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Thermophysical Properties of Launch Complex 17 of the Cape Canaveral Concrete

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Prepared by
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Thermophysical Properties of Launch Complex 17 of the Cape Canaveral Concrete

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Abstract

Accurate knowledge of thermophysical properties of concrete is considered extremely important for meaningful models to be developed of scenarios wherein the concrete is rapidly heated. Test of solid propellant burns on samples of concrete from Launch Complex 17 of the Cape Canaveral show spallation and fragmentation. In response to the need for accurate modeling scenarios of these observations, an experimental program to determine the permeability and thermal properties of the concrete was developed. Room temperature gas permeability measurements of Launch Complex 17 of the Cape Canaveral concrete dried at 50^{o}C yield permeability estimates of 0.07mD (mean), and thermal properties (thermal conductivity, diffusivity, and specific heat) were found to vary with temperatures from room temperature to 300^{o}C. Thermal conductivity ranges from 1.7-1.9 W/mK at 50^{o}C to 1.0-1.15 W/mK at 300^{o}C, thermal diffusivity ranges from 0.75-0.96 mm^2/s at 50^{o}C to 0.44-0.58 mm^2/s at 300^{o}C, and specific heat ranges from 1.76-2.32 /m^{3}K to 2.00-2.50 /m^{3}K at 300^{o}C.

ACKNOWLEDGMENTS

The authors would like to thank Scott Broome and Ron Lipinski for their critical review of this report. Ron Lipinski requested and supported this study.

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INTRODUCTION

Accurate knowledge of thermophysical properties of concrete is considered extremely important for meaningful models to be developed of scenarios wherein the concrete is rapidly heated. Test of solid propellant burns on samples of concrete from Launch Complex 17 of the Cape Canaveral show spallation and fragmentation. It was hypothesized that rapid heating of concrete with low permeability may cause thermal expansion of trapped fluids. This fluid thermal expansion may be the source of degradation caused by the spallation. In response to the need for accurate modeling scenarios of these observations, an experimental program to determine the permeability and thermal properties of the concrete was developed. Room temperature gas permeability measurements of Launch Complex 17 of the Cape Canaveral concrete first dried at 50^{o}C were completed, and thermal properties (thermal conductivity, diffusivity, and specific heat) were measured from room temperature to 300^{o}C.

TEST SETUP AND METHODS

Permeability

Permeability measurements were completed on 4 samples from a concrete block obtained from Launch Complex 17 of the Cape Canaveral Air Force Station using a gas permeameter with constant pressure and flow rate. The specimens were cored from the top of a block and ground lightly to approximately 1.5" diameter and 3" in length. The intent was to minimize disturbance at the top surface of the sample taken so as to capture actual attributes of the concrete's in situ state.

The test specimen was placed between two metal platens having central ports that permit the permeant (nitrogen) to enter and exit the specimen (Figure 1). Highly-permeable porous felt metal disks are placed in the interface between the platens and specimen to distribute the permeant and permeant pressure across the full cross-section of the specimen. The specimen is jacketed with a paint-on UV cured polyurethane that is sealed by adhesion to the platens and concrete and serves to protect the specimen from hydraulic confining fluid and also to prevent permeant from short-circuiting around the sides of the specimen during testing.

The jacketed specimen/platen assembly was placed inside a pressure vessel (permeameter) and the upstream and downstream ports of the platens are connected to a permeant source and to a flow meter (Figure 2,3). The annulus between the specimen and pressure vessel is filled with Isopar H fluid and pressurized during the test (applying a pressure to the external surfaces of the specimen) to primarily assure gas flow goes through the sample and not between the jacket and sample by maintaining the confining pressure higher than the permeant pressure.

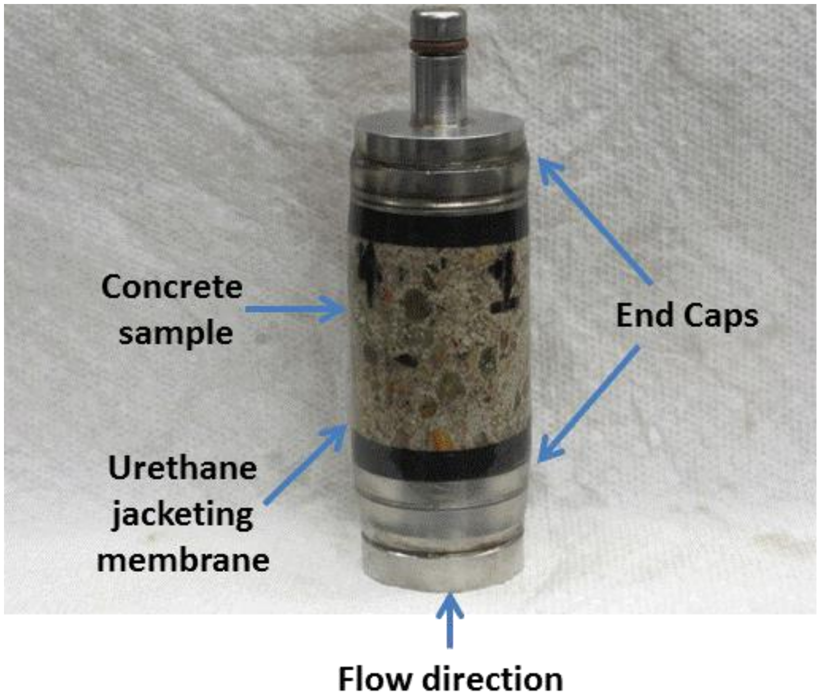

Figure 1 Sample assembly

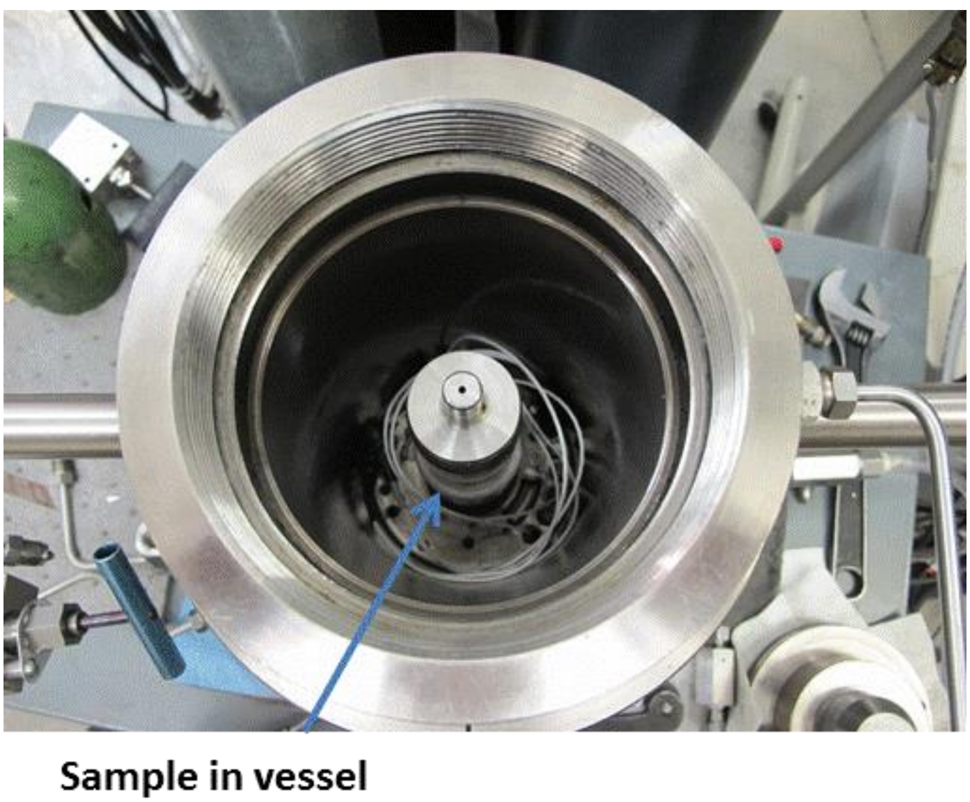

Figure 2 Concrete sample in pressure vessel.

The permeability measurement used a constant head (or pressure) technique with nitrogen as the permeant medium. In this technique, once the confining pressure is slowly raised and stabilized to a constant value, permeant was allowed to enter the upstream side of the specimen at a constant pressure (0.39-0.40 MPa). The pressure difference between the upstream and downstream ends of the sample was minimized. The downstream side of the specimen was vented to the atmosphere through a flow meter. The flow meter was connected to the data acquisition system and presented flow in cc/min.

