#25-117
2025 AFS Proceedings ©American Foundry Society

Qualifying Sand Blends for Surface Quality in Iron Castings

J. Morrison & C. Lee,
Carpenter Brothers, Mequon, Wisconsin, USA

S. Ramrattan
Western Michigan University, Kalamazoo, Michigan, USA

ABSTRACT

Chemically bonded sand molding technology remains an important part of metalcasting technology because it can produce precision sand castings. However, there is a lack of information available on chemically bonded sand blends. This paper relates the physical, mechanical, and thermomechanical properties of disc-shaped specimens made from silica sands and silica sand blended with ceramic granular media.

American Foundry Society (AFS) standard disc-shaped nobake core specimens were fabricated for this research study. This paper relates the physical and mechanical properties of disc-shaped specimens made from either silica or from silica and ceramic sand blends. Specimens were laboratory tested and evaluated in a gray iron casting trial. Testing included density, impact strength, permeability, abrasion, loss, and scratch hardness. All tests were accomplished according to AFS standards.

With blended sand it was possible to produce cores and molds having superior strength, and physical properties when compared to a round grain silica sand. The chemically bonded round grain silica sand provided a good surface finish but raised surface issues at the specimen/metal interface. Certain sand blends showed fewer casting surface issues, but the surface finish was not enhanced in the same iron casting trials.

Keywords: chemically bonded sand, core binder system, disc-shaped specimen, engineered sand additive, phenolic urethane nobake

INTRODUCTION

BACKGROUND

Several constraints such as improved surface quality, the economics of molding media, as well as safety and health have forced foundry engineers to consider sand blends. In an age of engineered sand additives, smart, green, sustainable, and alternative foundry molding materials, logic prevails; a superior molding material equals a superior casting. Foundry engineers must distinguish the difference between silica and silica sand blends for cured cores and molds used in cast iron foundries. A nobake chemical binder system with round grain silica sand was compared to various silica sand blends in as-cast surface quality.

The American Foundry Society (AFS) standard disc-shaped specimens (cookie cores) were fabricated to 50 mm in diameter with 8 mm section thickness.[1] The disc-shaped specimens are used to represent cores used in an iron casting trial. The purpose of this project was to test and compare a chemically bonded round grain silica sand to various silica sand blends in properties and casting characteristics at Western Michigan University (WMU) Metal Casting Laboratory. The round grain silica sands used in this study were from the same source. The silica sand was mixed in various proportions with synthetic granular ceramic media to produce blends.

PURPOSE

With the continued improvements in North America foundry environmental emissions, a low smoke, low odor Phenolic Urethane Nobake (PU_{NB}) system was selected for this precision sand casting study. Furthermore, PU_{NB} cores and molds have found a niche with medium- to large-size iron castings because the process offers a high degree of complexity, accuracy, thin walls, and surface finish.

One of the remarkable aspects of PU_{NB} is its ability to be successfully utilized with almost any type of aggregate used in the foundry to make cores and molds. The PU_{NB} cores and molds provide the required quality casting finish with coarser, more permeable sand. The as-cast surface roughness achieved with foundry sands are neither accurately measured nor documented. A GAR (C-9) Cast Microfinish Comparator® is the standard, but the procedure is not precise, and the data is not digital. Chemically bonded foundry sands require technology commensurate with Industry 4.0 in order to render process shift. This study will show that as-cast surface characteristics can be more objectively measured by noncontact means and using technologies such as a Keyence 3D macroscope.[2]

This research focused on quantifying property data for a round grain silica sand and blends with PU_{NB} as a cured disc-shaped sand specimen. The key tests used to monitor and control disc-shaped sand specimens include:

specimen weight (density), impact strength, permeability, abrasion loss, and scratch hardness.[1] The data are provided and compared for a chemically bonded silica sand and various blended systems studied.

OBJECTIVES

- To determine the physical and mechanical cured properties and characteristics for a chemically bonded sand specimen and various blended systems.
- Qualify the as-cast surface quality characteristics for a chemically bonded sand specimen and various blended systems in a cast iron trial.

