TENNESSEE CONCRETE MAGAZINE

Winter 2014/15
VOL. 28, NO. 3

CONCRETE COMMUNITY SERVICE:

Helping Raptors and the Upper Cumberland Area

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A CHEAPER ESTIMATE OF

Concrete Heat Evolution Due to Hydration

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by L. K. Crouch, Aaron Crowley, Daniel Badoe, Tony Greenway, Robert Craven and Heather P. Hall

A CHEAPER ESTIMATE

of Concrete Heat Evolution Due to Hydration

INTRODUCTION AND BACKGROUND

In early 2012, the Tennessee Department of Transportation (TDOT) Divisions of Materials and Tests, Structures and Construction sponsored a project entitled "Development of TDOT Class S-LH (lower heat) Concrete Mixture". The TDOT project is still in progress but the authors would like to share some of the results obtained thus far.

American Concrete Institute Report 207.1 (1) indicates that mass concrete causes a potential for significant temperature differentials between the interior and outside surfaces of the structure. Volume changes and restraint result in tensile strains and stresses that may cause cracking detrimental to the structure. A 2002 Concrete International article (2) indicated that "mass concrete" required a least dimension greater than 3-feet using a mixture that contained more than 564-lbs/CY of cementing materials. TDOT commonly uses many such structural elements but has no low heat of hydration mixture specifications. The current study builds on the findings of an unpublished 2004 Tennessee Technological University (TTU) study requested by TDOT Materials &Tests Division and Region 4 on heat of hydration at the Hernando Desoto Bridge in Memphis.

2006 TDOT Standard Specifications (3) Section 604.03 (Class S) requires a minimum cementing materials content of 682-lbs/CY and only allows 25% fly ash (or 35% slag) substitution for Portland cement. A PCC mixture meeting this specification has the potential to generate a lot of heat and induce thermal cracking in structural elements. The purpose of the study is to design a mix that reduces the heat generation of TDOT Class S PCC while maintaining satisfactory values of other engineering properties.

This paper focuses on one aspect of the study that addresses methods to estimate and compare concrete heat generation due to hydration. The target audience is ready mix concrete producers. However, the authors hope that other members of the concrete industry may also find it helpful.

METHOD 1 SEMI-ADIABATIC CALORIMETRY

The Calmetrix F-Cal 4000 records the temperature of concrete in four 4x8-inch cylinder molds. The device is shown in Figure 1. Unfortunately, there is no current AASHTO or ASTM method for semi-adiabatic (somewhat insulated) calorimetry of concrete mixtures. The device records temperatures every minute for approximately seven days (depending on battery life). The manufacturer's guide recommends comparing the temperature trace plots for evaluation.

Figure 1: Calmetrix F-Cal 4000 Field Calorimeter for Cement / Concrete Professionals

EXAMPLE OF USE: INITIAL SCREENING OF TDOT PROJECT LOWER HEAT MIXTURES

Three batches of four 4x8-inch cylinders were evaluated for each mixture in the device. The research team, with no ASTM or AASHTO guidance, decided to pay particular attention to the rise from initial temperature to maximum temperature. In hindsight, it may have been wiser to evaluate three samples of concrete and compare the rise to one cylinder of water. The mean temperature traces (average of 12 4x8 cylinders) for each mixture are shown in Figure 2.

TABLE 1. METHOD 1 SEMI-ADIABATIC CALORIMETRY SUMMARY

Test Parameter	
Sample Size	4x8-inch cylinder (~ 0.06 cubic feet)
Number of Samples	4
Field or Lab	Either
Hardware / software requirements	Built-in nothing additional
Output	Spreadsheet file
Sampling Frequency	60 seconds
Recording Time	About 1 week
Cost	Approximately $5000
Main Advantage	Ease of operation / clean up
Main Disadvantage	Small Sample size