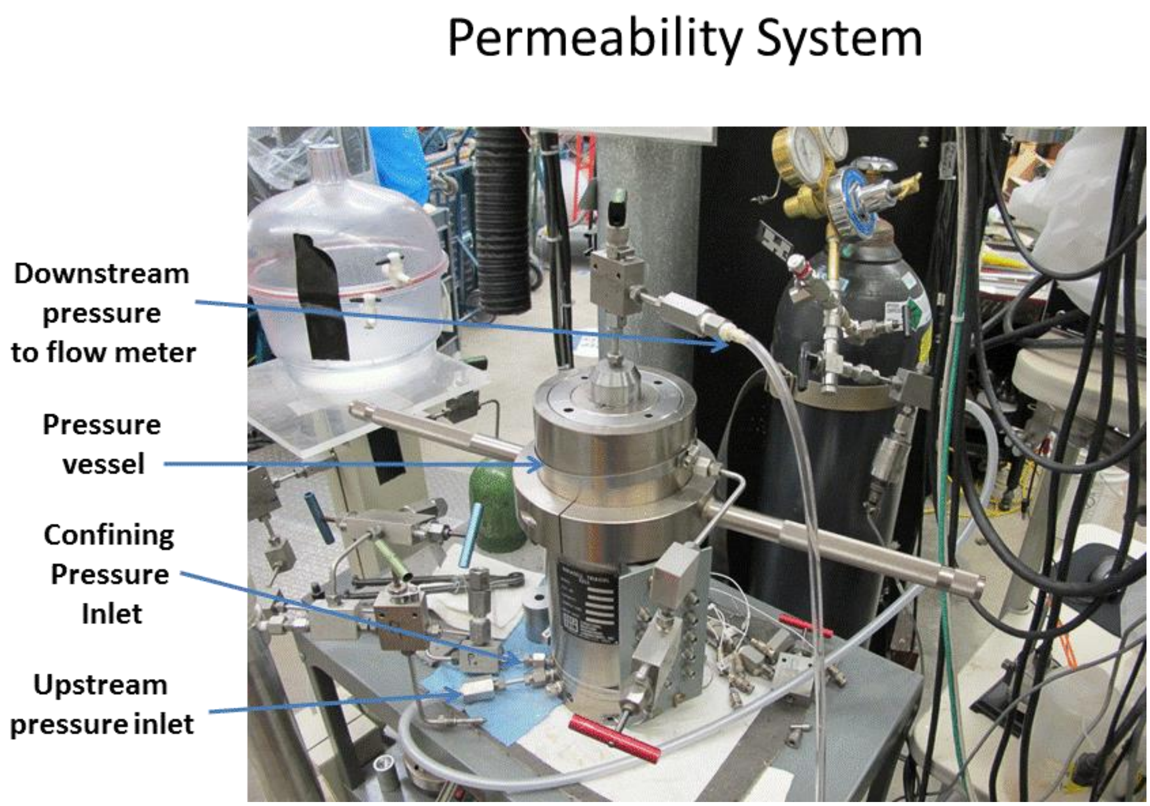

Figure 3 Permeability System.

Thermal properties

Thermal property measurements (thermal conductivity, diffusivity, and specific heat) were completed on 4 samples from a concrete block obtained from Launch Complex 17 of the Cape Canaveral Air Force Station.

Thermal measurements were made at ambient pressure and moisture conditions using a transient method based on the theory of the transient plane source technique. The Hot Disk® sensors used for these measurements serve as a heat source to increase sample temperature and as resistance thermometers for recording temperature increase over time.

Specimens were cored from the top of a block, cut and ground to approximately 2.0" diameter and 1" in length. The measurement was made across a matched interface in each sample, for each sample (Figure 4).

Sample mass was recorded at each temperature to determine the amount of water loss at each temperature interval. At each temperature the sample equilibrated for a few hours before a measurement was made. Measurements were made at room temperature and at 50°C intervals up to 300°C.

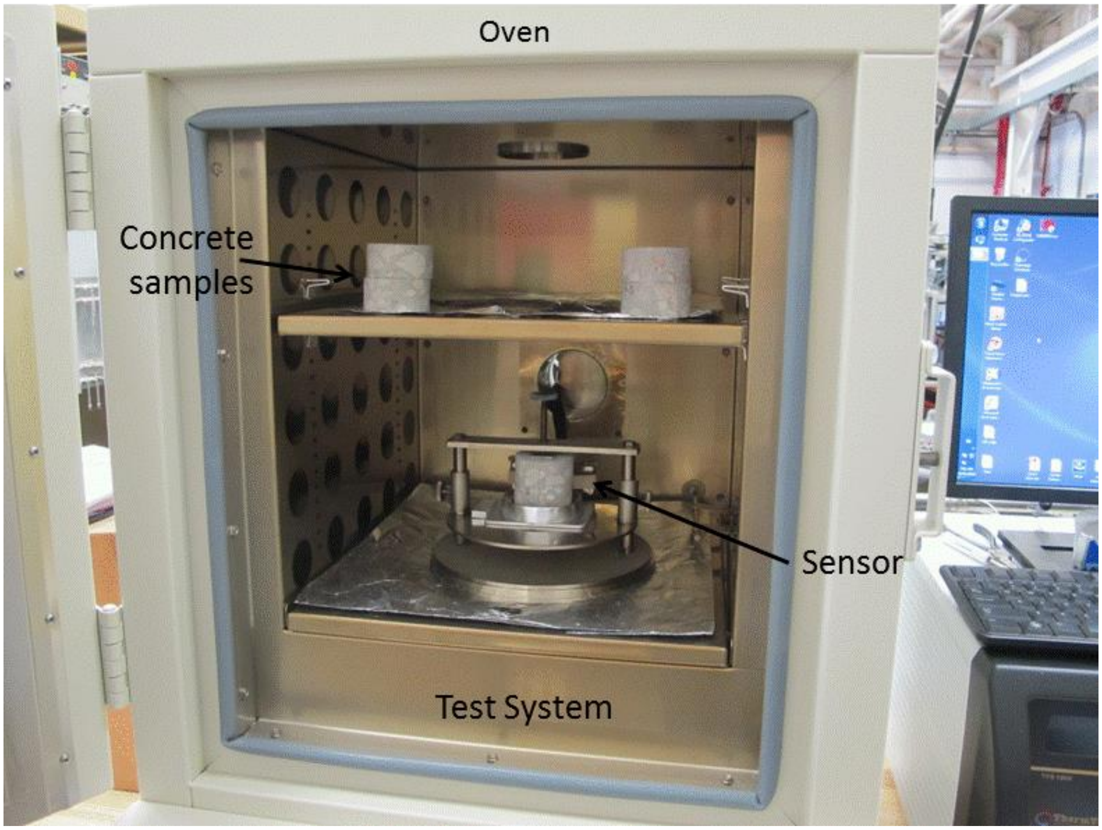

Figure 4 Thermal Measurements Test System.

EXPERIMENTAL RESULTS AND DISCUSSION

Intrinsic permeability, k (in units of meters squared) was calculated from the following equation:

$$k = \frac{2\mu L Q_e P_{ea}}{A\left(P_{ia}^2 - P_{ea}^2\right)}$$

where:

μ is dynamic viscosity of the permeant (= 0.018×10^{-3} N· sec/m^2 for nitrogen)
L = specimen length (in meters)
A = specimen cross-sectional area (in meters squared)
Q_e = steady-state permeant flow rate (in cubic meters per second)
P_{ia} and P_{ea} are the inlet and exit absolute pressures (in Pascals)

Table 1 contains sample number, flow rate (cc/min), upstream pressure (MPa), confining pressure (MPa), and calculated permeability in milliDarcies (mD). Measurements were made at two confining pressures for each sample, approximately 0.54 and 1.09 MPa. The confining pressure effect is small and insignificant, primarily because its value is small. Figures 5a-12a shows the test conditions and flow rate as a function of time for the samples; Figure 5b-12b shows permeability as a function of time. For these conditions, the average (mean) permeability of the concrete is 0.07 µD, and median permeability of 0.05 µD when the test conditions are in steady state after approximately 1000 sec of flow. The greater median value than mean value reflects the slightly higher permeability values for Sample 4.

Table 1 Sample numbers and parameters.

Sample	Upstream Pressure (MPa)	Flow rate at steady state (cc/min)	Confining Pressure (MPa)	Calculated Permeability (mD)
1-1	0.40	1.39	0.54	0.03
1-2	0.40	1.29	1.10	0.03
2-1	0.39	2.39	0.53	0.06
2-2	0.39	2.21	1.09	0.05
3-1	0.39	2.14	0.53	0.05
3-2	0.39	2.06	1.06	0.04
4-1	0.39	6.27	0.52	0.13
4-2	0.39	5.91	1.05	0.14
			Mean	0.07
			Median	0.05

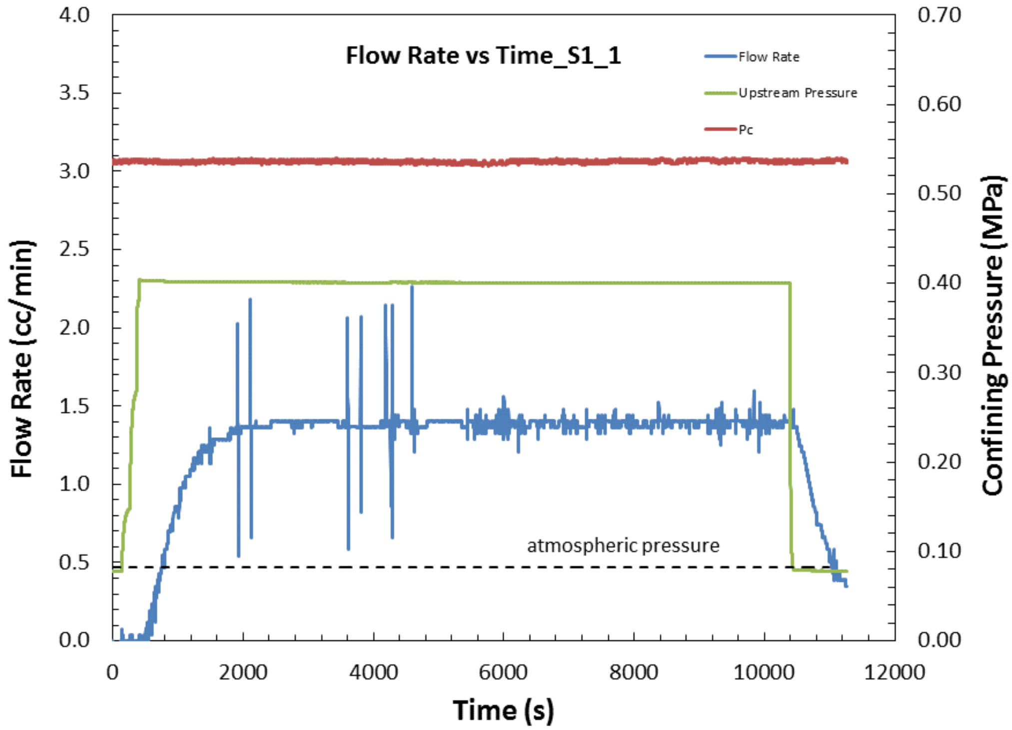

Figure 5a Flow conditions (confining pressure, upstream pressure, and flow rate) versus time.

