

Real Time Measurement of Mold and Core Quality in Chemically Bonded Sands

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ABSTRACT

This study presents a preliminary method to assess and predict the quality of chemically bonded sand molds through the use of embedded sensors. Utilizing miniature hardware, critical variables were measured and used as indicators of curing progression, ultimately predicting the 24-hour transverse strength of phenolic urethane nobake and furan nobake sand systems. Employing Analysis of Variance (ANOVA) and regression analyses, significant correlations were established between sensor data and strength prediction. This approach, if integrated into production, offers real-time evaluation with the potential to be automated by machine learning. While acknowledging the study's limitations, this research introduces an innovative strategy for optimizing molding outcomes in the foundry industry through wireless, sensor-based monitoring.

Keywords: Industry 4.0, chemically bonded sands, molds, sensors, Industrial Internet of Things (IIoT)

INTRODUCTION

Today's foundry professional faces a diverse selection of chemical binders in their daily operations. Since the 3rd industrial revolution, the introduction of new chemical binders has often resulted in enhanced productivity, improved integrity of the mold-metal interface, and superior cast surface quality. However, achieving high-quality castings with these chemical binders requires careful matching to specific applications and operating conditions. Each foundry operation is characterized by a unique combination of production factors, such as part size, alloy type, sand type, or even environmental conditions. Consequently, selecting the optimal binder system and determining the production factors that must be effectively controlled to utilize these binders poses a nuanced challenge for foundry professionals. Even once controllable parameters are defined and managed to a reasonable extent, normal variance in the foundry process can yield suboptimal results in the molding room. In this study, curing effectiveness of modern phenolic urethane

and furan binder systems will be covered, but first, a discussion of these chemical binders and their development over time is in order.

REVIEW OF NOBAKE BINDER SYSTEMS

A review of traditional nobake binder systems has been covered in previous research,¹ but the nobake sand molding concept originated in Europe and was first introduced to the American metalcasting industry in the early 1950s. These binders were comprised of drying oils, such as linseed or vegetable oils, and could air set at room temperature relatively quickly when accelerated by metallic dryers and/or oxidizing agents like sodium perborate ($\text{NaBO}_2 \cdot \text{H}_2\text{O} \cdot 3\text{H}_2\text{O}$). The mixes utilizing these binders typically exhibited low green strength, and often required minimal compaction to densify the sand mix in a pattern. While they were promoted as capable of being cast after air curing, achieving full strength development often required baking these resins.

After this preliminary system was tried, the first true air set systems were developed and were popularized under the name, acid-catalyzed furan binders in the late 1950s. Furan binders, which are typically urea-modified furfuryl alcohols, are thermosetting and incredibly reactive at room temperature when introduced to various acids. The reaction is condensation based with the main byproduct being water. Proper acid catalysts include phosphoric acid, toluene sulfonic, and benzene sulfonic acid, or blends thereof. The strength and quantity of these activators change the speed of the condensation reaction. Furans have changed significantly in modern times due to their popularity as binder for additive manufacturing of sand molds and cores.

The urethane family of chemical resins was introduced to the foundry industry in the mid-1960s. The first urethane system was the alkyd-isocyanate based nobake binder. This particular binder undergoes a two-stage curing process. In the initial stage, a urethane reaction takes place between the alkyd and an isocyanate resin, facilitated by a metal-ion catalyst, to achieve sufficient strength for stripping. Subsequently, in the second stage, the alkyd resin crosslinks by reacting with oxygen from

the atmosphere, resulting in up to three times the strength obtained from the prior urethane reaction. Metal dryers expedite this second stage oxidation and accelerate the overall curing process.

The second type of urethane nobake binder, developed in 1970, is known as the phenolic-urethane system.² Curing occurs through the reaction of a phenolic polyol with a polymeric isocyanate in the presence of a base catalyst. This system exhibits excellent properties with most molds or cores attaining rapid strength and becoming pourable within an hour after stripping. It offers flexibility in strip times, ranging from less than one minute up to 15 minutes, which enables seamless integration into high-speed, high-production core or mold making lines.

Other air set chemical resins exist such as: self-setting inorganic binders^{3,4} and acid-catalyzed phenolic resins.⁵ These are both useful systems for specific applications and will not be covered extensively in this review due to this study's emphasis on phenolic urethane and furan binder systems.