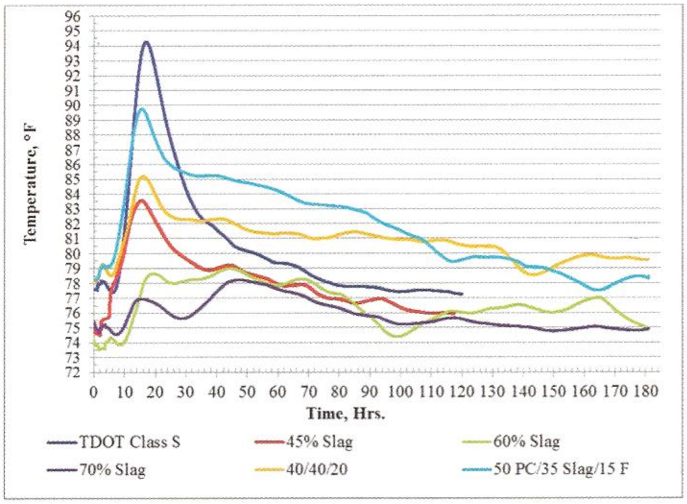

Figure 2: Mean Temperature Traces for TDOT Class S and Class S-LH Mixtures

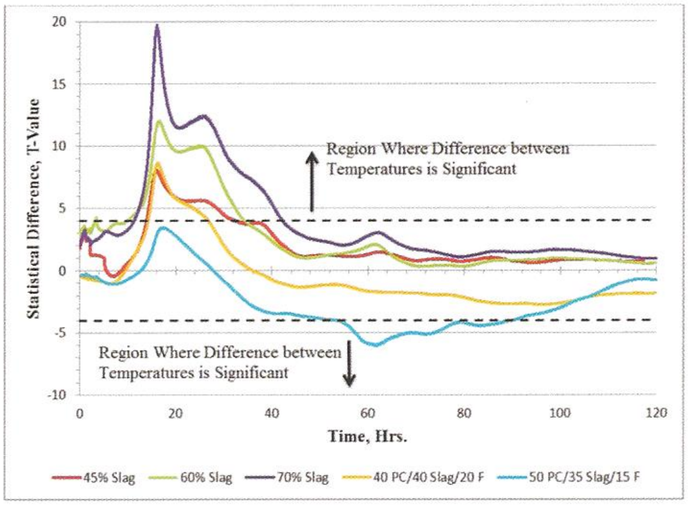

Figure 3: Statistical Difference in Mean Temperature Traces of Candidate S-LH Mixtures Compared to TDOT Class S Mixture

Figure 3 shows the statistical differences from comparing the mean temperature traces of candidate lower heat mixtures to the mean temperature trace of TDOT Class S mixture. A Student's t-test was utilized to test for the difference in temperature means of the S-LH candidate mixtures to the TDOT Class S mixture. A 5 percent level of significance was used for the test and the results are shown graphically in Figure 3. The dashed lines represent the critical t-values beyond which the temperature differences between the S-LH candidate mixtures and the TDOT Class S are statistically significant. For t-values exceeding t-critical, the greater the t-value, the greater the difference between the mean temperatures of the mixtures. The S-LH candidate which has the longest duration of significant temperature difference from TDOT Class S and which also has the largest temperature difference from TDOT Class S at any time is clearly S-LH with 70% slag.

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METHOD 2 FIELD TESTING WITH AUTONOMOUS TEMPERATURE SENSORS

The TDOT project field tests were conducted on Wednesday 8/07/13 at the TTU's School of Agriculture Farm near Cookeville, TN. Two earth-formed cubical cavities were excavated. Each cavity was approximately 8-feet in the x, y, and z dimensions. Autonomous temperature sensors were placed on a No. 3 rebar frame inside the excavations. An excavation with rebar frame and temperature sensors is shown in Figure 4. Temperature sensor quantities and locations are shown in Figure 5. A close-up of the temperature sensors in-place is shown in Figure 6.