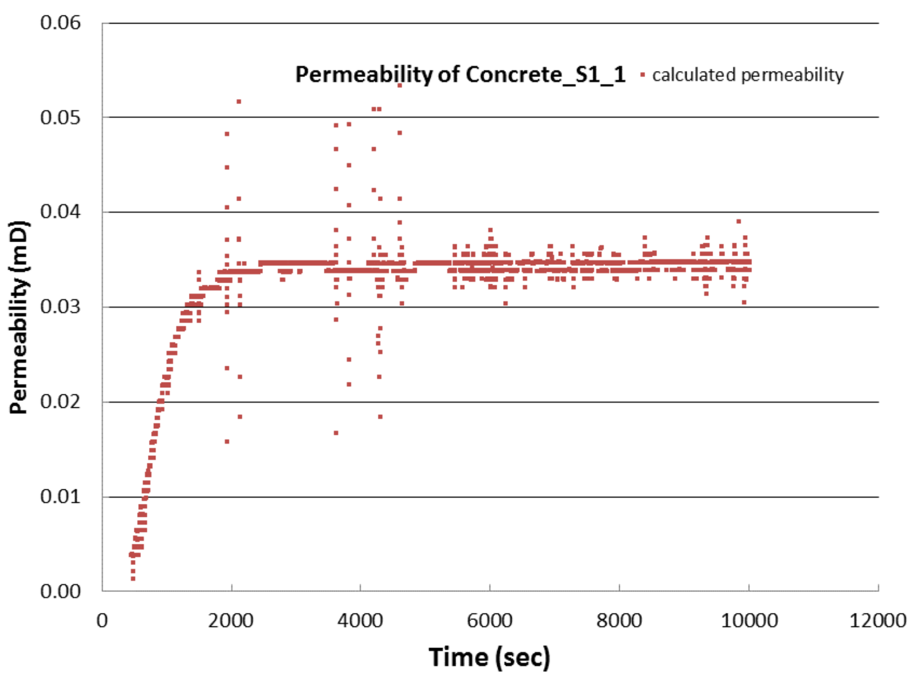

Figure 5b Permeability versus time.

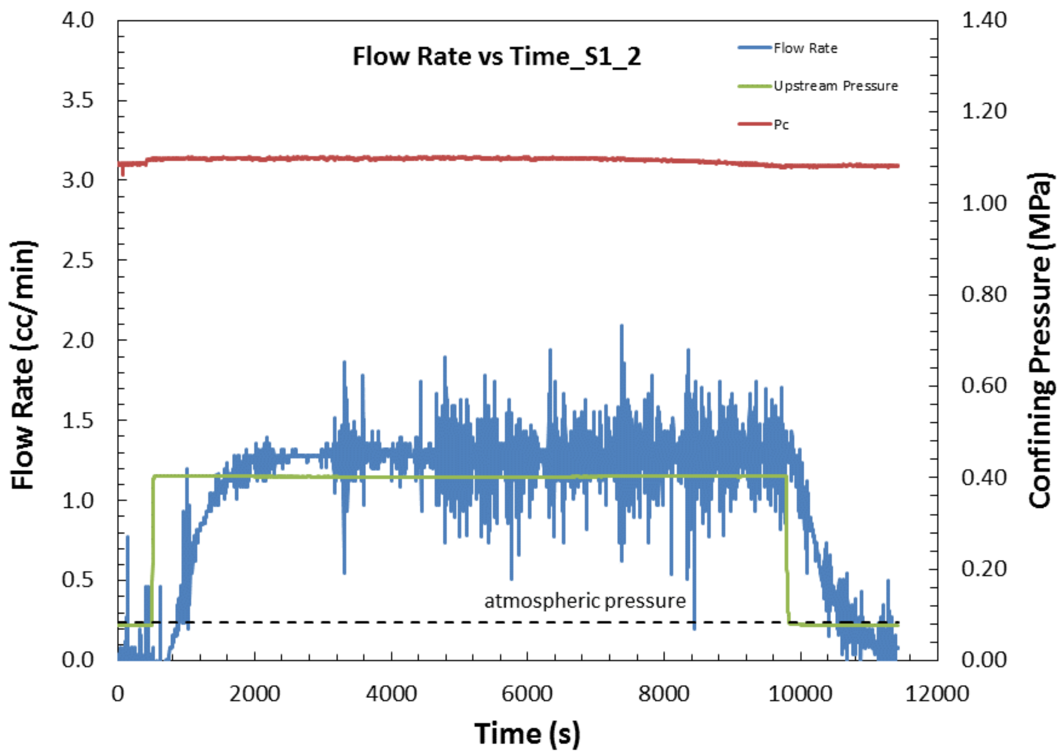

Figure 6a Flow conditions (confining pressure, upstream pressure, and flow rate) versus time.

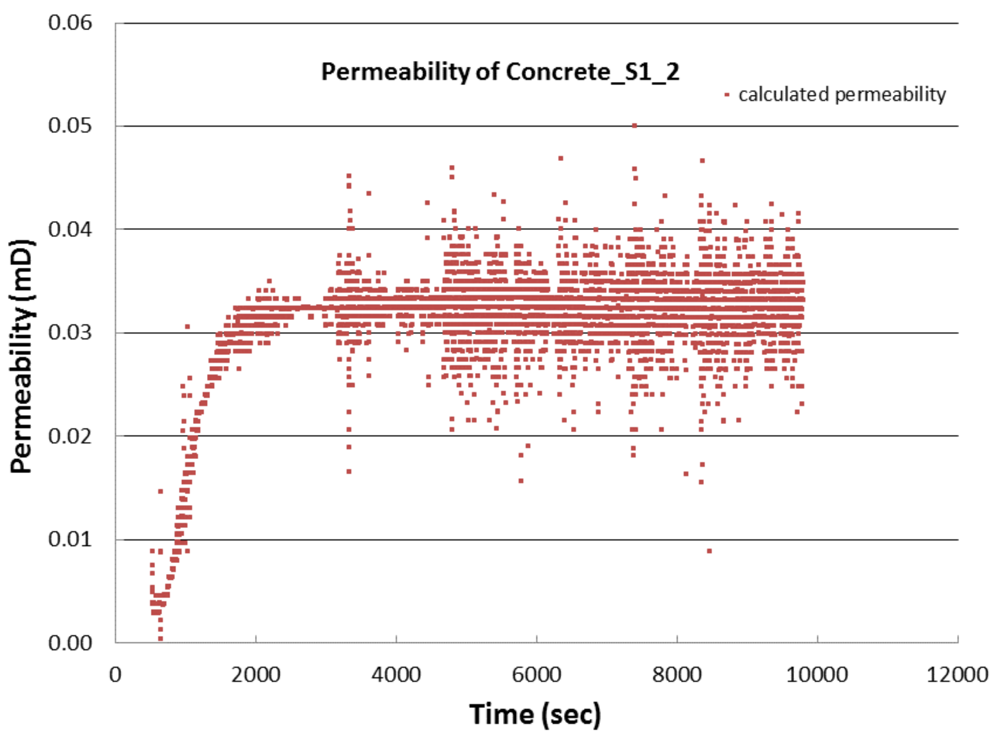

Figure 6b Permeability versus time

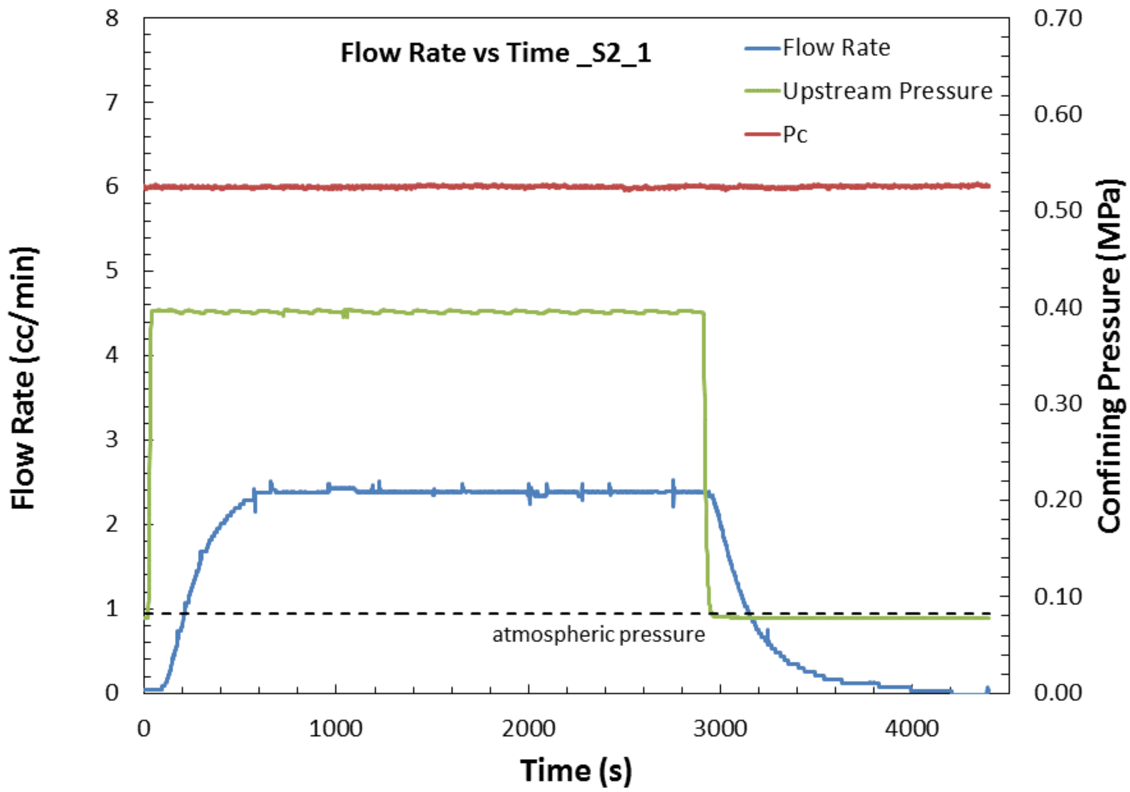

Figure 7a Flow conditions (confining pressure, upstream presure, and flow rate) versus time.