EMISSIONS FROM FOUNDRY BINDERS

These developments in chemical binders have led to widespread adoption throughout the foundry industry; however, this led to some concerns from governing bodies about environmental pollution. This became a notable issue in the 1990's with several publications outlining the hazardous emissions problem in the metalcasting industry.^{6,7} During casting processes, binders undergo pyrolysis and release hazardous air pollutants and volatile organic compounds (VOCs) into the atmosphere. There have been significant efforts to reduce foundry environmental impact such as the work completed by the Casting Emissions Reduction Program (CERP)⁸ which developed standardized practices for measuring the nature and abundance of gaseous species emitted from foundry molds during casting.

In parallel, the Ohio Cast Metals Association (OCMA) developed a laboratory-scale test that offered results for VOC emissions during mold production including both mixing and storage practices.⁹ This test method involved estimating the total VOC emissions from a sand mixture by tracking the weight loss over a specific duration, similar to other mass balance techniques. Although this method provided a cost-effective alternative to more advanced approaches like thermogravimetric analysis, it was restricted to a single numerical value as the outcome, specifically the total weight loss following a typical 12-hour curing period. Later, Roush & Tse improved the original OCMA method by modifying the equipment used.¹⁰ The new procedure utilized an electronic balance

with an integrated data acquisition system. The data acquisition device collected the mass of the curing sand sample from the scale automatically and recorded it with a computer. This allowed the results to be displayed as a function of time and provided some indication of curing effectiveness in chemically bonded sand. The main purpose of this test, however, was to demonstrate how chemical binders could be modified to reduce emissions during molding practices.

CURING EFFECTIVENESS OF CHEMICALLY BONDED SANDS

Ensuring optimal curing conditions for chemical resins is an essential consideration for achieving repeatable performance on the molding line. Unfortunately, accurately assessing the curing conditions, and thereby the curing effectiveness, has been a challenging task. Destructive testing to measure mechanical strength of sand molds using representative, standard samples can be utilized. Typically, mechanical strength is measured in four time intervals after the creation of a mold or core, with the most important information being the strength at the exact time when metal is poured in the mold. With modern production speeds in the realm of hundreds of molds per day, a fully traceable system from tensile specimens, or the OCMA test, to individual molds is infeasible.

To overcome these limitations and enhance the traceability of the chemically bonded sand process, there is a growing need for innovative monitoring techniques that enable continuous and precise evaluation of sand molds prior to pouring. In recent years, embedded sensor technologies have emerged as promising tools for real-time evaluation of industrial applications, usually referred to as the Industrial Internet of Things (IIoT). By introducing sensors within chemically bonded sand molds as they cure, it becomes possible to capture critical parameters, such as temperature, humidity, and volatile organic compound emissions, which is hypothesized to be linked to mechanical strength development of foundry resins.

The purpose of this paper is to present a preliminary study on the application of embedded sensors for measuring the curing effectiveness of chemically bonded sand molds. The goal is to explore the potential benefits of this technology in terms of predicting mechanical strength of sand molds in a non-destructive manner. This study will investigate the phenolic urethane and furan nobake binder systems, with an emphasis on prediction of 24-hour ultimate transverse strength as the response variable attributing to mold quality.

EXPERIMENTAL METHODOLOGY

It is widely known that sand temperature and moisture have a significant impact on the mechanical property development of chemically bonded sands. As such, two matrices were developed to manipulate the curing process in small batch mixing trials. These matrices are a classic 2² high/low factorial design, with each matrix consisting of four individual testing series. The first of the two experimental designs, focusing on the phenolic urethane binder testing, is shown in Table 1.

Table 1. Experimental Matrix for Phenolic Urethane Binder Testing

Experiment #	Sand Temperature	Moisture (%)
1	20C (68F)	0
2	20C (68F)	0.25
3	38C (100F)	0
4	38C (100F)	0.25

The second matrix focused on furan binder testing and is displayed in Table 2. Similarly, to the first matrix, sand temperature and moisture were manipulated in accordance to the experiment number. In these experiments, the sand temperature was reduced instead of increased due to the sand curing so quickly that the sensors couldn't be embedded in time.

