Time Evolution of Hot Permeability in Sand Systems

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ABSTRACT

A hot permeability test was designed to provide time series data to examine venting characteristics in foundry sands at an elevated temperature. This was achieved by modifying the standard AFS Mold Quality Indicator (MQI) permeability tester and applying induction technology to create a hot-surface tip which is in contact with the sand specimen. This technique can be used for both green and chemically bonded sand specimens. The focus of this study was to investigate any potential deviations in permeability number of foundry sand specimens at ambient and elevated temperatures to form a correlation within the mold-metal interface and venting characteristics in foundry sand.

For each sand system in this study, the time evolution of the permeability number was measured from ambient to 500C (932F). From this time series data, the rate of change of the permeability number and an overall change in permeability number was captured by calculating a permeability index. Furthermore, Darcy's number was calculated using the permeability number and characteristic length of the sand system. This results from these tests show that as the green sand moisture (compactability) condensation layer is driven back in the specimen due to heat transfer, the permeability number changes, and its rate of change can be determined. Correspondingly, hot permeability rates of change are shown among various chemically bonded sand binder specimens at various binder levels.

The findings of this study offer an enhanced understanding of the gas flow venting in foundry sand systems. The measured time series data at elevated temperatures can provide improved information to casting simulations regarding the venting characteristics of foundry sand.

Keywords: permeability, hot permeability, sand testing

INTRODUCTION

BACKGROUND

In the foundry industry, permeability is the property of a molding material to allow the passage of mold/core gases during the filling of molten metal. AFS permeability is the rate at which 2000 cm^3 of air passes through an AFS standard specimen with a head pressure of four inches (10 cm) of water. Gases vent readily through green sands with high permeability.[1] Many factors can affect permeability, but the compaction and sand grain fineness are important variables.

The higher the density to which the sand is compacted, the lower the permeability because the sand grains are forced tightly together, leaving smaller voids between the grains through which air can pass. The grain fineness and distribution of the base sand is another important factor. The finer the sand, the lower the permeability; again, because the voids between the sand grains are smaller.[2]

The degree of mulling also influences permeability because it affects the distribution of the clay and additives on the sand grain. Usually, the higher the degree of mulling, the higher the permeability of the sand.
Low permeability produces a smoother casting surface finish because the voids between the sand grains are smaller. Low permeability, however, increases the likelihood of problems with blows, pinholes and other gas-related defects. Low-permeability sands as a result of the high packing density will produce expansion defects.

The AFS permeability provides a relative measure of the venting characteristics of the green sand. The test produces such a relative number since it determines the time required for a given amount of air, at a standard pressure and at room temperature, to pass through a standard specimen. This relative test shows that permeability is determined by the size of the pores, not by the total quantity of voids. Since large sand grains produce large pores, permeability varies directly with grain size.[3] The additives in green sand are water, Bentonite clay premix and other carbonaceous materials. Furthermore, adequate venting in metalcasting remains a relative term, since it must vary with the quantity of gas produced. However, the gases are produced during molten metal filling. High-temperature alloys will produce a greater volume of gas for the same levels of moisture or organics in the sand. The AFS permeability does not consider this state.

The AFS permeability test was designed primarily for use with green sand specimens.[3] Today chemically bonded precision sand systems are widely used in gravity sand and semi-permanent mold casting processes. In an ambient foundry environment, chemically bonded sands are rigid mold systems. The chemically bonded sands can be either an organic or inorganic binder formulation. Though these binders allow the production of complex internally cored cavities and thin wall sections. There remains no standard permeability test for use with chemically bonded sand.

GAS FLOW IN FOUNDRY SANDS

Gases are produced in green and chemically bonded sand molds from the heat of the molten metal. The water in the mold produces steam and the carbonaceous materials in the sand produce other gases. A requisite of foundry sand systems is adequate porosity. Porous media such as green and chemically bonded sand contains open spaces or voids between the grains. Green and chemically bonded sands can be defined as a system of interconnected pores with resistance to gas flow so low that the pressure of the gas generated in the mold cavity is never higher than the metallostatic pressure of the liquid metal. Gases under pressure always tend to travel to a lower pressure area and always take the path that offers the least resistance. If it is easier for the gas to bubble through the liquid metal than to travel through the pores in the sand, the gas will take the easier route.