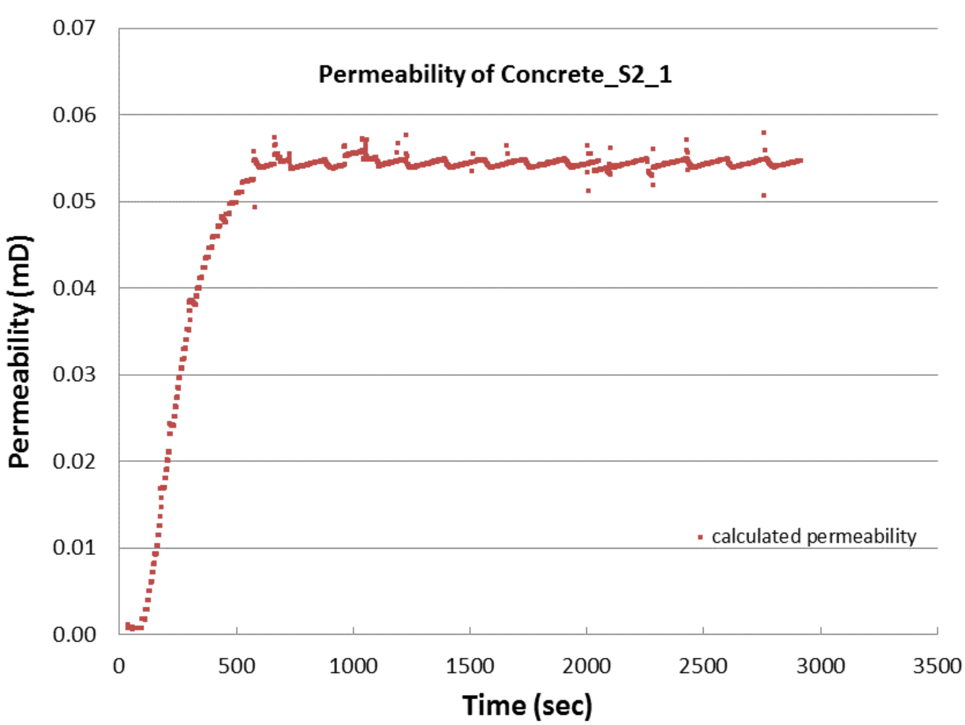

Figure 7b Permeability versus time

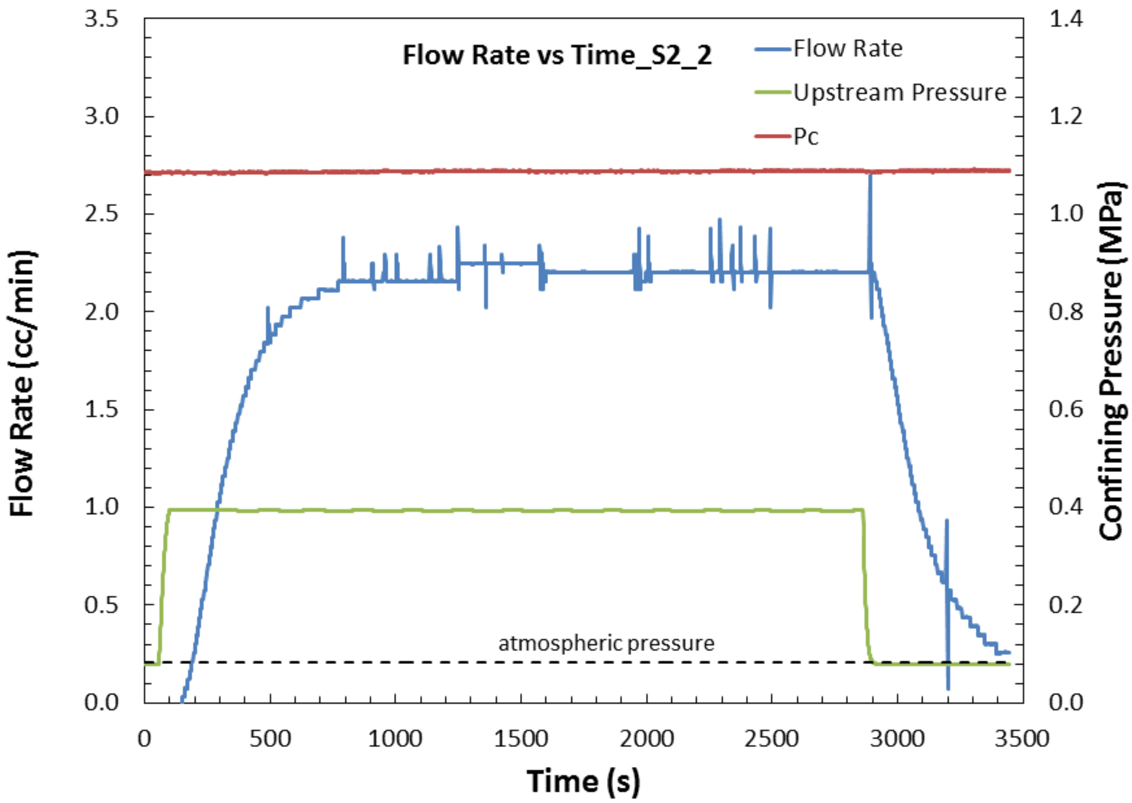

Figure 8a Flow conditions (confining pressure, upstream pressure, and flow rate) versus time.

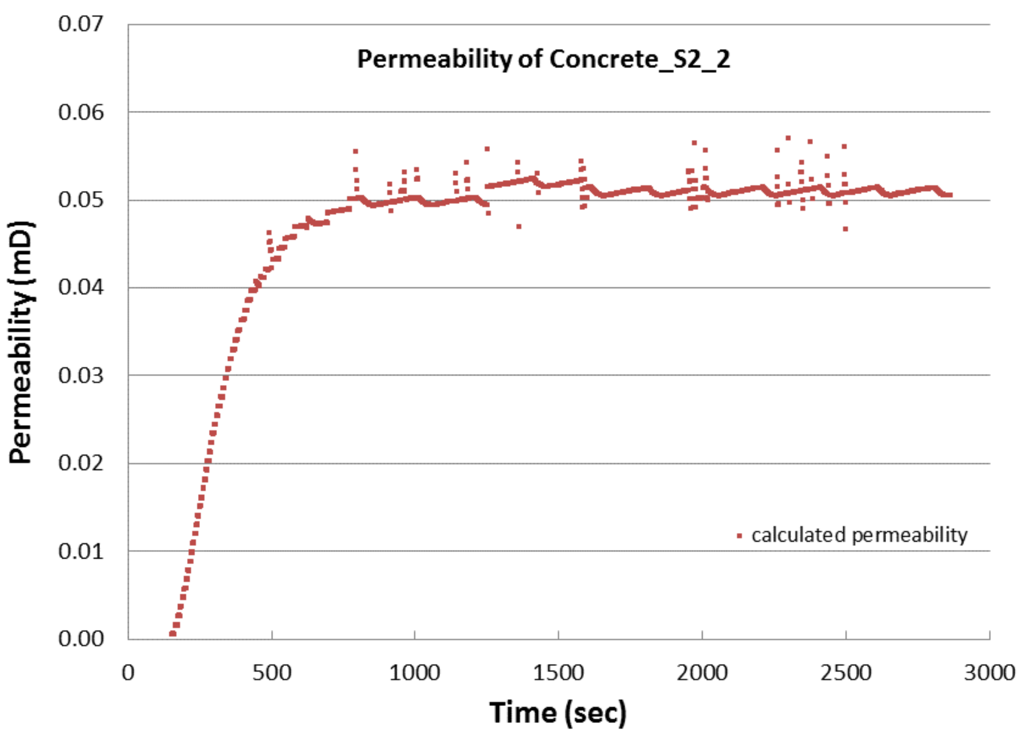

Figure 8b Permeability versus time.