Table 2. Experimental Matrix for Furan Binder Testing

Experiment #	Sand Temperature	Moisture (%)
1	16C (60F)	0
2	16C (60F)	0.25
3	24C (75F)	0
4	24C (75F)	0.25

To facilitate data acquisition, a microcontroller equipped with two sensors was developed. The ESP12F microcontroller utilized Arduino programming language. The embedded software contained the necessary libraries to activate the BME680 environmental sensor and SGP40 VOC sensor. These sensors were connected to the microcontroller by "I²C" protocol and data was acquired from the sensors at a frequency of 8 seconds. This system allowed for measurement of environmental temperature, relative humidity, and volatile organic compounds. The SGP40 has an inherent limitation in the VOC measurement based on the environmental conditions. Over time, water molecules will bind to the sensing area, causing readings to drift. To eliminate drift, the SGP40

includes a humidity compensation function by reading environmental conditions and mathematically removing the influence of humidity. Therefore, the humidity data collected from the BME680 sensor was substituted into the compensation function of the SGP40 sensor to eliminate drift in the VOC reading. The total amount of VOCs emitted was estimated for each experiment using the trapezoidal rule, which approximated the area under the curve.

Additional calculations were conducted using the data collected from the BME680. The dew point temperature is the temperature that air must be cooled to reach the saturation limit of water vapor in isobaric conditions. Upon reaching the dew point, airborne water vapor condenses to form dew or fog. Thus, the dew point provides an absolute measure of water vapor in the environment rather than a measure relative to the temperature of the environment. The temperature and relative humidity responses were used to approximate the dew point (Dp) using the Magnus formula, as seen in Equation 1.

$$Dp(T, RH) = \frac{\lambda \cdot \left(\ln\left(\frac{RH}{100}\right) + \frac{\beta \cdot T}{\lambda \cdot T} \right)}{\beta - \left(\ln\left(\frac{RH}{100}\right) + \frac{\beta \cdot T}{\lambda \cdot T} \right)} \quad \text{Eqn. 1.}$$

Where:

T = the temperature response from the BME680 sensor (°C);

RH = relative humidity response from the BME680 sensor (%);

λ and β = appropriate constants (243.12C and 17.62 respectively).

Small batch mixing trials were conducted in accordance with the experimental variables described in the factorial matrices. All tests utilized commercially available materials, including round grain silica sand with a grain fineness number (GFN) of 65, a phenolic urethane nobake binder (PUNB) system, and a furan nobake binder system typically utilized in 3D sand printing applications. The PUNB experiments were conducted using 1% total binder based on the sand weight and a 55:45 P1:P2 ratio. Catalyst content was controlled at 4% binder based on the weight of part 1. The FNB trials utilized 1.25% resin based on the weight of the sand and 20% activator based on the weight of resin. Constituents were mixed using a stand mixer for 60 seconds and the batch was flipped between mixing cycles to ensure a homogenized sample. After mixing a specified experiment, the SGP40 and BME680 sensors were embedded in the curing sand for 24 hours.

Additional replicates were mixed and used to create 8" x 1" x 1" (203.2mm x 25.4mm x 25.4mm) transverse bars. The strength of these bars was measured 24 hours after strip time using a Simpson Electronic Universal Sand Strength machine with appropriate settings.

Finally, statistical analysis was performed on the experimental data using IBM-SPSS including the calculation of descriptive statistics, regression analysis, and analysis of variance (ANOVA). The response variable in the statistical analysis was the transverse strength of the sand specimen after 24 hours of curing, with input variables being the moisture additions and sand temperature, which was manipulated with the design of experiments approach. ANOVA uses a hypothesis-based method to compare experimental variances and thereby attributes variance either to normal or random error versus experimental influence. The ANOVA was conducted using a confidence level of 95%. In this case, acceptance of the null hypothesis would indicate that the strengths of chemically bonded sand were not directly influenced by the experimental variables. If the null hypothesis was rejected, then the experimental variables significantly influenced the outcome, that being the strength of the sand sample.

RESULTS AND DISCUSSION

In the results section, the measurements for both phenolic urethane and furan binder systems were interrogated using the aforementioned statistical methodologies. All charts and relationships provided were statistically significant at $\alpha = 0.05$. Additionally, the null hypothesis was rejected when comparing means in both cases (phenolic urethane and furan binders), justifying the difference between experiments in terms of the output variable, transverse strength.