As air in a mold is heated and increases in volume, an organic binder decomposes to gaseous products. These gases must be vented away from the mold cavity. The greater the super-heat temperature of an alloy, a greater gas volume may develop, and more venting is needed. Much of the gas can escape through risers and vents in the mold. Foundry engineers are trained in venting strategies for producing defect-free castings. Any excessive fines in the sand system should be considered impurities that reduce permeability and necessitate more bond for adequate handling strength.

Selecting raw sand is usually a compromise between small grains for the required surface finish and large grains for the necessary permeability. A sand might have adequate permeability when rammed to a density of 85 lb/ft^3 and be the opposite when rammed to a density of 95 lb/ft^3. Pore size can also be varied by the intensity of compacting. Chemically bonded sand, regardless of its grain size and distribution, has a natural minimum size of void. Increasing binder level could easily change the permeability of a given chemically bonded sand system from adequate to inadequate.

Large grains are desirable because of the free-venting properties they provide in the sand. They also have a low surface-area-to-volume ratio and thus require less bonding material to coat all their surfaces. Finer sands have smaller pores and restrict the flow of any generated gas. In addition, fine sands usually require more binder and produce more gas. On the other hand, the surface finish of the casting is impaired by large pores. The selection of raw sand therefore usually is a compromise between the venting ability desired and the surface finish required. A slight decrease in pore size or an increase in the quantity of gas generated can produce epidemics of blows. A slight increase in pore size, or a decrease in compacted density, can produce rough castings. The lack of permeability is one of the most negative aspects of utilizing higher AFS/GFN sand to improve casting surface finish. This is one reason why certain refractory coatings are introduced at the mold/core metal interface.

PERMEABILITY TESTING

Permeability testing is very common in the foundry industry and is part of the sand control tests performed on a regular basis at most foundries. In the foundry industry permeability test data is not generally provided with either incoming shipments of sand or outgoing shipments of castings. Permeability testing is as an in-process sand control test for which there is little credibility due to high variability in data and poor test reproducibility.

AFS Permeability

AFS permeability is a measure of gas flow through a porous media, such as a sand mold or core.[1] It was calculated for each specimen using Eqn. 1.

$$\text{Perm} = (V*H)/(P*A*T) \qquad \textbf{Eqn. 1}$$

Where:
Perm = Permeability Number
V = vol. air = 2000 cm^3
H = height of sand specimen = 2.0 in. (5.08 cm)
P = pressure = 10 g/cm^2
A = cross-sectional-area sand specimen = π in^2 (20.3 cm^2)
T = time, min, for 2000 cm^3 air to pass through specimen.

The formula reduces to: Perm = 3007.2/T sec. Today most foundries use electronic permmeters that are direct digital read instruments for green sand testing.

There are a few techniques that allow the measurement of permeability in chemically bonded sand. Most of which remains research apparatus and is not designed for in process testing. A technique for measuring permeability in chemically bonded sand was developed at Western Michigan University (WMU).[4] The procedures for measuring permeability in both green and chemically bonded sands are described in the Methodology section.

Darcy's Law

Permeability describes how easily air is able to move through the porous material.[5,6] Thus, it is related to the connectedness of the void spaces of the sand system. It is calculated using a formula widely known as Darcy's Law. For quality control, units of measurement may be irrelevant, but for scientific research it is essential to be able to express results in absolute units. Permeability measurements expressed in units of air flow or time cannot be compared directly with pore dimensions. For this reason, there is a need for calculating permeability results in absolute units.

Current equations describing fluid transport in porous media are based on semi-empirical equations derived in the 19th century by Darcy, for single-phase flow and in the 20th century for multi-phase flow. These equations describe the average behavior of a mixture of a porous medium and one or more fluids. Darcy's Law (Eqn. 2) describes the kinetics of fluid flow through porous media in terms of the driving force and the permeability of the medium.[5,6]

$$Q = (K*\Delta P*A)/(\Delta L*\eta) \qquad \textbf{Eqn. 2}$$

Where:
Q = flow rate (m^3/s)
K = permeability, (m^2)
ΔP = pressure drop or difference, (Pa)
ΔL = flow length or thickness of test sample, (m)
A = area of cross-sectional area to flow, (m^2)
η = fluid viscosity, (Pa-s)