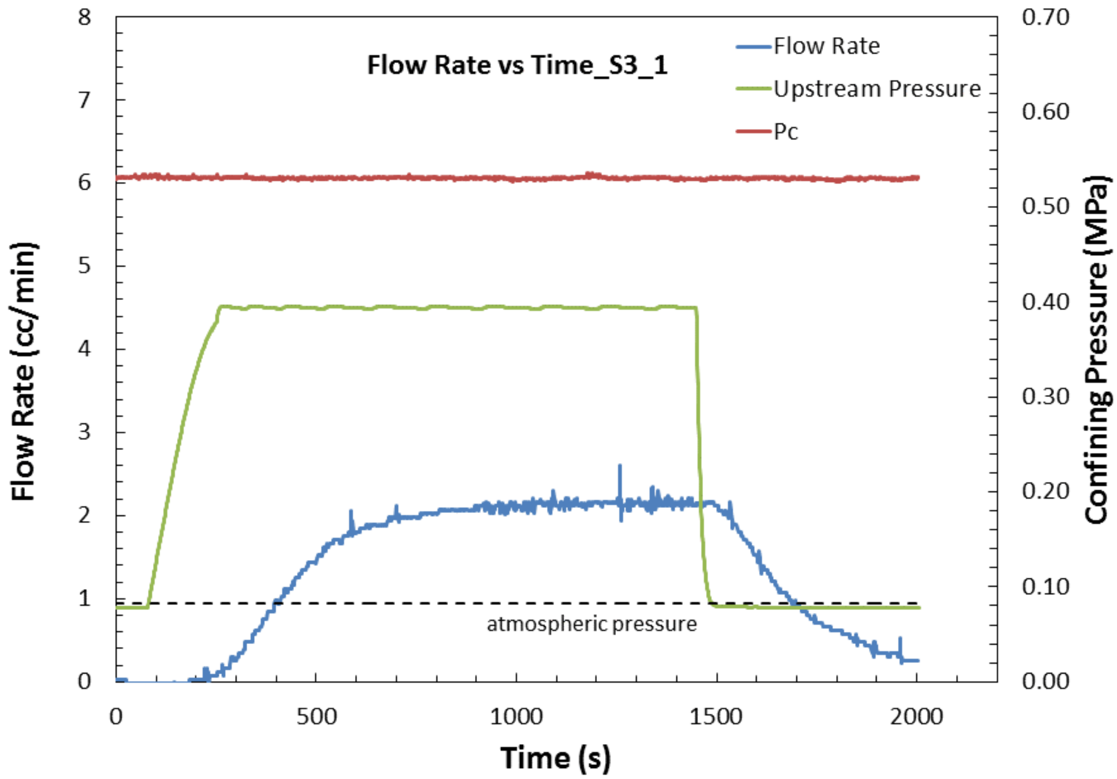

Figure 9a Flow conditions (confining pressure, upstream pressure, and flow rate) versus time.

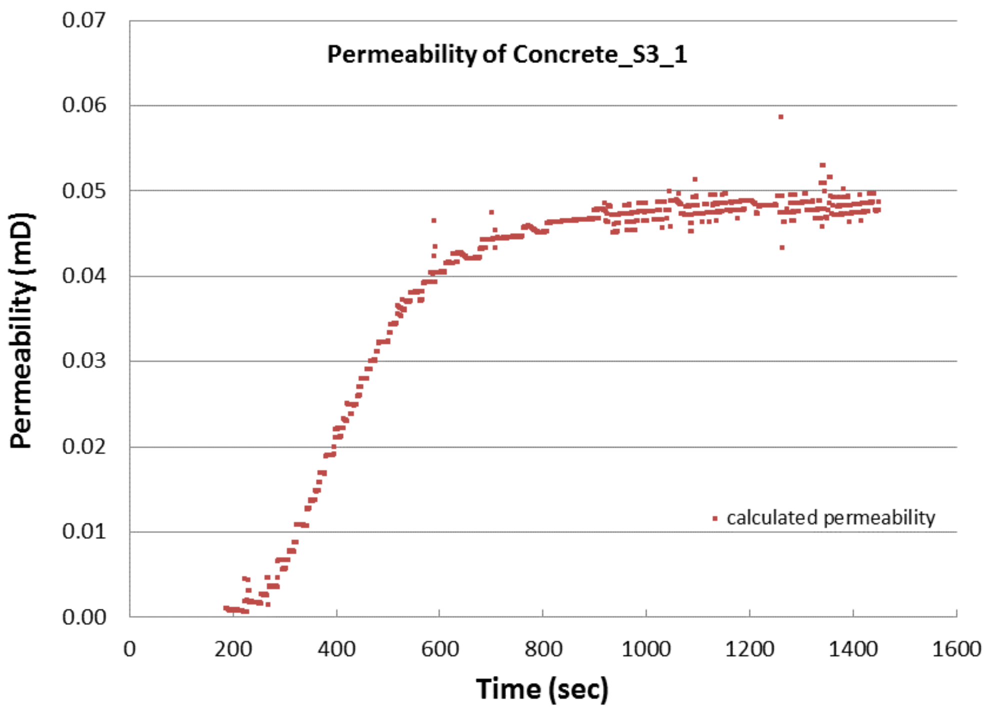

Figure 9b Permeability versus time.

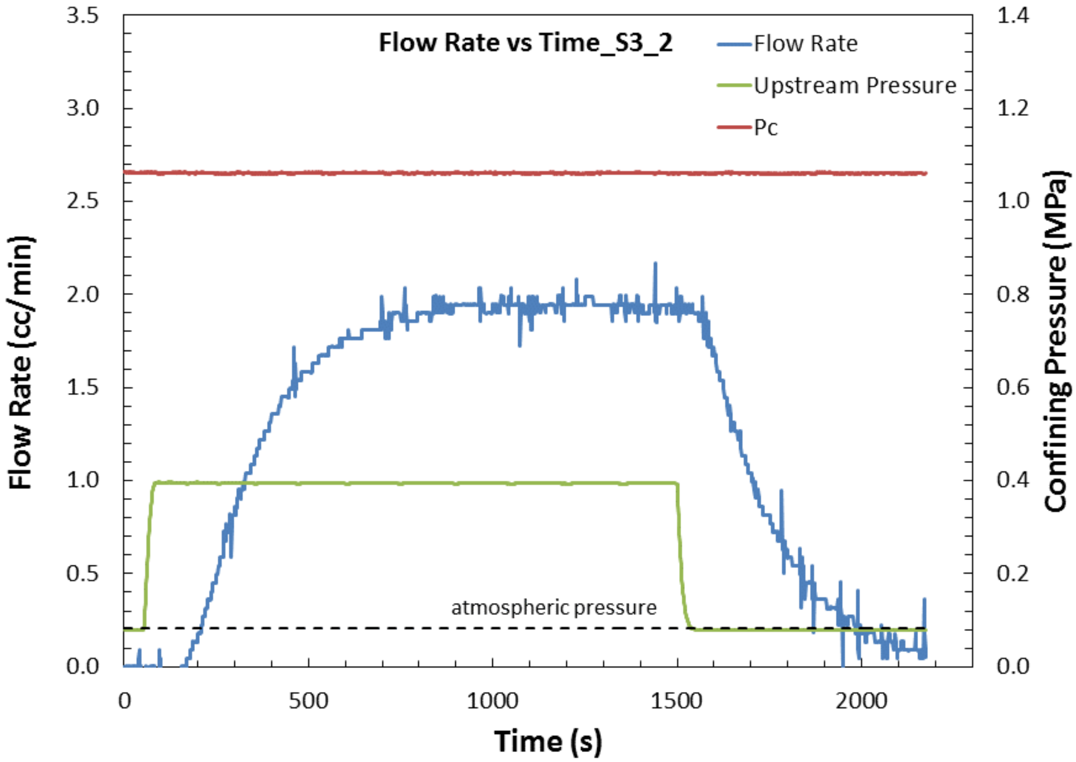

Figure 10a Flow conditions (confining pressure, upstream pressure, and flow rate) versus time.

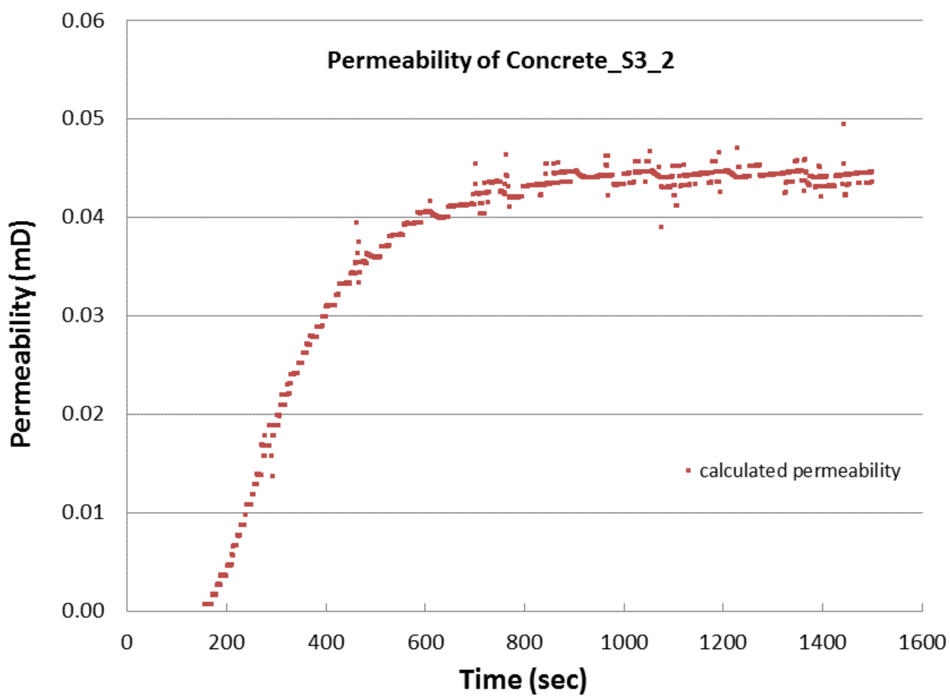

Figure 10b Permeability versus time.