RESULTS FROM SENSOR DATA ACQUISITION Phenolic Urethane NoBake

In Figure 1, the VOC response from the SGP40 sensor is displayed for all four PUNB experiments over the 24-hour curing period. Experiment 1, conducted at room temperature and without moisture additions, produced the lowest amount of VOC emissions as a function of time. All other experiments, which had either moisture additions or elevated temperature sand, changed the emission characteristics of the batches. These changes generally resulted in higher emittance when compared to Experiment 1.

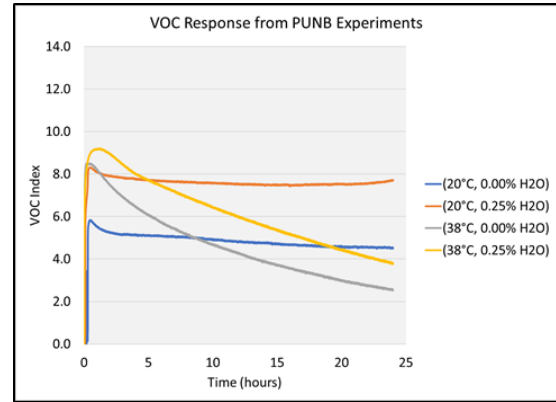


Figure 1. VOC emissions as a function of time for the phenolic urethane nobake experiments.

The total VOC for each PUNB experiment, as approximated by the trapezoidal rule, is provided in Table 3. The 1 hour and 24-hour results demonstrate the quantity of VOCs that were emitted in those specific time intervals, the ratio between them is representative of the percentage of VOCs that were emitted within the first hour versus the total. For instance, Experiment 1 emitted the least amount of VOCs in the first hour of curing, while Experiment 4 emitted the most VOCs within the first hour of curing.

Table 3. SGP40 Sensor VOC Response from PUNB Experiments

Experiment #	Total VOC		1:24 Hour VOC Ratio
	1 Hour	24 Hour	
1 (20C/68F, 0.00% H ₂ O)	4.07	115.5	3.53
2 (20C/68F, 0.25% H ₂ O)	7.14	182.17	3.92
3 (38C/100F, 0.00% H ₂ O)	8.12	111.39	7.29
4 (38C/100F, 0.25% H ₂ O)	8.54	148.07	5.76

The dew point over the 24-hour testing period is shown for all four PUNB experiments in Figure 2. In this case, the dew point was similar for most of the experiments, with the exception being Experiment 2. Experiment 2 added 0.25% moisture by weight of the sand, which clearly increased the amount of water vapor in the curing sand. Interestingly, Experiment 4, which utilized both a moisture addition and sand at 38C (100F), did not exhibit similar behavior to Experiment 2.

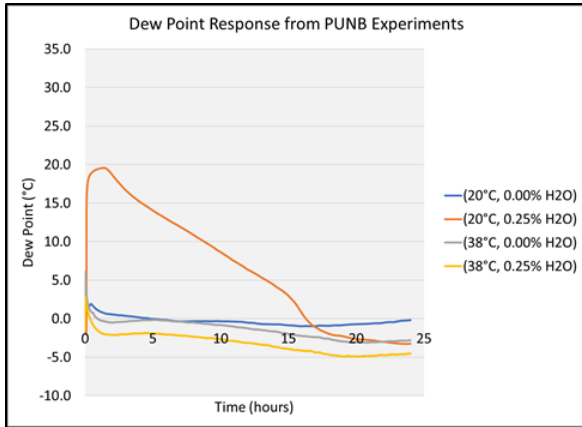


Figure 2. Internal dew point as a function of time for the phenolic urethane nobake experiments.

The average dew point for each PUNB experiment was calculated from the BME680 sensor data, which is provided in Table 4. The average dew point was calculated within the first hour and across the 24-hour time periods. Experiment 2 exhibited the highest average dew point at both 1 hour and 24 hours with a value of 16.60C (61.9F) and 6.42C (43.6F) respectively. Experiment 4 was the driest environment, as indicated by the low dew point at both 1 and 24 hours.