METHODOLOGY

The procedure consisted of six major steps: 1) preparation of disc-shaped specimens and weight (density), 2) impact testing, 3) permeability testing, 4) abrasion testing, 5) scratch hardness testing, and 6) casting trial [surface defect model]. All specimens were prepared and tested at WMU, Metal Casting Laboratory. All testing procedures followed AFS standards.[1] Twelve specimens were tested for each set of data. After laboratory testing was completed iron casting trials were conducted to investigate any specimen metal interfacial issues.[3,4] Ambient conditions were controlled where the temperature was at 20 ± 1□C (68 ± 1.8□F) and relative humidity was at 50%+/-2.

PREPARATION OF DISC-SHAPED SPECIMENS

The silica sands can be described as 8 sphericity /8 roundness, 60 GFN, 4 screen; with an estimated surface area of ~155 cm^2/g. AFS standard procedures were followed in the fabrication of disc-shaped specimens. The sand screen distribution, properties, and characteristics for the granular media investigated are shown in Table 1.

A nobake phenolic urethane resin (Part 1) cured by a catalyst (Part 2) was mixed with sand additives according to Table 2. The mixture was manually packed into a tool (Fig. 1) to produce disc-specimens (PU_{NB}). Table 2 identifies the PU_{NB} specimens A through G that were fabricated for testing.

Procedure

1) Add weighed sand(s) to the mixing bowl.
2) Make a pocket in the sand.
3) Add Part 1 binder component into the pocket and mix thoroughly.
4) Add Part 2 binder component into the pocket and mix for 2 minutes.
5) Manually pack the sand mixture into the twelve cavities disc-shaped specimen nobake tool and strike-off (Fig. 1).
6) After 40 minutes of cure the specimens were stripped from the tool and weighed.

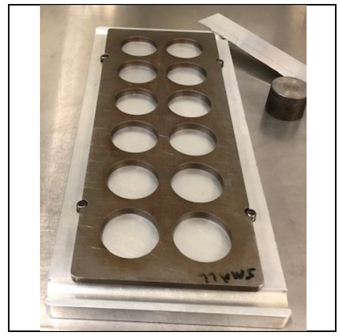


Figure 1. A nobake disc-shaped specimen tool.

Specimen designation and mix preparation for sand blends are identified in Table 2. Specimens were stored in controlled laboratory conditions: temperature at 20 ± 1°C (68 ± 1.8□F) and relative humidity at 50 ± 2 %.

Table 1. Typical Properties of the Granular Media

Sand Type	Silica	Andalusite	Glass
Source	WI, USA	France	Recycled
Process	Natural aggregate	Natural Mineral	Crushed
Chemical Analysis (%)			
Al_2O_3	0.07	60.8	<0.001
SiO_2	99.65	37.9	>99
Fe_2O_3	0.02	0.58	<0.001
TiO_2	0.01	0.15	<0.001
Other	0.25	0.37	<0.002
USA Sieve No.	(% Retained)		
6	0.00	0.00	0.00
12	0.00	0.00	0.00
20	0.00	0.00	0.00
30	0.20	0.20	0.30
40	7.10	4.10	14.30
50	19.50	30.9	4.15
70	28.10	44.00	30.00
100	33.90	19.80	9.40
140	10.20	0.70	2.10
200	1.00	0.20	0.10
270	0.10	0.09	0.00
Pan	0.00	0.00	0.00
Screens	4	3	3
AFS-GFN	59.5	51	46
~Surface Area (cm^2/g)	155	135	120
Density (g/cm^3)	1.78	3.10	2.00
LOI (%)	0.085	0.01	<0.01
Fusion/Melt Point (°C)	1710	1860	1510
pH	7.0	7.0	7.0
Acid demand pH-7	0.1	0.1	0.1
Roundness/ Sphericity (Krumbein)	0.8/0.8	0.5/0.2	0.3/0.2
Shape	Rounded	Angular	Angular

Table 2. Blends and Binder Level of Specimens

Specimen	% Sand	% Blend	% Binder
A-PU_{NB}	100 Silica	0	1.5
B-PU_{NB}	100 Ceramic	0	1.5
C-PU_{NB}	70 Silica	30 Ceramic	1.5
D-PU_{NB}	50 Silica	50 Ceramic	1.5
E-PU_{NB}	98 Silica	2 Glass	1.5
F-PU_{NB}	94 Silica	6 Glass	1.5
G-PU_{NB}	90 Silica	10 Glass	1.5