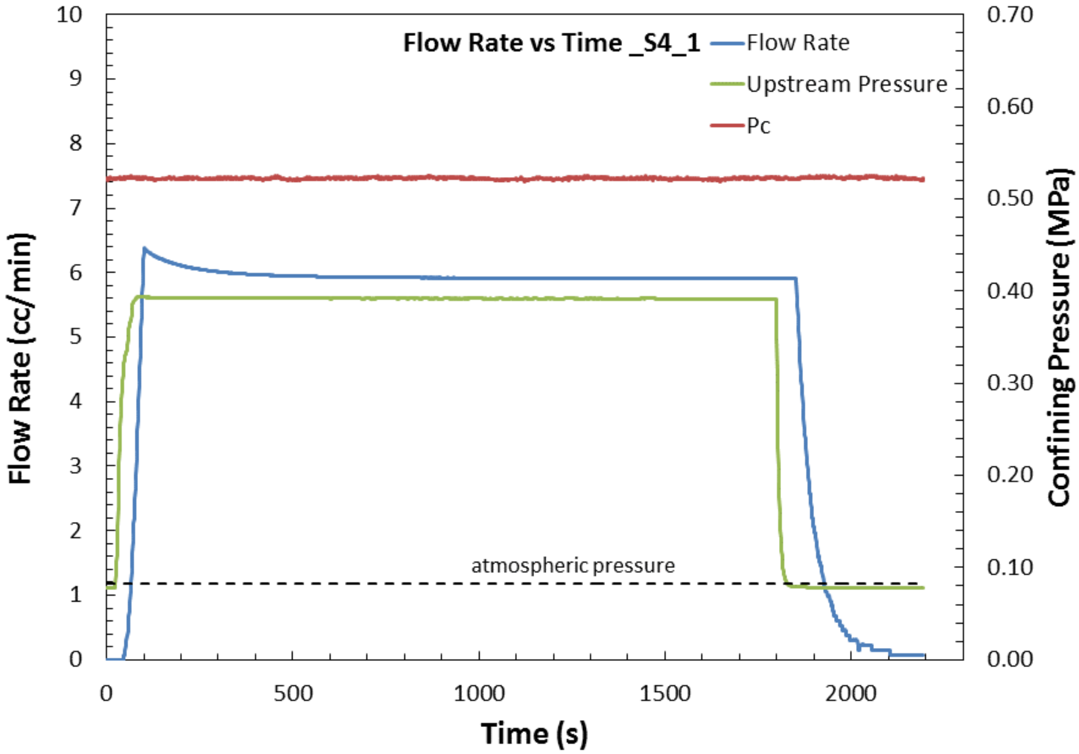

Figure 11a Flow conditions (confining pressure, upstream pressure, and flow rate) versus time.

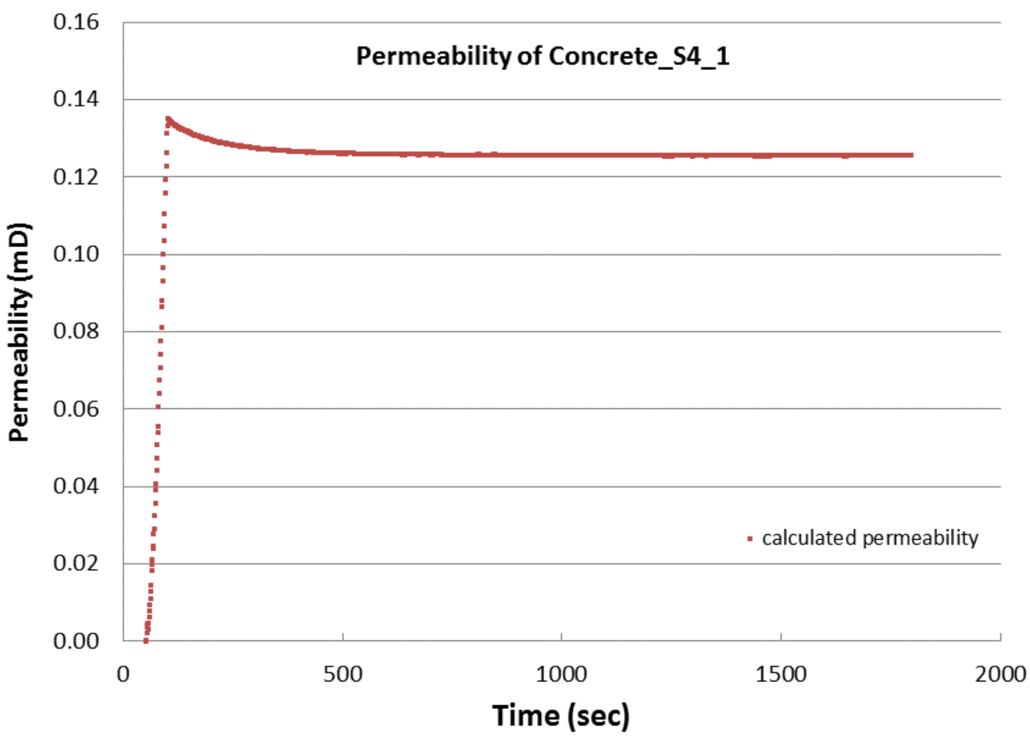

Figure 11b Permeability versus time.

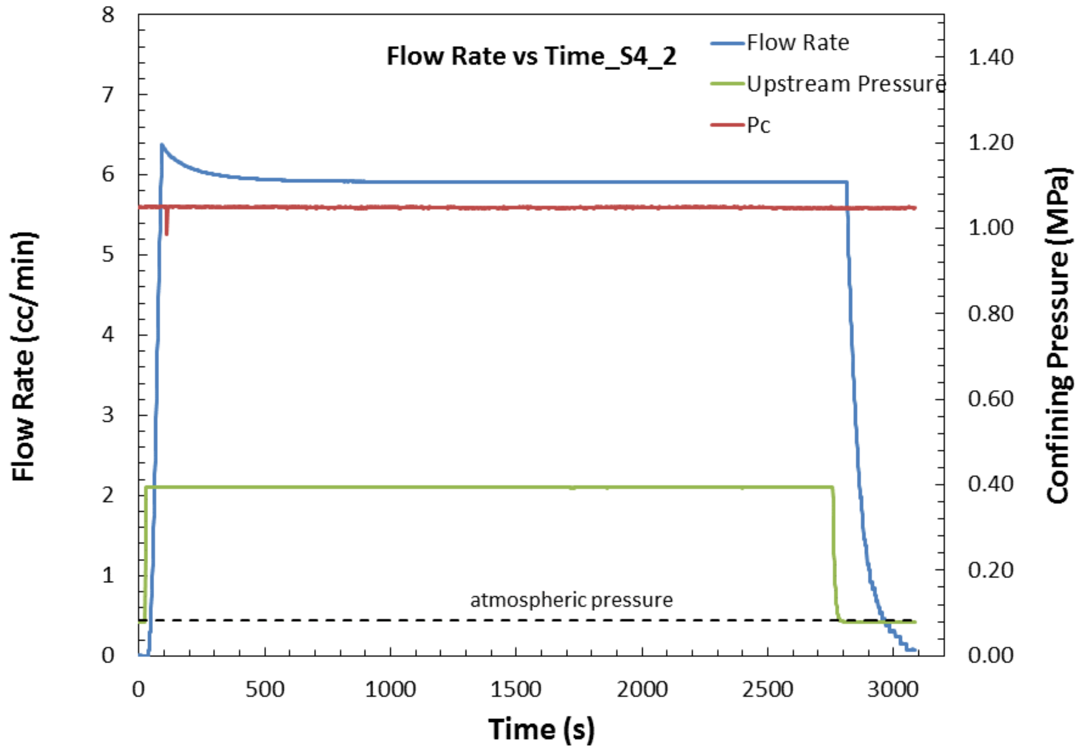

Figure 12a Flow conditions (confining pressure, upstream pressure, and flow rate) versus time.

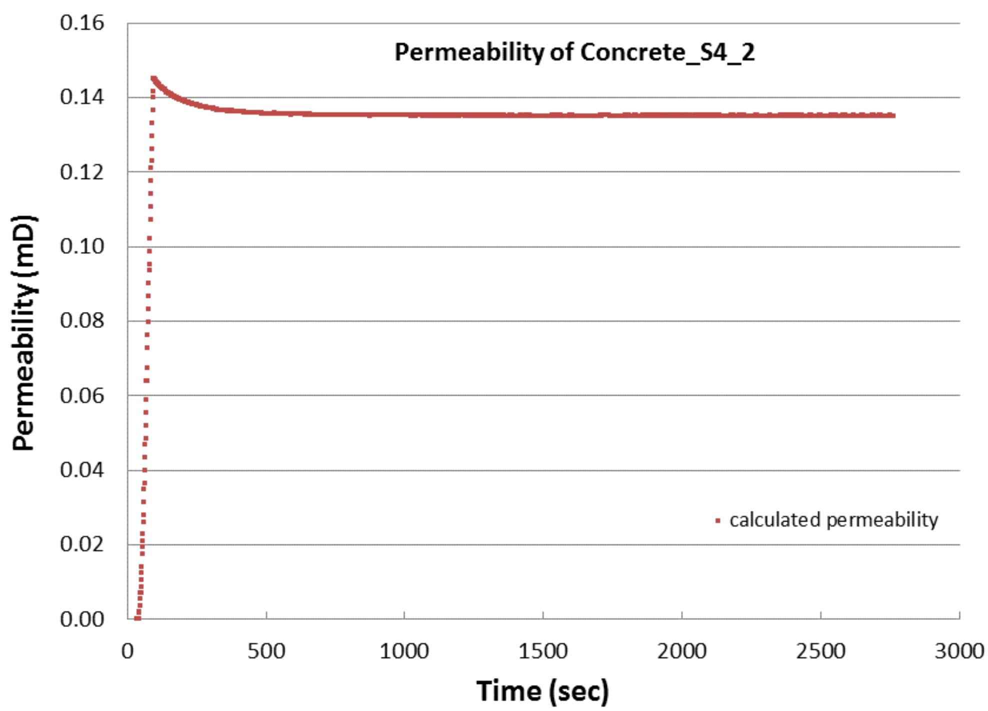

Figure 12b Permeability versus time.

