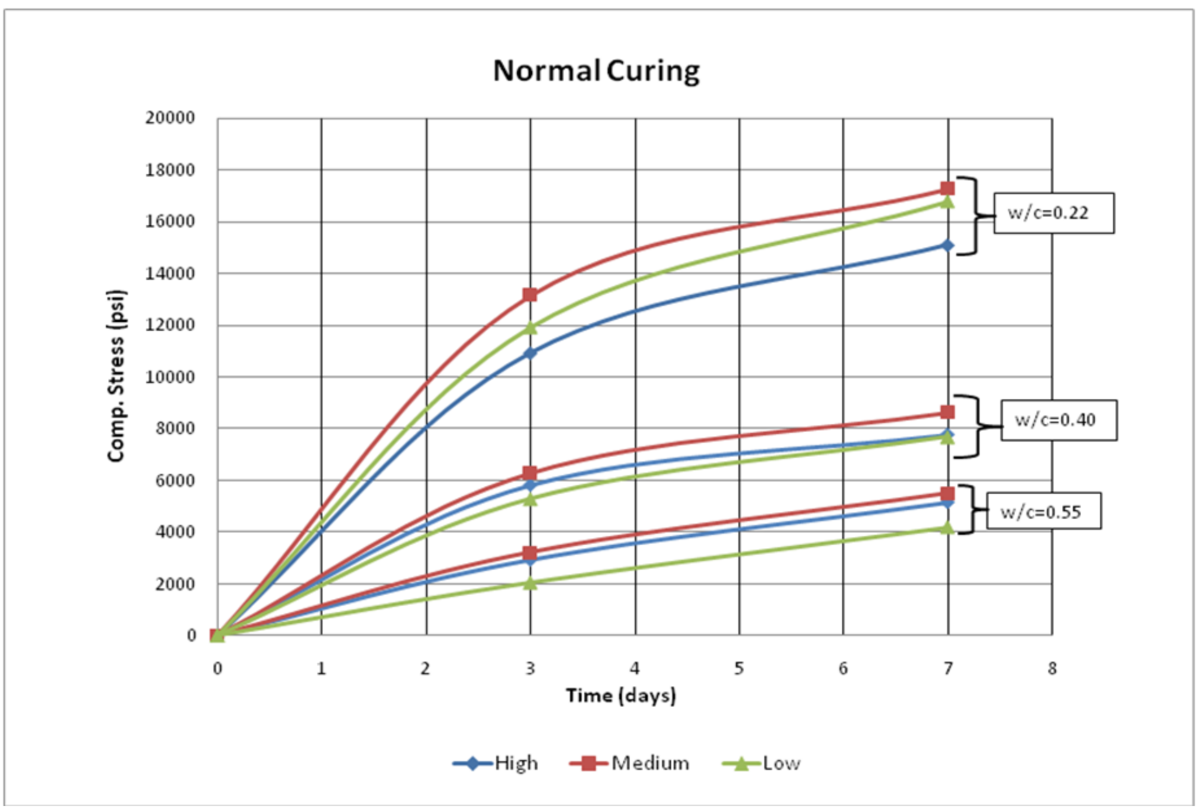

Figure 5: Groups Strength Comparison

The Medium group acquires the highest strength for any w/c ratio mix for normal curing, which is not the case for accelerated curing. This is due to the fact that the High group has a higher excess of unhydrated cement that reacts when it's heated, which leads to a higher increase in strength. The next table is a summary of the data used to create the graphs.

Table 5: Groups Strength Comparison

w/c	**Group**	**3**	**7**	**28**	**3-6**
0.22	H	10930	15108.33	19124.67	28917
0.4	H	5813	7760.333	12648	16442
0.55	H	2927	5149		11576
0.6	H	2226	4062.667	7318	
0.8	H	2258	2551.667	5645.5	7113.5
0.2	M	9962.5	14048.5	19767	
0.22	M	13156	17274.33		24866
0.285	M	9742	12865	15855.67	
0.35	M	7017	8783	13716	
0.4	M	6294.5	8634.5		15555.5
0.55	M	3225.5	5511.5		8600.3
0.75	M	1106	2373.333	4641.667	
0.22	L	11906.5	16768		24454
0.25	L	7147	13419.33	18223	
0.4	L	5287.5	7686.333		14303.33
0.55	L	2044	4181.5		6632
0.6	L	2391.667	3989.333	6709.5	
0.8	L	1531.333	2255	4154.667	

From the graphs and the table a selection was made in order to obtain three mixes with 5, 17.5 and 30ksi of compressive strength. The selection of the mixes was the following:

- ✓ 5ksi:
  - High Cement
  - 0.8 w/c ratio
  - 7-2 curing
- ✓ 17.5ksi:
  - High Cement
  - 0.38 w/c ratio
  - 3-6 curing
- ✓ 30 ksi:
  - High Cement
  - 0.22 w/c ratio
  - 7-2 curing

From the three groups only the High group was selected in order to maintain the morphology and properties of the materials as close as possible. The 7-2 curing process was selected for the H-0.8 mix, because the 3-6 process would've acquired 7ksi and a higher w/c ratio wouldn't work with fiber reinforcement.

3. CONCLUSIONS

- When the w/c ratio decreases, the compressive strength increases.
- For normal curing the Medium cement gives the highest compressive strength.
- For heat curing Cor-Tuf (High cement) is by far the highest compressive strength.
- Curing can be accelerated by heating the specimens. Also a much higher strength can be achieved.

References

ASTM Standard C109, 2008, *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)*, ASTM International, West Conshohocken, PA.

ASTM Standard C305, 2006, *Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency*, ASTM International, West Conshohocken, PA.