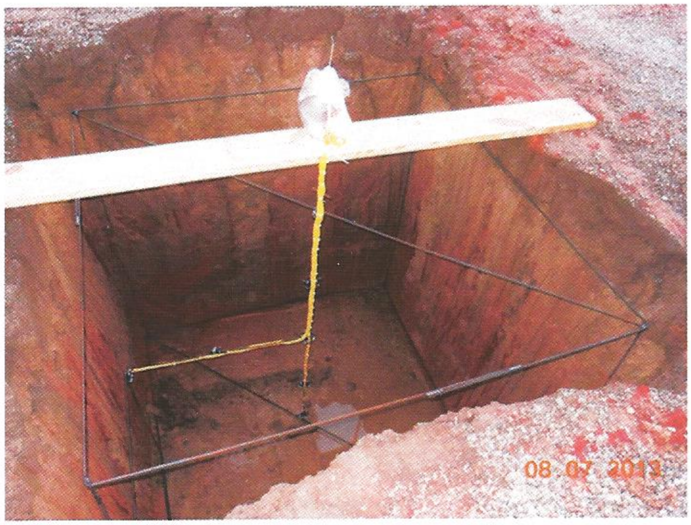

Figure 4: Excavation with Rebar Frame and Temperature Sensors

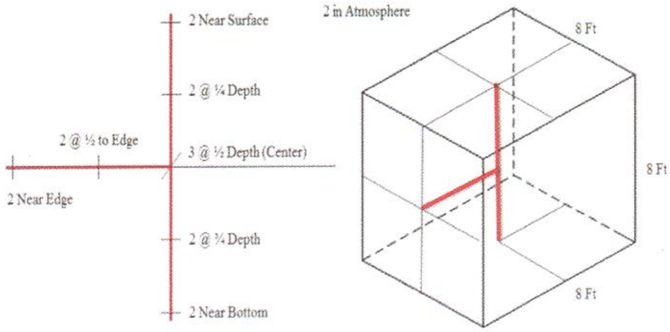

Figure 5: Temperature Sensor Number and Locations

Figure 6: Close-up of Temperature Sensors In-place

Autonomous temperature sensors (reading every 30 minutes for 56-days) were placed on a No. 3 rebar frame inside each excavation. All sensor locations used at least two temperature sensors and the geometric center used three sensors to minimize the possibility of data loss due to sensor malfunction. The amount of temperature data collected was extremely large (over 86,000 data points).

Figure 7 shows a comparison of maximum internal temperatures. As expected, maximum internal temperatures were recorded by the sensors at the geometric center of the excavations. TTU researchers reasoned that keeping the maximum concrete temperature below 150°F would help to prevent durability problems cited by Gajda (2) if temperature after placement exceeds 155 to 165°F. Class S-LH with 70% slag met the suggested requirement for maximum temperature in an 18-CY cube placement without benefit of pre-cooling of the mixture (by ice or liquid nitrogen). TDOT Class S did not meet the requirement. The maximum temperature produced by the S-LH was about 83% of the maximum temperature produced by the Class S.

Figure 8 shows the results of a hypothesis test of the equality of the mean temperatures taken in the two mixes over time. A Student's t-test is used to determine the validity of the null hypothesis of temperature means taken over time in the two PCC cube placements being equal. A 5 percent level of significance is used for this test. The results, shown in Figure 8, concisely depict Class S-LH with 70% Slag to be significantly cooler at early ages out to approximately 280 hours. The t-critical for the hypothesis test is shown in the dashed lines. Outside the region between the dashed lines, the greater the t-value, the greater the difference between the mean temperatures of the two mixes. Class S-LH with 70% slag produced a significantly lower maximum temperature than a TDOT Class S with 20% Class C fly ash in side-by-side 18-CY cube field placements.

TABLE 2. METHOD 2 FIELD TESTING WITH AUTONOMOUS TEMPERATURE SENSORS SUMMARY

Test Parameter	
Sample Size	8x8x8-foot (~ 18CY = 486 ft^3) excavations
Number of Samples	2 or more
Field or Lab	Field
Hardware / software requirements	Temperature sensor reader/controller
Output	Spreadsheet file
Sampling Frequency	30 minutes
Recording Time	56 days
Cost	Approximately $10,000
Main Advantage	Real World
Main Disadvantage	Cost and finding a cooperative location

TABLE 3. METHOD 3 PROPOSED METHOD USING 55-GALLON DRUMS SUMMARY

Test Parameter	
Sample Size	55-gallons (7.35 cubic feet)
Number of Samples	2 or more
Field or Lab	Lab
Hardware / software requirements	Desktop or laptop computer with Windows 7 and one available USB port; National Instruments Signal Express 2010 or later
Output	Spreadsheet file
Sampling Frequency	30 seconds
Recording Time	200 hours or more
Cost	Approximately $ 750
Main Advantage	Cheaper
Main Disadvantage	Barrel Disposal