Table 2 contains sample number, weight, step weight change (weight change from previous measurement), apparent density (assuming no thermal expansion) and percent water loss (assuming 300^{o}C mass ids the dry mass) at each temperature. The may be chemistry changes in concrete at these and greater temperature that could cause the water loss/retentions observed. From one temperature to the next, samples were heated at approximately 1^{o}C/min to minimize thermal gradients; equilibration time at each temperature level was on the order of two hours. Samples lose weight (dry) with increasing temperature, each losing about 4 grams of mass, with the biggest mass drop (sensibly) at the 100^{o}C – 150^{o}C measurement owing to dewatering. Cumulative weight (Figure 13) decreases with increasing temperature, and the change in weight (Figure14) graphically shows the weight change decrease for the 100^{o}C – 150^{o}C temperature interval.

Table 2 Sample number, weight, step change, apparent density and percent weight water loss at each temperature.

	Weight (g) at Temperature						
Sample	25C	50C	100C	150C	200C	250C	300C
1a	109.46	109.21	108.55	106.84	105.95	105.53	105.38
1b	116.13	115.83	115.07	113.23	112.24	111.82	111.66
2a	115.85	115.59	115.17	113.50	112.70	112.35	112.21
2b	111.70	111.36	110.80	108.71	107.73	107.32	107.15
3a	111.65	111.40	110.77	109.08	108.15	107.81	107.61
3b	112.01	111.70	110.89	109.00	107.92	107.50	107.32
4a	116.49	116.19	115.54	114.05	113.13	112.80	112.65
4b	115.66	115.37	114.68	113.13	112.13	111.77	111.61
	Step change						
1a	0	-0.25	-0.66	-1.71	-0.89	-0.42	-0.15
1b	0	-0.30	-0.76	-1.84	-0.99	-0.42	-0.16
2a	0	-0.26	-0.42	-1.67	-0.80	-0.35	-0.14
2b	0	-0.34	-0.56	-2.09	-0.98	-0.41	-0.17
3a	0	-0.25	-0.63	-1.69	-0.93	-0.34	-0.20
3b	0	-0.31	-0.81	-1.89	-1.08	-0.42	-0.18
4a	0	-0.30	-0.65	-1.49	-0.92	-0.33	-0.15
4b	0	-0.29	-0.69	-1.55	-1.00	-0.36	-0.16

Apparent Density (g/cc) at Temperature

	25C	50C	100C	150C	200C	250C	300C
1a	2.11	2.10	2.09	2.06	2.04	2.03	2.03
1b	2.11	2.10	2.09	2.05	2.03	2.03	2.02
2a	2.12	2.12	2.11	2.08	2.06	2.06	2.05
2b	2.13	2.12	2.11	2.07	2.05	2.04	2.04
3a	2.11	2.10	2.09	2.06	2.04	2.03	2.03
3b	2.11	2.11	2.09	2.06	2.03	2.03	2.02
4a	2.11	2.11	2.09	2.07	2.05	2.05	2.04
4b	2.10	2.09	2.08	2.05	2.03	2.03	2.02

Percent water weight loss

Sample	25C	50C	100C	150C	200C	250C	300C
1a	n/a	6.13	22.30	64.22	86.03	96.32	100.0
1b	n/a	6.71	23.71	64.88	87.02	96.42	100.0
2a	n/a	7.14	18.68	64.56	86.54	96.15	100.0
2b	n/a	7.47	19.78	65.71	87.25	96.26	100.0
3a	n/a	6.19	21.78	63.61	86.63	95.05	100.0
3b	n/a	6.61	23.88	64.18	87.21	96.16	100.0
4a	n/a	7.81	24.74	63.54	87.50	96.09	100.0
4b	n/a	7.16	24.20	62.47	87.16	96.05	100.0

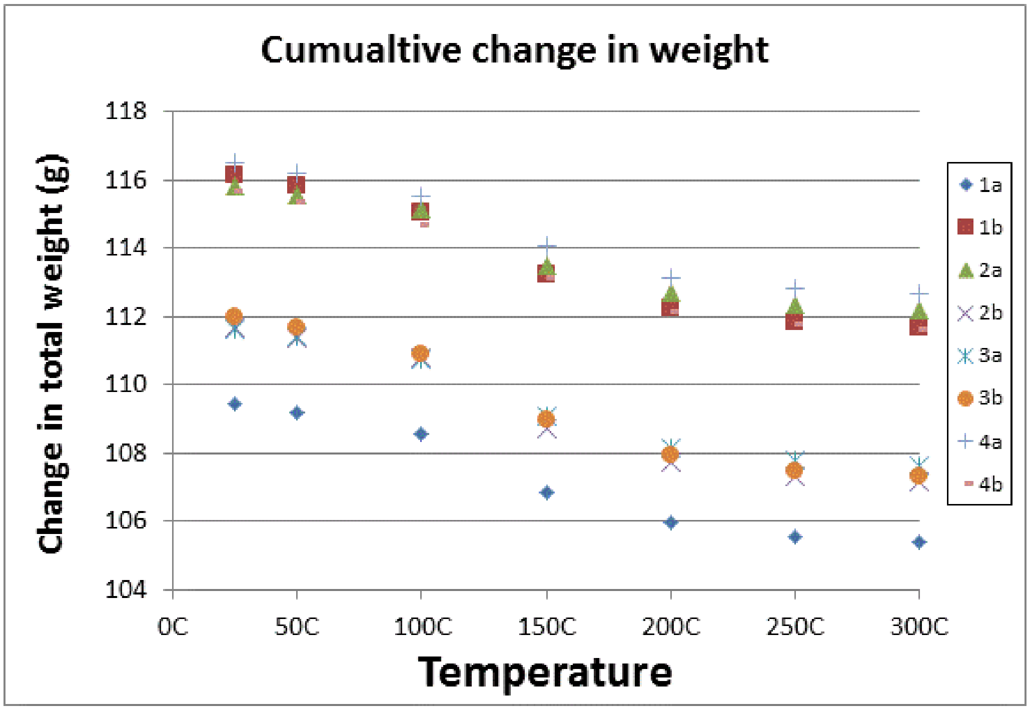

Figure 13 Cumulative weight change.

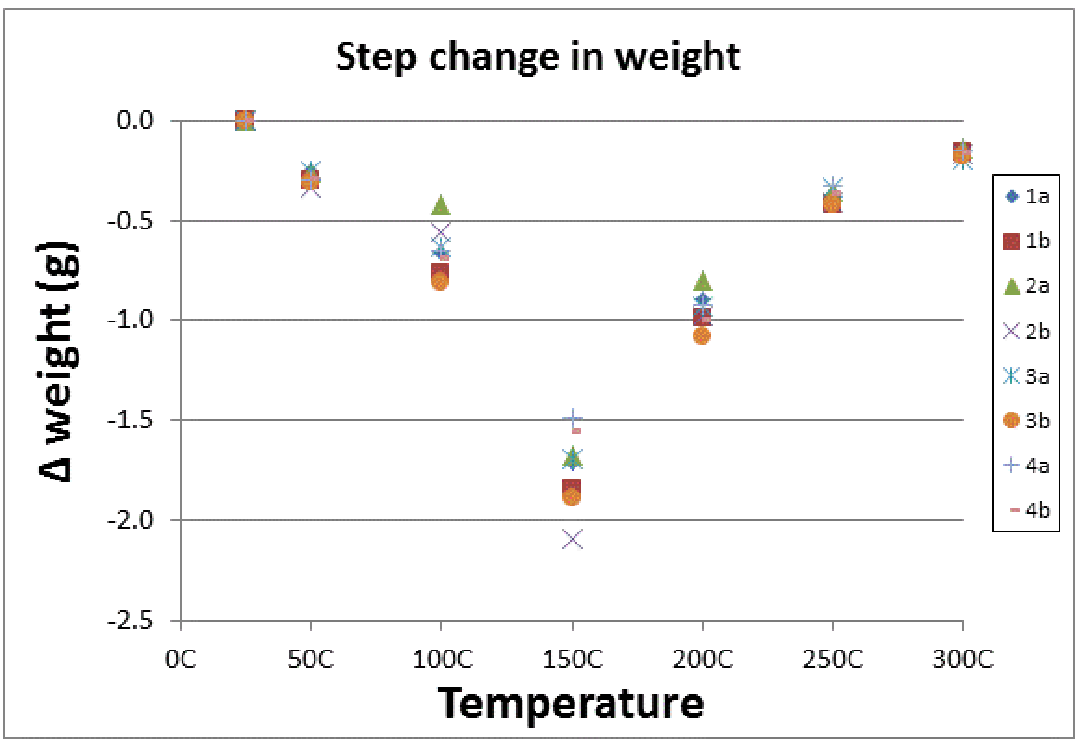

Figure 14 Step weight change.

Thermal conductivity, the property of a material to conduct heat, thermal diffusivity, the measure of thermal inertia, and the specific heat, the amount of heat per unit mass required to raise the temperature by one ^{o}C, as determined in this study are displayed in Figure 15, 16, and 17. The operative mechanisms resulting in the observed changes of these thermal properties is beyond the scope of this study; minor aberrations in "smooth curves" obtained for most samples may be caused by changes for most of the data could be the result of experimental error.