The permeability coefficient K depends on the combination of the fluid and porous material used. The greater the value of K, the higher will be the rate of flow of a fluid through a material. When the differential form of Eqn. 2 is nondimensionalized, one obtains the Darcy number, $D_a = K/d^2$, where d is the characteristic length of the sample. The Darcy number thus captures the relative impact of the permeability of a medium versus its characteristic length, such as the diameter of particles in the medium. Due to its non-dimensionality and origin in differential hydraulic flow equations, the Darcy number has potential value in casting simulation tools.

While Darcy's equation was formulated from experimental data over a century ago, it was only recently proved theoretically. By means of the reasoning of irreversible thermodynamics, Mokadam was able to derive a general equation for flow through porous media.[5,6] He further demonstrated that Darcy's equation was a special case of this general relationship. It may therefore be stated that Darcy's equation is a theoretically and experimentally valid law in the flow regime known as viscous or laminar flow.[5,6]

Darcy's equation cannot determine the permeability of cores and molds accurately. Forcheimer's equation better predicts gas flow rates through typical foundry molds, cores, and coatings. Forcheimer found that the flow rates of gas through a porous media were lower than those predicted by Darcy's equation due to momentum loss from gas particles colliding with the pore walls. In Forcheimer's flow regime, the gas velocities are large enough, which should be considered. More detailed descriptions on Darcy's and Forcheimer's flow can be found in the Reference section.[5,6]

The researchers believe that is an area that needs additional studies beyond the current quest for a hot permeability number. The intent is to develop a test to discriminate between the venting characteristics of a sand binder system at ambient and elevated temperatures, but we believe there is more room for research into the physics that can provide the apparatus for these further investigations.

HOT PERMEABILITY OBJECTIVE

In 2018, Ramrattan et al. described a Hot Permeability Test in *AFS Transactions* Paper 18-037.[4] A limitation of the hot permeability test device was that only autonomous digital data was read. This paper presents arguments and provides time series data for a more meaningful approach to permeability testing in the foundry industry. The new hot permeability test provides a rate of change measure for venting in both green and chemically bonded foundry sands at an elevated temperature. The new permeability data can prove to be beneficial to foundry engineers and solidification simulation developers alike.

METHODOLOGY

This work was divided into two tests: (1) a method for the calculation of a hot permeability index on standard green sand specimens, and (2) a method for the calculation of a hot permeability index on chemically bonded disk-shaped specimens. The permeability tests were performed to provide a measure of the specimen's venting characteristics at an elevated temperature of 932F (500C).

FOUNDRY SAND SYSTEMS

Preparation of Green Sand

It was important to keep the bonding formulation simple to reduce potential errors in preparing the green sand batch and simplifying the analysis. Apart from sand, clay, and water; no additives were introduced to the green sand systems used in this study. Compactability was monitored continuously, while water additions were raised or lowered to produce the 35% target compactability. The sand was not discharged until the compactability was on target. Thus, the green sand systems used in this study were tempered to a desired compactability and tested.

The silica base aggregate (olivine sand, 60 GFN, 3 screen) used in the study came from a working foundry in Michigan. The green sand system used 6.0% Southern Bentonite BOS (methylene blue clay was 5.5%), and water added to produce the desired compactability.

Chemically Bonded Sand

In the present work, 2% shell hot-box AFS disc-shaped specimens of silica (SHL_S) and ceramic (SHL_C) were fabricated. Additionally, disc-shaped specimens of phenolic urethane amine cold box produced in industry at two binder levels 1.4% ($PUCB_{1.4}$) and 0.9% ($PUCB_{0.9}$) were shipped to WMU. Table 1 identifies the chemical sand binder systems utilized in this study along with the related thermophysical properties. Specimen fabrication techniques are documented.[7,8]

Note: All sand specimens were tested in laboratory conditions. Ambient conditions were controlled: temperature at 20C ± 1°C (68F ± 1.8°F) and relative humidity at 50 ± 2%.

HOT PERMEABILITY—GREEN SAND

The purpose of this test procedure is to compare the venting characteristics between ambient and elevated temperature in a standard green sand specimen.