TESTING OF DISC-SHAPED SPECIMENS

The disc-shaped specimens were used in a variety of AFS standardized physical and mechanical tests. The following five tests were conducted with a sample size of twelve specimens for each test: 1) specimen weight (density), 2) impact, 3) permeability, 4) abrasion, and 5) scratch hardness. The purposes and procedures for these tests are documented in the "AFS Mold & Core Handbook" and in AFS technical papers.[1]

CASTING TRIAL

A casting trial (cookies-in-doughnut) was developed to evaluate the specimen/metal interface for the bonded sand specimens. A chemically bonded sand mold with the mold-metal interface protected by a refractory coating was produced with a pouring sleeve and filter for constant head-pressure and fill velocity. The mold contained cavities with coreprints. This approach allowed possible variation in casting quality to be assigned to only disc-shaped core specimens.[3,4]

Surface Defect Casting Trial

A surface defect casting trial was used to compare casting surfaces for the chemically bonded disc-shaped specimens. Burn-in, veining and penetration are among the more common iron casting surface defects. Therefore, the proposed casting trial aims to qualify against these surface defects. Ramrattan et al[3] identified one important mechanism for veining. The postulation is that one mechanism for veining is stress cracking in the sand binder system where metal can penetrate. The aim was to wet the surfaces of the disc-shaped specimens while being poured to a 20 cm iron head. Specifically, common surface defects, such as penetrations and veining on the surface can be related to thermal-mechanical issues.[3,4] The CAD representation of this surface defect casting trial for multiple specimens under the same metallostatic pressure is shown in Fig. 2.[5]

The 4 casting trial procedure steps:

1. Ram mixed chemically bonded sand against the matchplate to produce molds
2. Refractory coat mold metal interface
3. Pour molds
4. Shakeout and inspect casting

Note: The mold was prepared and poured at WMU, Metal Casting Laboratory. Ambient conditions were temperature controlled at 20 ± 1°C (68 ± 1.8□F) and relative humidity was controlled at 50 ± 2%.

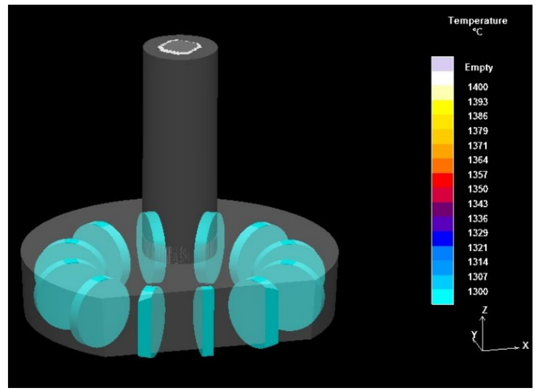


Figure 2. A CAD representation for the surface defect casting trial showing doughnut shaped casting with disc-shaped specimens.[5]

Preparation of the Chemically Bonded Sand Molds

The silica base aggregate (silica lake sand, 55 GFN, 3 screen) used in the study came from Michigan. A nobake alkaline phenolic resin cured by an organic ester co-reactant (1.5% BOS) binder system was applied in a batch mixer. After the mold cured the pattern was stripped the mold walls were protected by a zircon refractory coating (90 Baume).

Procedure

Mold halves were fabricated according to an experimental pattern (Fig. 3). The pattern cavity was refractory coated so any sand issues at the disc-shaped specimen metal interface would be due to the specimens themselves. The drag mold with specimens set on coreprints is shown in Fig. 4. A 20 cm tall pouring sleeve was affixed to the cope as a sprue to deliver the metallostatic head. The gating was a central sprue pouring sleeve fitted with an appropriate filter prior to the gate for wetting specimen surfaces Fig. 5.

Figure 3. Matchplate drag pattern for the surface defect casting trial.

Figure 4. The disc-shaped specimens placed on the coreprints in the drag half of the mold.

Figure 5. Chemically bonded sand mold fitted with sleeve ready for pour.

Melting and Pouring

The mold was poured where the chemically bonded disc-shaped specimens were placed randomly. The sand-to-metal weight ratio for all molds was 2:1. The molds (2) were manually poured to a super-heat (12 seconds fill, temperature at pour ladle was 1434C (2613F), and gray cast iron (Grade 30) alloy was delivered through a direct pouring sleeve fitted with a ceramic screen filter. The mold was poured to a 20 cm head-height. The gray iron chemistry is shown in Table 3. The casting was allowed to solidify by air-cooling prior to shakeout and sectioned near the specimen/metal interfaces.