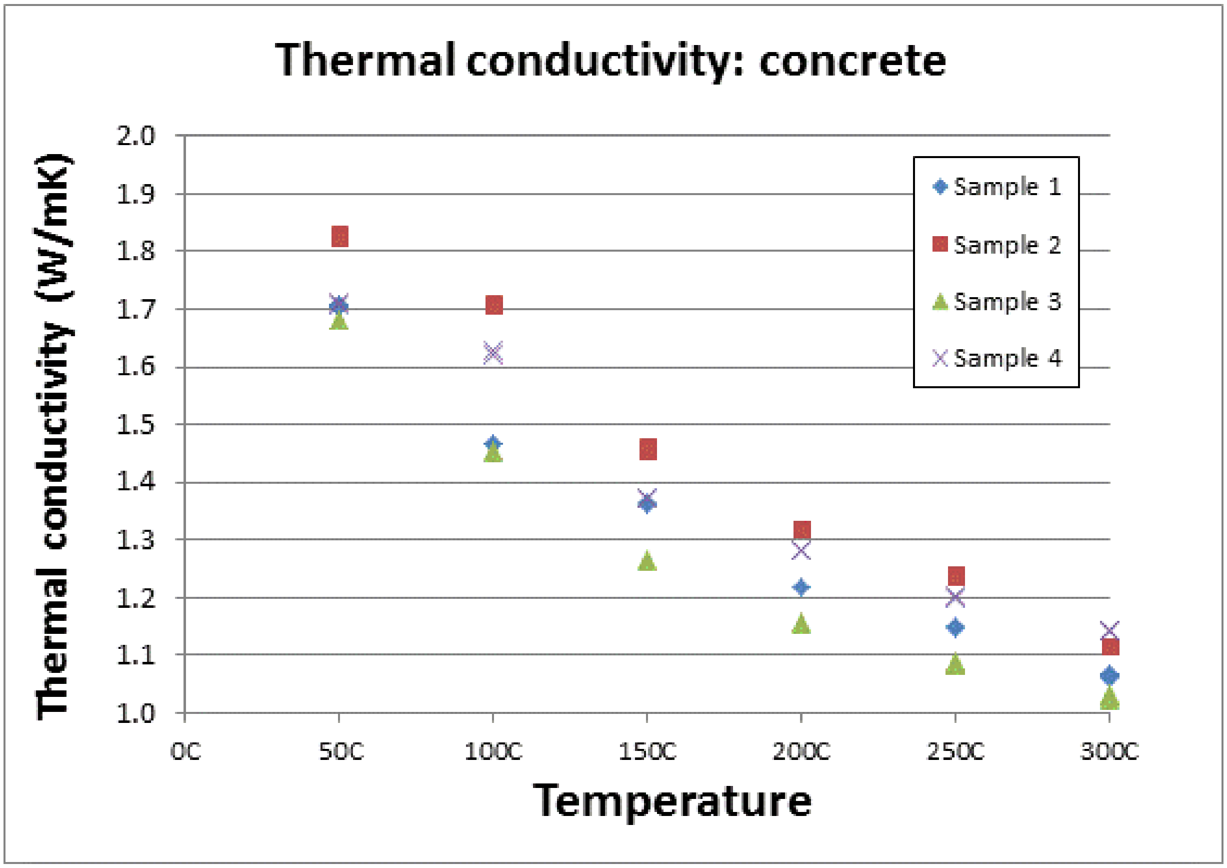

Figure 15 Thermal conductivity versus temperture

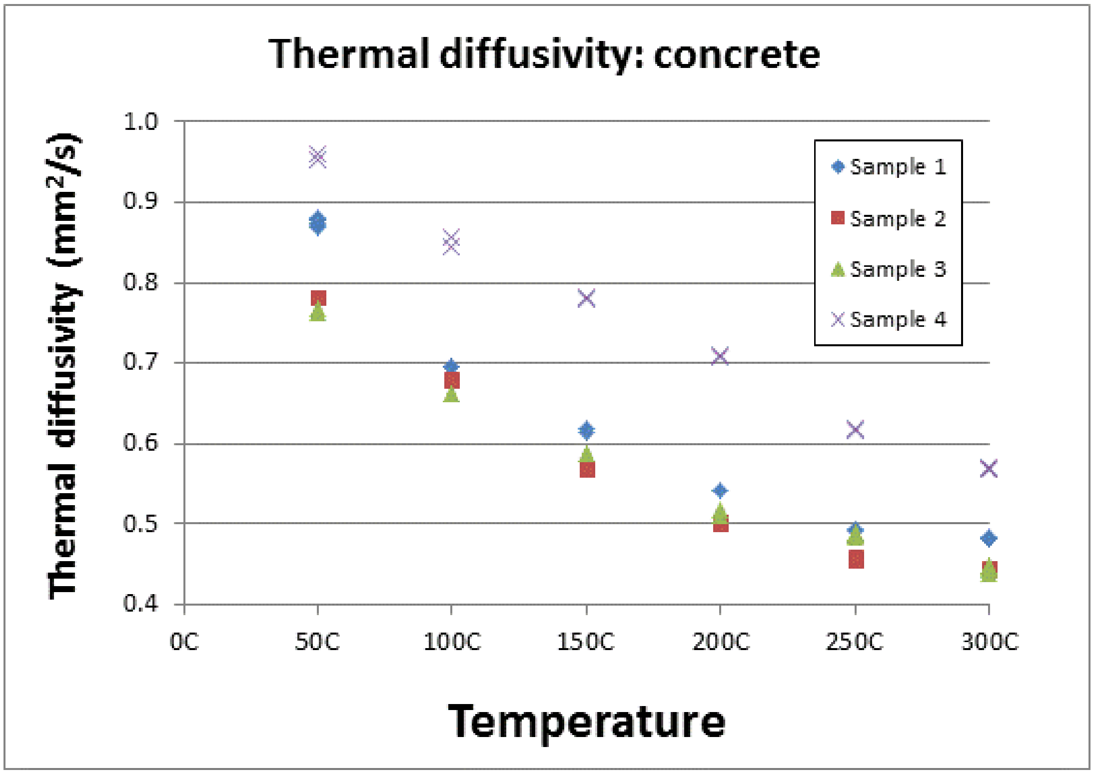

Figure 16 Thermal diffusivity versus temperture

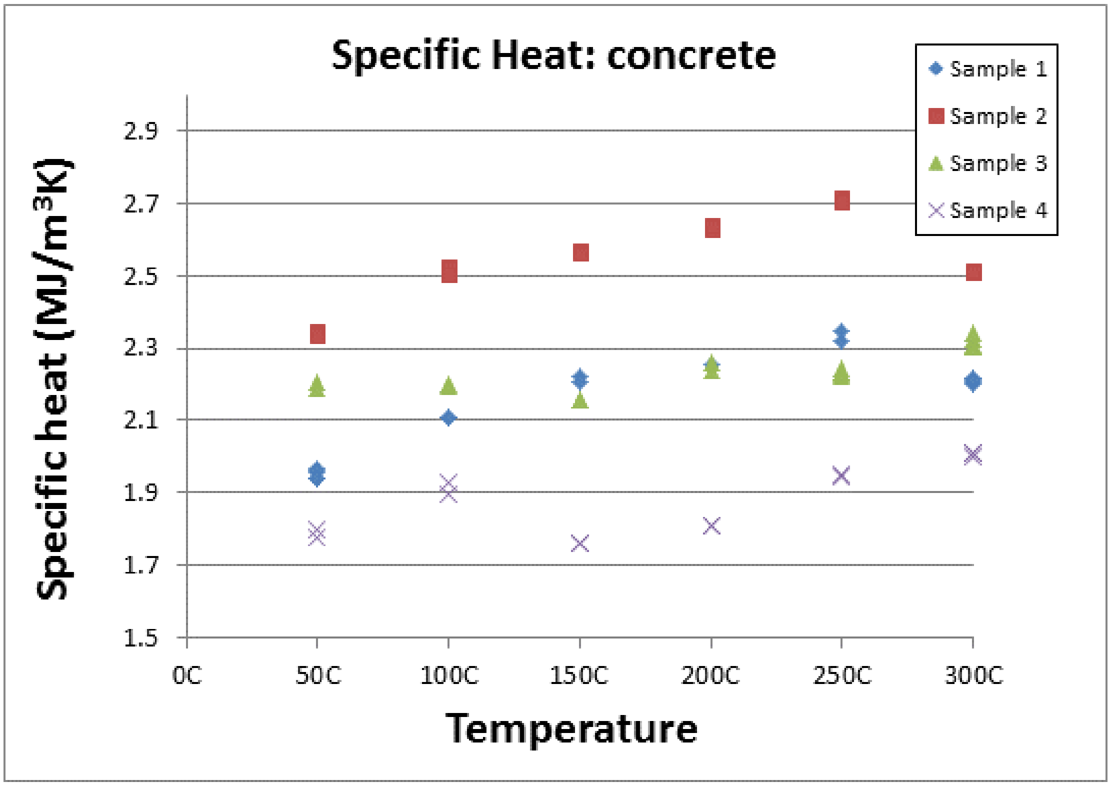

Figure 17 Specific Heat versus temperture

SUMMARY

Permeability and thermal properties of concrete from Launch Complex 17 of the Cape Canaveral were determined to support modeling efforts of spill and burn scenarios. Thermal properties were determined up to temperatures of 300^{o}C. Room temperature permeability of the concrete is low, with a mean value of 0.07 mD. The concrete is observed to dry with increasing temperature, with the largest decrease in weight between 100^{o}C and 150^{o}C. Thermal conductivity generally increase with increasing temperature, thermal diffusivity generally decreases with increasing temperature, and specific heat increases slightly with increasing temperature. Thermal conductivity ranges from 1.7-1.9 W/mK at 50^{o}C to 1.0-1.15 W/mK at 300^{o}C, thermal diffusivity ranges from 0.75-0.96 mm^2/s at 50^{o}C to 0.44-0.58 mm^2/s at 300^{o}C, and specific heat ranges from 1.76-2.32 /m^{3}K to 2.00-2.50 /m^{3}K at 300^{o}C.

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