TABLE 4. FINAL SUMMARY COMPARISON OF CONCRETE HEAT EVOLUTION DUE TO HYDRATION

Test Parameter	Semi-adiabatic Calorimetry	Field Testing with Autonomous Temperature Sensors	55-gallon Drums
Sample Size	4x8-inch cylinder (~ 0.06 cubic feet)	8x8x8-foot (~ 18CY = 486 ft^3) excavations	55-gallons (7.35 cubic feet)
Number of Samples	4	2 or more	2 or more
Field or Lab	Either	Field	Lab
Hardware / software requirements	Built-in nothing additional	Temperature sensor reader/controller	Computer with Windows 7 and one available USB port National Instruments Signal Express 2010 or later
Output	Spreadsheet file	Spreadsheet file	Spreadsheet file
Sampling Frequency	60 seconds	30 minutes	30 seconds
Recording Time	About 1 week	56 days	200 hours or more
Cost	Approximately $5,000	Approximately $10,000	Approximately $750
Main Advantage	Easy / clean up	Real World	Cheaper
Main Disadvantage	Small sample size	Cost and finding a cooperative location	Barrel Disposal

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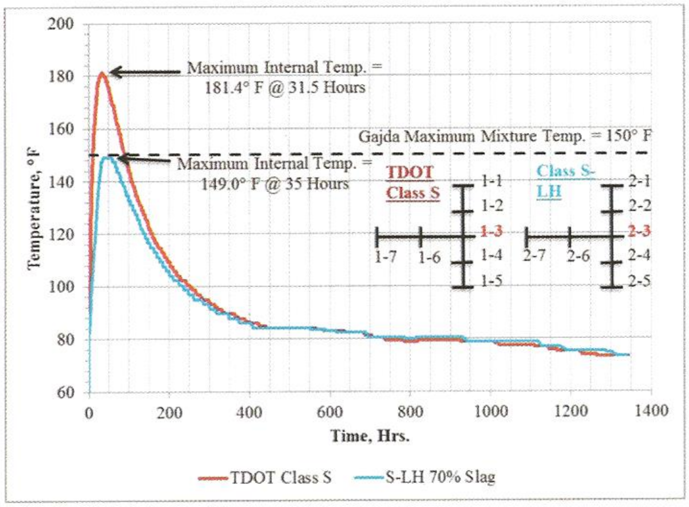

Figure 7: Comparison of Maximum Internal Temperatures over Time

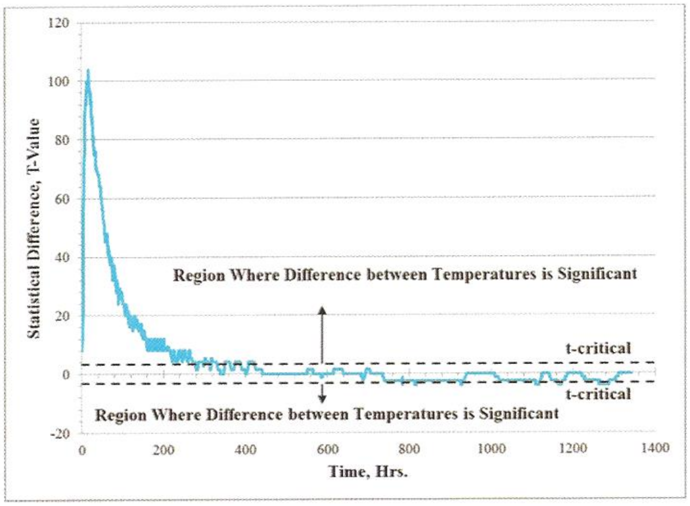

Figure 8: Statistical Difference between Mean Temperatures of TDOT Class S and S-LH with Time

METHOD 3 PROPOSED METHOD USING 55-GALLON DRUMS

The research team wanted to do a test much larger than a 4x8-inch cylinder (used in the semi-adiabatic calorimeter) but avoid the expense of 18-CY cubes in the field. Figure 9 shows the compromise solution. Two fifty-five gallon drums were used (most PCC producers have 55-gallon drums readily available). Each drum had a thermocouple wire secured at the geometric center of the drum. One drum was filled with water and one drum was filled with the concrete being evaluated. The research team reasoned that the difference in temperature between the sensors would be due to hydration heat. The thermocouple output was sent to a data acquisition system (see Figure 10) and subsequently stored on a computer hard drive. Temperatures were recorded every 30 seconds for approximately 200 hours. Large but not immense quantities of data were generated at a much lower expense.