Note: Standard AFS 2020 specimen preparation should follow procedure AFS 5220-05-S.[8]

Safety

- Use safety glasses and gloves. Refer to the chapter in Reference 8 on Safety.

Equipment/Materials Required

- Disa George Fisher Mold Quality Indicator (MQI) (AFS 5224-03-S).[8]
- Standard green sand specimen tube
- Induction heating source
- Digital balance

Test Procedure

1. Record the mass (g) of the green sand specimen.
2. Fix the green sand specimen tube (Fig. 1) onto the MQI.
3. Place the specimen on top of a 20-mm diameter hot-surface (Fig. 2), such that the specimen makes symmetrical contact with the hot-surface.
4. Begin the test recording the measured permeability at ambient.
5. Heat the hot-surface up to 500C (932F), continuously measuring the permeability as the hot-surface heats up to the target temperature.
6. After 7 minutes, turn the hot-surface off and continue to measure permeability for an additional minute.
7. Calculate permeability index using Eqn. 3, and Darcy's number from Eqn. 4.

Figure 1. Green sand at ambient in 80 mm tall tube for permeability testing.

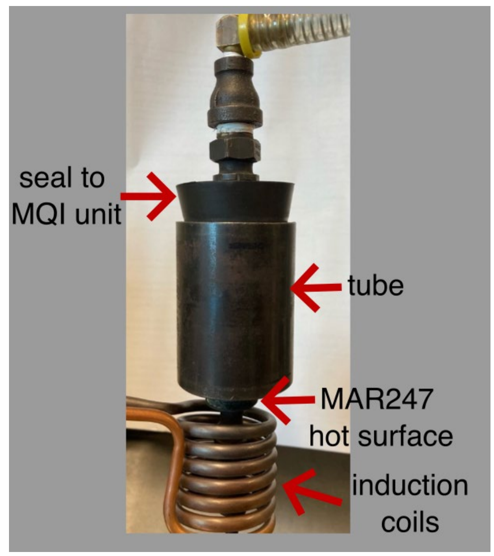

Figure 2. Permeability measurement of green sand at ambient and elevated temperature.

Calculation

The permeability index as shown in Eqn. 3 was modified using a change in time from the original Hot Permeability test.[4,8]

$$\text{Perm. Index} = [A_P - H_P]/\Delta T \qquad \textbf{Eqn. 3}$$

Where:
Perm. Index = Permeability Index
H_P = Hot permeability number, (#)
A_P = Ambient permeability number, (#)
ΔT = Length of time to transition from A_p to H_p, (min)

$$Da = (Perm*\mu*1.02*10^{-6})/(d^2) \qquad \textbf{Eqn. 4}$$

Where:
Da = Darcy Number
Perm = Permeability Number
μ = dynamic viscosity of air (kg m^{-1} s^{-1})
d = average characteristic diameter of sand (m)

HOT PERMEABILITY— CHEMICALLY BONDED SANDS

The purpose of this test procedure is to compare the venting characteristics between ambient and elevated temperature in a in a disc-shaped specimen.

Note: Specimen preparation should follow procedure AFS 3343-00-S.[8]

Safety

- Use safety glasses and gloves. Refer to the chapter in Reference 8 on Safety.

Equipment/Materials Required

- Disa George Fisher Mold Quality Indicator (AFS 5224-03-S).[8]
- Custom sample holder for disc-shaped specimens
- Induction heating source
- Digital balance

Test Procedure

1. Record the mass (g) of the disc-shaped specimens.
2. Secure the specimen into the specimen holder (Fig. 3).
3. Fix the specimen holder onto the permeability tester (Fig. 4).
4. Place the specimen on top of a 20-mm diameter hot-surface (Fig. 4), such that the specimen makes symmetrical contact with the hot-surface.
5. Begin the test recording the measured permeability at ambient.
6. Heat the hot-surface up to 500C (932F), continuously measuring the permeability as the hot-surface heats up to the target temperature.
7. After 7 minutes, turn the hot-surface off and continue to measure permeability for an additional minute.
8. Calculate permeability index using Eqn. 3, and Darcy's number from Eqn. 4.

Figure 3. Disc-shaped specimen inside specimen holder.