Table 4. BME680 Sensor Dew Point Response from PUNB Experiments

Experiment #	Average Dew Point (C/F)	
	1 Hour	24 Hour
1 (20C/68F, 0.00% H ₂ O)	1.52	-0.31
2 (20C/68F, 0.25% H ₂ O)	16.6	6.42
3 (38C/100F, 0.00% H ₂ O)	1.2	-1.41
4 (38C/100F, 0.25% H ₂ O)	-0.18	-3.21

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In Figure 3, the VOC response from the SGP40 sensor is displayed for all four FNB experiments over the 24-hour curing period. The most unique behavior was observed during Experiment 2, which was doped with 0.25% moisture. The other three experiments followed fairly consistent VOC trends over time, regardless of changes in the control variables.

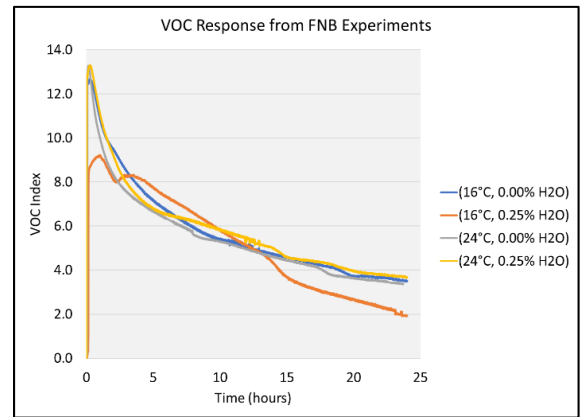


Figure 3. VOC emissions as a function of time for the furan nobake experiments.

Just as before, the total VOC for each FNB experiment was approximated by the area under the curve, as shown in Table 5. Experiment 2 released the least amount of VOCs in the two time intervals. Conversely, Experiment 4 released the most VOCs within the two time intervals. To reiterate, the 1:24 hour VOC ratio is representative of the percentage of VOCs emitted within the first hour versus the total 24-hour curing period. As expected based on the VOC data, Experiment 2 and 4 were the lowest and highest emitters respectively.

Table 5. SGP40 Sensor VOC Response from FNB Experiments

Experiment #	Total VOC		1:24 Hour VOC Ratio
	1 Hour	24 Hour	
1 (16C/60F, 0.00% H ₂ O)	11.58	137.47	8.42
2 (16C/60F, 0.25% H ₂ O)	8.81	123.61	7.12
3 (24C/75F, 0.00% H ₂ O)	10.91	128.86	8.46
4 (24C/75F, 0.25% H ₂ O)	12.33	140.28	8.79

The dew point over the 24-hour testing period is shown for all four PUNB experiments in Figure 4. Experiment 3 initially released the most water vapor, but started emitting the lowest amount of water after approximately 12 hours of curing. Experiment 1, on average, released the lowest amount of water as a result of curing. Experiment 2 showed an interesting delay in water vapor emissions compared to the other experiments.

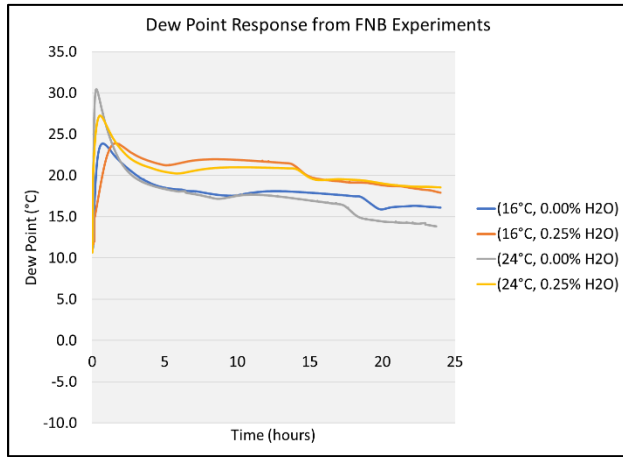


Figure 4. Internal dew point as a function of time for the furan nobake experiments.

The average dew point for each FNB experiment was calculated from the BME680 sensor data, which is provided in Table 6. The 1-hour average results show that increasing the sand temperature proportionally increases the amount of water vapor emitted. Contrarily, when moisture in the form a deionized water was added to the sand prior to mixing, there was less water vapor emitted from the curing sand. At 24 hours, the opposite behavior was observed. Experiments where no deionized water was added (1 & 3) on average were drier than those where no deionized water was added (2 & 4).