All molds were prepared and poured at WMU, Metal Casting Laboratory. Ambient conditions were controlled at: a temperature 20 ± 1°C (68 ± 1.8□F) and relative humidity 50 ± 2 %.

DATA COLLECTION AND OBSERVATION

Dimensional data from the casting trial specimen-metal interface was collected using non-contact measurement technology. Prior to casting trials all the specimens were examined with a 3D macroscope to document surface finish. Through the use of the 3D macroscope and its accompanying software, high-speed, high-accuracy 3D measurement can be obtained.[2]

With conventional measurement equipment (e.g., profilometers, human visual inspection) significant time and skill is required to achieve repeatable and reproducible dimensional measurements for either the disc-shaped specimen or the resulting casting trial metal interface. In addition, it is challenging to obtain measurements of distortion, surface texture, and roughness measurements within difficult-to-reach areas, such as cracks.

Disc-shaped specimens used in casting trials were destroyed or damaged so no direct observations could be made from those surfaces. The specimens must shakeout for surface observations to be imaged. Observations from the surface defect casting trial were made after the castings were solidified, shaken-out, and sectioned at the specimen/metal interface. Data was then collected using the 3D macroscope. Dependent measures were obtained with the 3D macroscope for surface roughness, Ra µm of the disc-shaped specimen and the as-cast iron interface.

Table 3. Gray Iron Chemistry

C	Si	P	S	Mn	Cr	Ni	Al	Cu	Ti	Sb	Fe	C.E.	Chill
3.42	1.99	0.094	0.094	0.63	0.082	0.009	0.002	0.15	0.000	0.001	~93	4.05	0

RESULTS AND DISCUSSION

PROPERTIES OF THE DISC-SHAPED SPECIMENS

Table 4 provides a summary of the physical and mechanical properties of the disc specimens used in this study. The silica sand specimens (A) had a greater bulk density than the ceramic sand (B). The increased loading of glass into silica reduces the bulk density.

Blending the glass media up to ~6% into the silica can increase toughness. Specimens E, F, and A were the toughest systems while the 100% ceramic sand system (B) was the least. The ceramic sands blends (C & D) gain toughness with increased loading of the silica sand. The 100% ceramic sand system (B) showed significantly higher venting characteristics regardless of sand type and blend.

The abrasion test would represent an operator rubbing their hands against a core or mold resulting in sand loss and scuffing. Blending the glass media up to ~6% into the silica can increase abrasion resistance. Abrasion loss was lowest in specimens E, F, and A. Alternatively, the 100% ceramic sand system (B) and the 50:50 ceramic to silica sand blend (D) were the most friable systems. Similarly, but not surprisingly, the scratch hardness value was highest in specimens E, F, and A.

All sand specimens were characterized in surface roughness upon receipt using a 3D macroscope and results are shown in Table 5. The surface roughness among the disc-shaped specimen was not significantly different.

Table 4. Properties of Disc-Shaped Specimens

Test Sand/Binder System	A	B	C	D	E	F	G
Specimen Weight (g)	25.60 (0.11)	22.75 (0.53)	24.95 (0.42)	25.53 (0.20)	25.54 (0.16)	25.40 (0.18)	23.81 (0.12)
Impact Strength (J)	1.24 (0.04)	0.85 (0.04)	1.02 (0.09)	1.19 (0.06)	1.47 (0.05)	1.36 (0.09)	0.90 (0.12)
Permeability (#)	188 (0.13)	212 (0.14)	193 (0.10)	193 (0.15)	190 (0.11)	192 (0.13)	203 (0.13)
Abrasion Loss (%)	1.68 (0.18)	7.64 (0.42)	4.06 (0.62)	8.71 (0.33)	1.07 (0.12)	1.64 (0.16)	4.83 (0.17)
Scratch Hardness (#)	95 (0.02)	70 (0.09)	80 (0.06)	84 (0.06)	95 (0.05)	94 (0.06)	85 (0.06)

Note: Standard deviations are shown in parenthesis

CASTING TRIAL SHAKEOUT

The cast iron castings were allowed to solidify prior to shakeout. For shakeout, the casting was placed on a steel-grated metal table with the drag side down. Shakeout was conducted using a pneumatic air-chisel with a modified blunt-tip. More specifically, the air-chisel was brought in contact with the outer circumference and moved along the periphery of the casting for a predetermined amount of time (45 secs.). All sand that shook out was free to flow out of the coreprints.