Calculation

The permeability index is calculated by using Eqn. 3 and Darcy's number is calculated by using Eqn. 4.

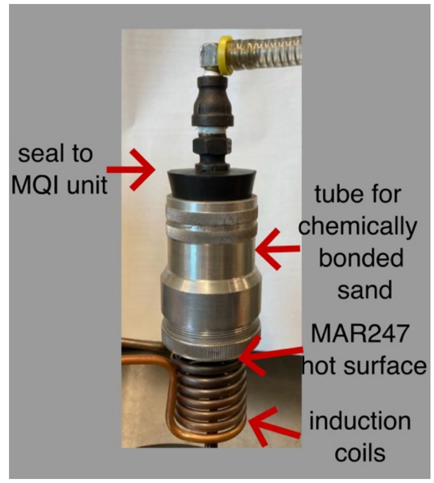

Figure 4. Permeability measurement of chemically bonded sand at ambient and elevated temperatures.

RESULTS AND DISCUSSION

A Disa George Fisher Mold Quality Indicator tester was used to perform the permeability tests conducted in this experiment. However, modification to the equipment and a specialized specimen holder was designed and fabricated at WMU. Additionally, a plug was used to restrict the airflow in order for the Disa George Fisher machine to detect the permeability in chemically bonded disk-shaped specimens. The permeability was measured at both ambient temperature and at an elevated temperature and the permeability index was calculated.

To test if the 20mm hot surface would impact the permeability measurement, at ambient temperature the permeability of a standard green sand specimen was measured with and without a penny (20 mm diameter) on the surface of the standard specimen (as shown within Fig. 1). The permeability measurement did not change between the two tests, meaning the 20 mm diameter object place on the surface of sand specimen will not impact the resulting permeability measurement. There is a scientific explanation for this fact. Consider air as the fluid flowing steadily through the permeability tester; there is a relationship between area (A) and velocity (v). As the bell drops on the permeability machine; at the nozzle, the exit velocity increases as per the "continuity equation" (Eqn. 4).

$$A_1v_1 = A_2v_2 = \text{a constant} \qquad \textbf{Eqn. 4}$$

Figure 5 shows two cross sections, A and B of different areas, A1 and A2, respectively. The velocities at these two different points are v1 and v2 respectively. The volume that flows through any point of the system in a given duration is the same. In other words, where the area is smaller, the velocity is higher.

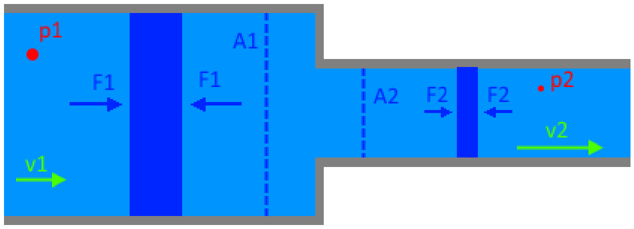

Figure 5. The Law of Continuity.

A relationship between pressure and velocity as given by Bernoulli's principle (Eqn. 5) shows how pressure and velocity are inversely proportional. In the scenario where air flows into a narrower cross section, the pressure decreases as the velocity increases.

$$P+\frac{1}{2}\rho v^2+\rho gh = C\text{, a constant} \qquad \textbf{Eqn. 5}$$

It can be seen from the above that, the more the velocity, the lesser the pressure. Pressure is inversely proportional to velocity, so there is lower pressure at the exit of the nozzle. When there is a change in cross-sectional area: $A_2<A_1$; implying $v_2>v_1$ and $p_2<p_1$. When the penny is placed on the green sand specimen there will be no change in permeability numbers. Consequently, air flows faster around the penny while the air flow rate remains constant.

The permeability of green sand and chemically bonded sand is affected by several factors including the size, shape, distribution, and the method of compaction of the sand in the mold or core box. Hot permeability reduces the permeability number in foundry sands. The various amounts of moisture, clay and organic additives in green sand are affected by heat to restrict permeability. Figure 6a shows that permeability number drops from 114 at ambient to 101 at the elevated testing temperature in the same green sand sample. This drop in the permeability number is most likely caused by the green sand moisture (compactability) condensation layer being driven back in the specimen due to heat transfer. Figure 6b, which shows the rate of change in the permeability number of the green sand over the testing time, indicates that this occurs rapidly over an approximately two-minute time frame and then remains relatively stable after this initial period of change in the permeability number. Correspondingly the green sand sample had the largest permeability index of any sand sample tested (Table 1).