Figure 9: Less Expensive "Field" Test for Heat of Hydration Comparison

HARDWARE AND SOFTWARE REQUIREMENTS

Thermocouples were chosen as the temperature sensor because simply joining two dissimilar metals causes a voltage to be generated proportional to the temperature at the point of the junction. This makes for an inexpensive temperature sensor that can be readily left embedded in the concrete. There are three junctions in a thermocouple measuring system as shown in Figure 10 and there is an equation for each pair of metals (junction) in the system. If the temperature of the cold junctions at the data acquisition system is known, the voltage contribution of these two junctions can be compensated for to permit calculation of the temperature in the concrete. Fortunately all the equations, cold junction measurements etc. are built into the National Instruments thermocouple measuring system purchased for this study.

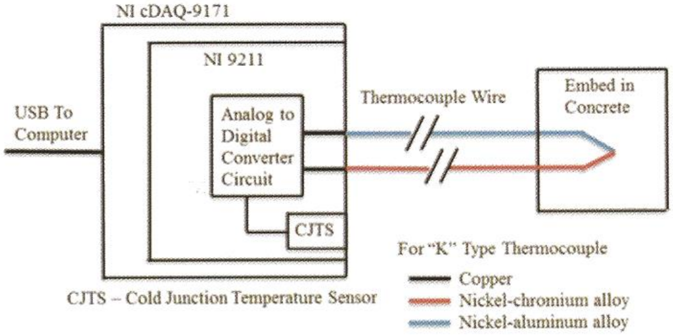

Figure 10: Three dissimilar metal forming three junctions for a thermocouple measurement system.

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Monitoring of the thermocouples can be accomplished with a National Instruments NI 9211 4-channel thermocouple analog to digital converter and a single device chassis, the NI cDAQ-9171, to provide USB communication to a PC for data logging. The NI signal express LE (light edition) software comes with the hardware purchase and can be upgraded at a cost to their full version if the software is to be used for more than just data logging. For this project the data logging capability is sufficient and graphs can be produced in the Signal Express LE program or with Microsoft Excel or any similar plotting package (there are a number of free spreadsheet programs available on the internet). The cost of the National Instruments hardware was about $750. If no computer is available an inexpensive model can be purchased since the data logging requirements are not computationally intensive. If an inexpensive $350 computer is added to the cost of the DAQ system the total is still only $1100.

FIRST EXAMPLE OF USE OF PROPOSED METHOD: CLASS A, CLASS A MODIFIED AND LGM CONCRETES

Figure 11 shows plots of the differences between temperature at the center of the concrete drum and the center of the water drum over time for TDOT Class A, Class A modified with 70% slag, and LGM mixtures (Crouch et al 4, 5). A Student's t-test was utilized to test the validity of the null hypothesis of the equality of the means of temperatures taken in the two drums over time. A 5 percent level of significance was used for the test. T-values exceeding t-critical lead to the rejection of the null hypothesis of equality of mean temperatures and the conclusion of a significant difference existing in heat evolution between each of the PCC mixtures and the water in the drum. Class A modified with 70% slag was significantly different from both TDOT Class A and LGM PCC.