Table 6. BME680 Sensor Dew Point Response from FNB Experiments

Experiment #	Average Dew Point (C/F)	
	1 Hour	24 Hour
1 (16C/60F, 0.00% H ₂ O)	21.16	18.08
2 (16C/60F, 0.25% H ₂ O)	19.08	20.6
3 (24C/75F, 0.00% H ₂ O)	27.4	17.6
4 (24C/75F, 0.25% H ₂ O)	25.4	20.56

24-HOUR TRANSVERSE STRENGTH RESULTS Phenolic Urethane NoBake

In Table 7, the SPSS output for descriptive statistics of the PUNB specimens is provided. In this table, \bar{x} is representative of the mean transverse strength at 24 hours, σ is the standard deviation, and N is the sample size.

Table 7. Descriptive Statistics for PUNB Experiments

Moisture (%)	Temperature (C/F)	\bar{x}	σ	N
0	20C/68F	573.0	29.0	6
	38C/100F	363.0	24.4	6
	Total	468.0	112.6	12
0.25	20C/68F	501.3	47.1	6
	38C/100F	620.0	56.7	6
	Total	560.7	79.5	12
Total	20C/68F	537.2	52.9	12
	38C/100F	491.5	140.5	12
	Total	514.3	106.4	24

The resultant transverse strength measured 24 hours after strip time for all PUNB experiments can be observed in Figure 5. Error bars represent $\pm 1\sigma$ from the mean of each experiment. The specimens created from Experiment 1 showed an average transverse strength of 573psi. The strength decreased when moisture or temperature was added independently, as shown in Experiments 2 and 3 respectively; however, Experiment 4 showed an increase in strength when both moisture and temperature were increased simultaneously. This was a statistically significant interaction between the effects of moisture and temperature.

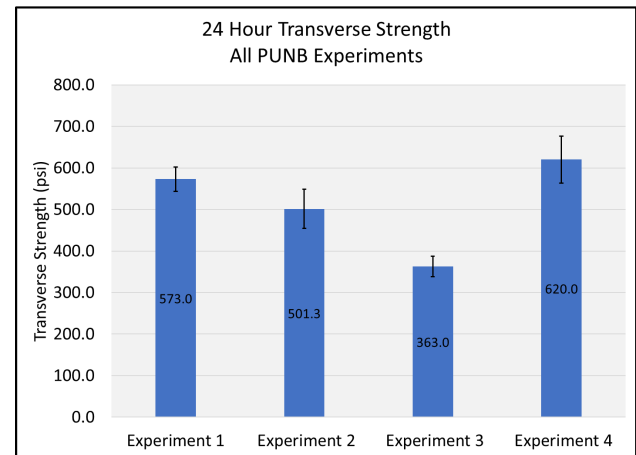


Figure 5. The 24-hour transverse strength results for the PUNB experiments.

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In Table 8, the SPSS output for descriptive statistics of the FNB specimens is provided. As stated previously, \bar{x} is representative of the mean, σ is the standard deviation, and N is the sample size. In general, the addition of

moisture during mixing decreased the resultant strength of the material from 417.5psi to 277.2psi on average. Within the temperature range tested, increasing the temperature generally increased the strength of the material from an average of 326.3psi to 368.4psi when the sand was heated from 16C (60F) to 24C (75F).

Table 8. Descriptive Statistics for FNB Experiments

Moisture (%)	Temperature (C/F)	\bar{x}	σ	N
0	16C/60F	413.5	64.8	6
	24C/75F	421.5	35.9	6
	Total	417.5	50.1	12
0.25	16C/60F	239.1	20.4	6
	24C/75F	315.3	37.4	6
	Total	277.2	49.1	12
Total	16C/60F	326.3	102	12
	24C/75F	368.4	65.6	12
	Total	347.4	86.5	24

The resultant transverse strength measured 24 hours after strip time for all FNB experiments can be observed in Figure 6. Error bars represent $\pm 1\sigma$ from the mean of each experiment. The data within the figure is representative of the average strength from each experiment individually. Experiment 3 yielded the highest strength at 421.5psi at 24 hours, while Experiment 2 exhibited the lowest strength at 239.1psi at 24 hours.