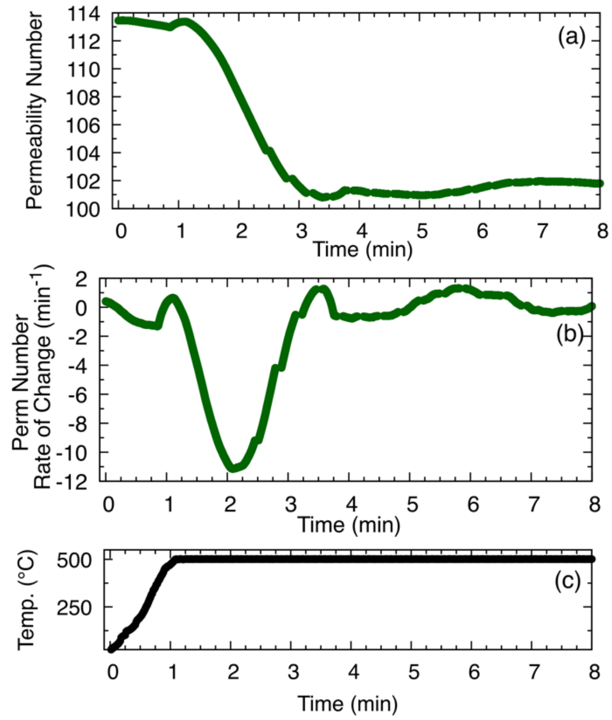

Figure 6. (a) Permeability number measured from ambient to elevated temperature on a green sand specimen. (b)The calculated rate of change of the permeability number for the green sand sample over the entire testing time. (c) The temperature of the hot surface throughout the test.

Elevated temperature testing of chemically bonded sands also showed reduced venting. This reduction in venting can be caused by secondary polymerization at binder bridges may soften to restrict venting from ambient to elevated temperature (Table 1). For the $PUCB_{0.9}$ and $PUCB_{1.4}$ samples the permeability numbers changed at a slower rate compared to the green sand sample. Both PUCB samples reach the same minimum permeability number, but at different times (Fig. 7). Over the first four minutes the lower binder level sample ($PUCB_{0.9}$) initially had a slower rate of change than the higher bind level sample ($PUCB_{1.4}$). However, after approximately four minutes the rate of change of the permeability number leveled off in the higher binder level sample but continued in the lower binder sampled. This fact is captured in the permeability index, with the $PUCB_{0.9}$ sample having a higher permeability index than the $PUCB_{1.4}$ sample (Table 1). This result shows that in chemically bonded sand the amount of resin binders has impacts on the permeability at elevated temperatures.

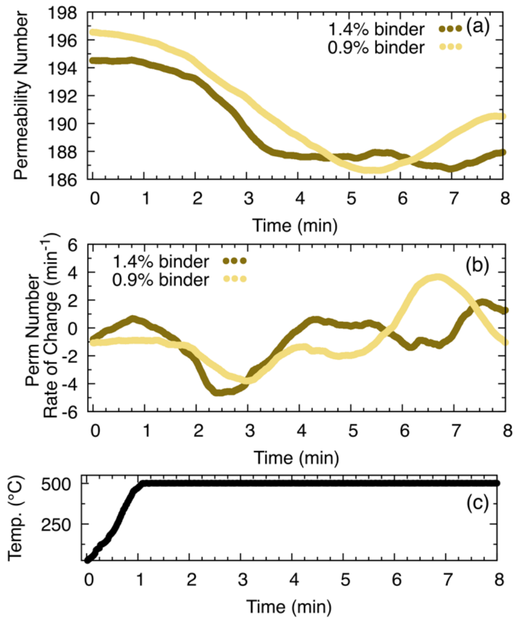

Figure 7. (a) Permeability number measured from ambient to elevated temperature on silica PUCB specimens. (b)The calculated rate of change of the permeability number for the PUCB specimens over the entire testing time. (c) The temperature of the hot surface throughout the test.