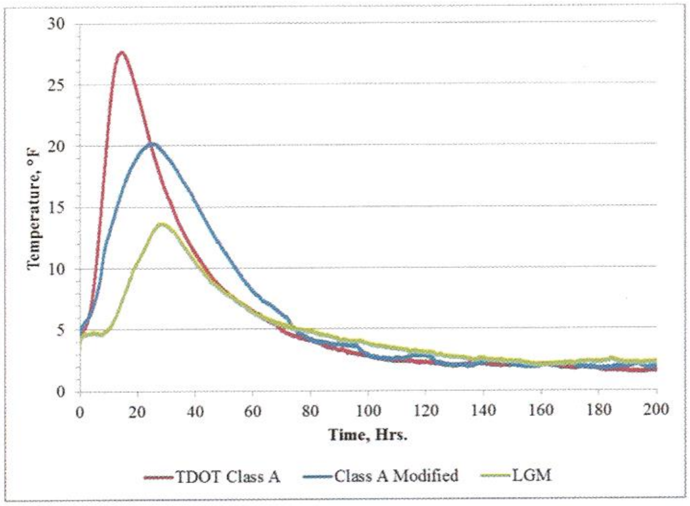

Figure 11: Temperature Differences from Water Barrel for Three Concrete Mixtures

SECOND EXAMPLE OF USE OF PROPOSED METHOD CLASS S AND S-LH WITH 70% SLAG CONCRETES

Figure 12 shows plots of the differences between temperature at the center of the concrete drum and the center of the water drum over time for TDOT Class S and Class S-LH with 70% slag mixtures. A Student's t-test, undertaken with a 5 percent level of significance, indicated there was a significant difference in heat generation between the two mixtures.

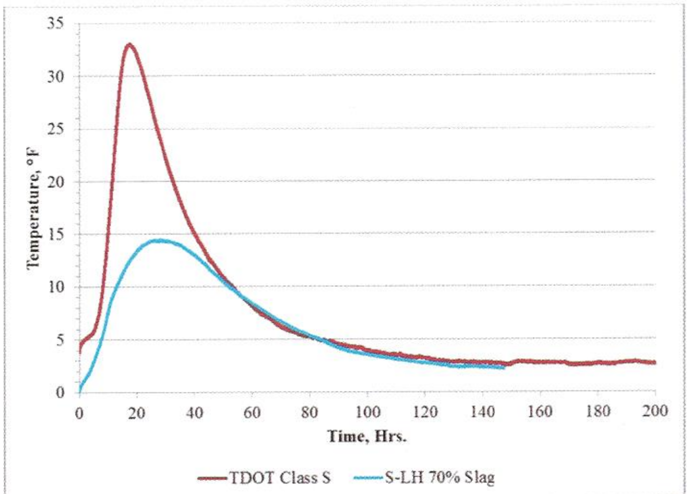

Figure 12: Temperature Differences from Water Barrel for Three Concrete Mixtures

CAUTIONS FOR USE OF THE PROPOSED NEW METHOD

1. Make sure the initial temperatures of mixtures to be compared are very similar.
2. Make sure water (control) temperatures used with mixtures to be compared are very similar.
3. Tests should be conducted indoors so that ambient temperature does not vary too much.
4. The method does not actually measure heat evolution, but rather is only to be used for relative comparisons under similar conditions.

SUMMARY

Table 4 shows a summary comparison of the three methods described in the paper. The proposed new method using 55-gallon drums offers an intermediate sample size at a much lower cost. Further, the new method makes use of materials that most concrete producers have in abundance—concrete, 55-gallon drums, and computers.

DISCLAIMER

The opinions expressed herein are those of the authors and not necessarily the opinions of the Federal Highway Administration, the Tennessee Department of Transportation, or the Tennessee Concrete Association.

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ACKNOWLEDGEMENTS

The authors wish to gratefully acknowledge the support of the Tennessee Department of Transportation and the Federal Highway Administration. Special thanks to Gary Head, Brian Egan, Jamie Waller, Amanda Neighbors and Bill Trolinger.

We also wish to thank Frank Lennox of Buzzi-Unicem, Denny Lind of BASF, Irving Materials Inc., and Alan Sparkman of the Tennessee Concrete Association for their extensive donations of materials to the project.

In addition, the authors would like to thank Mark Davis, Jeff Holmes and Perry Melton for their patience and skill in fabrication, maintenance, and repair of the equipment. We would also like to thank James Locum, Jacob Brooks, Sarah Dillon, and Caleb Smith for their help in the field and/or laboratory.

Further, we appreciate the support of the Tennessee Technological University Department of Civil and Environmental Engineering.

Finally, the authors appreciate the administrative support provided by the Tennessee Technological University Center for Energy Systems Research, particularly Etter Staggs and Linda Lee.

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