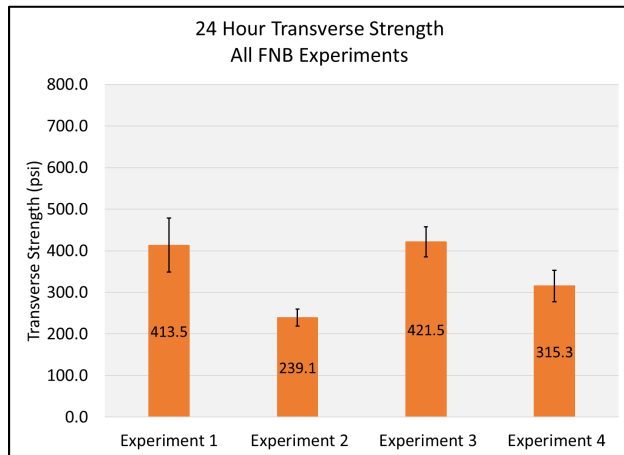


Figure 6. The 24-hour transverse strength results for the FNB experiments.

PREDICTION OF 24-HOUR TRANSVERSE STRENGTH Phenolic Urethane NoBake

The VOC and dew point responses from the sensors were then compared to 24-hour transverse strength of transverse specimens through regression analysis. A quadratic regression analysis was performed to quantify the relationship between the VOC ratio (from Table 3) as the independent variable and 24-hour transverse strength of PUNB sand as the dependent variable. The sample size was 24 samples. The ratio between the VOCs emitted within the first hour of curing and the total amount of VOCs provided a promising prediction for 24-hour transverse strength, as depicted in Figure 7. The error bars present in the figure represent $\pm 1\sigma$. The VOC ratio accounted for 79% of the variance in transverse strength, as denoted by the coefficient of determination of 0.79. The parabolic nature of this fit indicated that an optimal amount of VOC emissions can be determined by calculating the vertex. In this case, the highest strength of PUNB sand would be predicted when ~4.98% of the total VOCs are emitted in the first hour of curing.

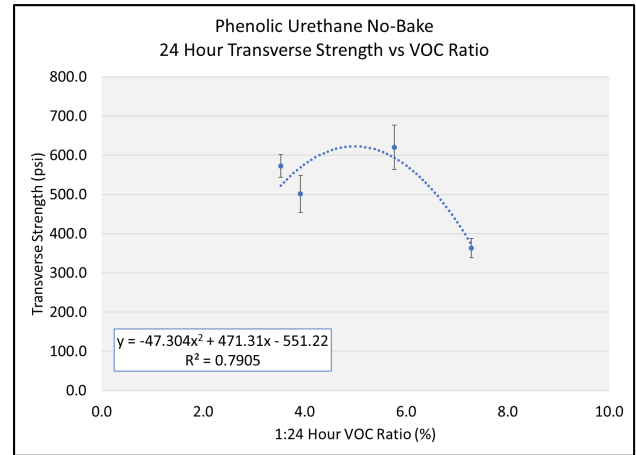


Figure 7. The 24-hour transverse strength of PUNB sand as a function of VOC emittance.

Further, the 24-hour transverse strength of PUNB sand was unable to be predicted using the dew point in a linear regression, as seen in the ANOVA table (Table 9). An insignificant relationship was defined between average dew point over the 24-hour curing period and the resultant transverse strength of PUNB sand. Thus, within the confines of the design of experiments, the dew point is not a critical variable in prediction of PUNB bonded sand strength ($F(1,22) = 0.5$; $p = 0.483$).

Table 9. ANOVA Results for PUNB Linear Regression Between Average Dew Point and Transverse Strength

Source	Type III Sum of Squares	df	Mean Square	F	p
Regression	5888.1	1	5888.1	0.5	0.483
Residual	254567.6	22	11571.3		
Total	260455.7	23			

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In Figure 8, another promising prediction equation was found when the transverse strength of FNB specimens was plotted as a function of the 1:24 hour VOC ratio from Table 5. In this case, the VOC ratio accounted for 99.4% of the variance in transverse strength, as denoted by the coefficient of determination. Similarly, to the PUNB trials, the parabolic nature of this relationship suggested that the highest strength of FNB sand is achieved by the calculation of the vertex. Within the context of these experiments, the highest strength would be achieved when 8.05% of the VOCs are emitted within the first hour of curing.