The type of sand used in chemically bonded sand-binder systems can also have an impact on the permeability number at elevated temperatures. Figure 8 shows the time evolution data for the hot permeability of silica and ceramic shell sands with the same binder levels. The ceramic sand initially has a slower rate of permeability number change over the first two minutes compared to the silica sand. However, past this time the silica sand's rate of change of the permeability number slows as the permeability number of the silica sand stabilizes, while the ceramic sand's permeability continues to decrease over the entire testing time. This difference in behavior between the two sands leads to a higher permeability index for the ceramic sand compared to the silica sand (Table 1).

In addition to the permeability index that was calculated for each sand sample investigated with the hot permeability test, the test provided the opportunity to determine the property of the sand-binder system instead of a characteristic. Combining the permeability measurements with the measured average particle size of the sands, a Darcy number was calculated at both ambient and elevated temperatures for all samples (Table 1). However, further work is needed to understand how this measured property can be correlated to casting quality.

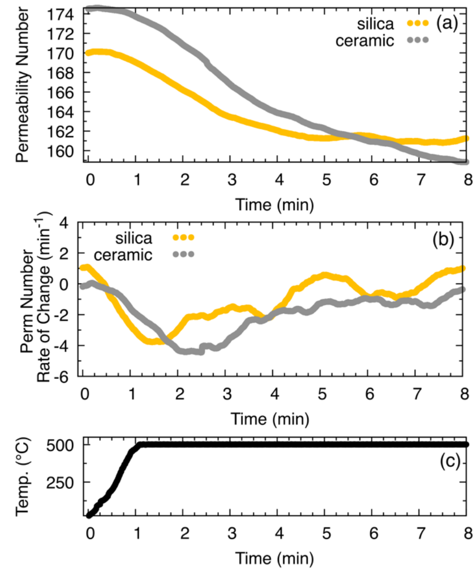

Figure 8. (a) Permeability number measured from ambient to elevated temperature on silica and ceramic shell sands. (b) The calculated rate of change of the permeability number for the silica and ceramic shell sands over the entire testing time. (c) The temperature of the hot surface throughout the test.

CONCLUSIONS AND RECOMMENDATIONS

This work shows there is the potential for hot permeability as a new testing technique for both green and chemically bonded sand specimens used in the foundry industry. There was permeability drop from the ambient to heated specimens. During hot permeability testing of either green or chemically bonded foundry sand specimens the permeability number generally diminishes. Venting characteristics of the foundry sand become more restricted at elevated temperature. As the green sand moisture (compactability) condensation layer is driven back into the specimen due to heat transfer; the permeability number and resulting index decreases. Correspondingly, hot permeability differences are shown among various chemically bonded sand binder specimens at various binder level. As certain sand binder systems experiences heat a secondary polymerization can ensue where binder bridges soften and block the interstitial spaces of sand grains reducing permeability.

This paper introduced an enhanced testing approach where elevated temperature gas flow venting measurement in foundry sands can be investigated. It is recommended that further testing be carried out in working foundries where sand system data and gas defect data can be related. More testing with larger sample sizes must be undertaken to show if the differences between ambient and elevated temperate measures are significant. A more comprehensive study will determine the optimal temperature and time needed for hot permeability testing as a new process control tool.

Table 1. Hot Permeability Data on Green and Chemically Bonded Sands

Process	Sand Type	AFS-GFN [screen]	Binder Type	Binder Level (%)	Ambient Darcy number	Hot Darcy number	Ambient Perm. (#)	Hot Perm. (#)	Perm. Index
Green Sand	Olivine	60 [3]	Ca Bentonite	5.5	0.0809	0.0719	113	101	3.82
$PUCB_{1.4}$	Silica	60 [3]	Phenolic Urethane	1.4	0.1736	0.1667	194	187	1.26
$PUCB_{0.9}$	Silica	60 [3]	Phenolic Urethane	0.9	0.1754	0.1666	197	187	1.79
SHL_S	Silica	79 [3]	Shell hot-box	2	0.2252	0.2129	170	161	1.27
SHL_C	Ceramic	82 [3]	Shell hot-box	2	0.2847	0.2588	175	159	1.90

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