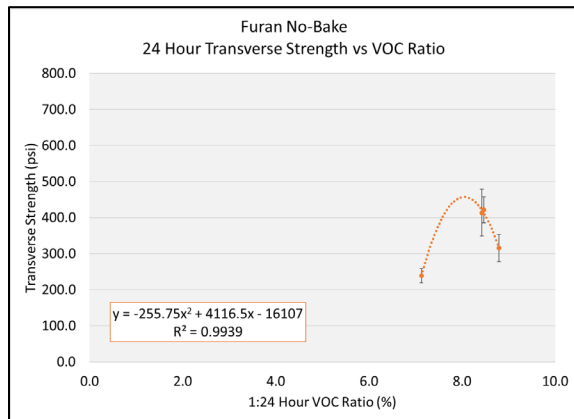


Figure 8. The 24-hour transverse strength of FNB sand as a function of VOC ratio.

In Figure 9, the 24-hour transverse strength of FNB specimens is plotted as a function of the dew point of the curing environment averaged over the 24-hour testing period. In this case, a strong linear relationship was found. The average dew point over 24 hours accounted for 87.2% of the variance in 24-hour transverse strength for the furan experiments. The equation suggested that curing of furan bonded sand is suboptimal in environments where more water vapor is present.

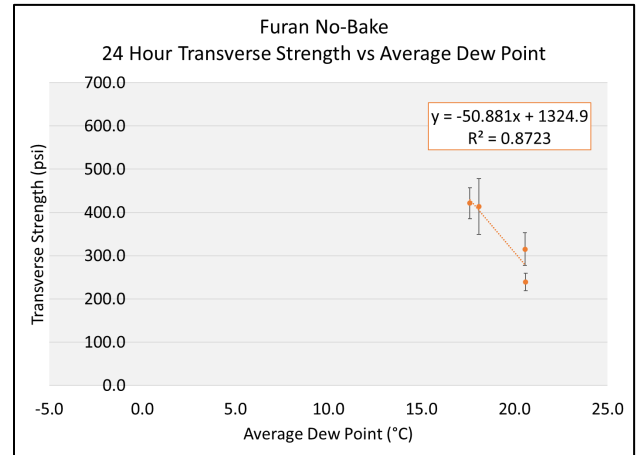


Figure 9. The 24-hour transverse strength of FNB sand as a function of the dew point of the environment averaged over the curing period.

CONCLUSION

This study has successfully demonstrated the potential of embedding sensors within chemically bonded sands as a promising non-destructive means to assess curing effectiveness. By employing the SGP40 sensor to measure the VOC ratio, we were able to predict the 24-hour transverse strength of both phenolic urethane nobake and furan nobake sand. The adoption of this approach within a production environment could facilitate the continuous collection of data, which, in turn, could be harnessed by machine learning algorithms to autonomously evaluate mold quality in real time.

Nonetheless, to unlock the full potential of this method and establish a robust correlation between sensor data and transverse strength, a more comprehensive design of experiments is recommended. Expanding the experimental design to include a 3³ factorial approach would allow for a more detailed exploration of the effectiveness of this strategy in non-destructively predicting the strength of nobake sand.

While this investigation has provided valuable insights, it's important to acknowledge the study's limitations. The current design of experiments for both binder systems consisted of only four trials, which may not fully capture the complexity and variability inherent in foundry processes. Thus, further research with a more comprehensive experimental setup would be essential to validate and refine the proposed approach.

In conclusion, this study offers a foundation for advancing quality control in foundry operations by introducing an innovative sensor-based technique for assessing mold quality. With the implementation of a more extensive experimental design, this strategy has the potential to empower foundries with the tools needed to optimize nobake sand curing processes, ensuring consistent and reproducible molding outcomes.

ACKNOWLEDGEMENTS

This research is sponsored by the DLA-Troop Support, Philadelphia, PA and the Defense Logistics Agency Information Operations, J68, Research & Development, Ft. Belvoir, VA.

The authors wish to acknowledge the efforts of University of Northern Iowa staff member Nico Costleigh and student Claire Kipp for their assistance in conducting the experiments.

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