After casting shakeout, with a constant energy input, observations could be made of the disc-shaped specimen/metal interface. After the solidification certain specimens collapsed and fell out the prints without need for shakeout while other specimens required mechanical shakeout to remove. Figure. 6 shows a section of casting at the coreprints prior to shakeout where one specimen collapsed (left) and fell out while another specimen remained embedded (right). Ultimately, all specimens were able to shakeout.

Figure 6. Section of cast iron showing coreprints after shakeout.

The castings were sectioned near the disc shape specimen/cast iron interface. The plane in Fig. 7 shows a section cut performed on the casting to reveal the specimen/cast iron interface. As-cast interfacial conditions are reported in Table 5. These surfaces were then examined using a 3D macroscope. Images of the specimen/metal interfaces were captured and surface roughness was measured to infer surface texture (Table 5).[2]

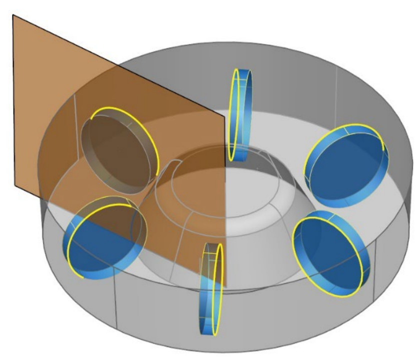
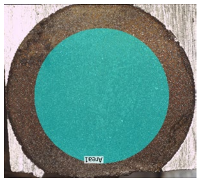
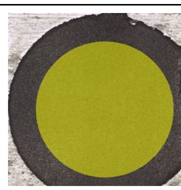
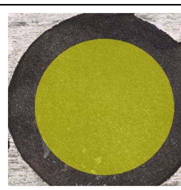
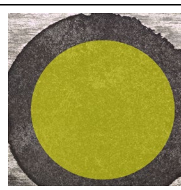


Figure 7. Cutting plane imposed on the casting with cores in place.

Table 5. Casting Sections Showing Specimen/Cast Iron Interface and Surface Roughness

SPECIMEN	SPECIMEN / CAST IRON INTERFACE	DISC-SHAPED SPECIMEN	SURFACE ROUGHNESS		OBSERVATIONS FROM INTERFACIAL CONDITION
			Casting S_a (μm)	Disc Specimen S_a (μm)	
A-PU_{NB}			20	38	Vein present and slight burn-on
B-PU_{NB}			28	40	Significant burn-on
C-PU_{NB}			33	42	Penetration and significant burn-on
D-PU_{NB}			35	45	Penetration and significant burn-on
E-PU_{NB}			25	40	Vein present and sight burn-on
F-PU_{NB}			28	40	Vein present and significant burn-on
G-PU_{NB}			35	40	Penetration and significant burn-on

SURFACE QUALITY ASSESSMENT

This section relates the surface quality observations and findings from the gray cast iron trials. AFS does not define a difference between casting surface quality and casting surface roughness. Thus, the authors have chosen to compare the as-cast surface roughness and surface condition using Table 5.

The results from the casting trials are pictured in Table 5 and are compared according to surface roughness measurements. The surface roughness measurements were automatically generated by the macroscope and used a consistent 35mm diameter region that is concentric with the cast surface.

The purpose of this work was to observe whether casting trials with the "doughnut" casting geometry could identify specimen/iron interfacial issues and distinguish differences among the blended and unblended sand binder systems. As can be seen in Table 5 the surface roughness measurements and surface conditions differed across the disc-shaped specimens studied.

Specimen A (100% silica sand) provided the best surface finish (the lower the number, the smoother the surface) logically because it was a rounded and the finest sand distribution. It is important to point out that specimen A showed veining and slight burn-on. The surface finish of specimens worsened by blending more glass into silica sand (E, F, and G). Two reasons for the deterioration, the glass addition had a coarser distribution than the silica sand lending to a rougher surface finish. Secondly, a fluxed glass softening temperature can be less than 1400F (760C) that is significantly lower than the superheat temperature in this experiment. Ultimately veins, burn-on, and penetration persisted with the increased additions of glass.

Specimen B (100% ceramic sand) had a rougher surface finish compared to specimen A. Basically the ceramic sand was angular with a coarse distribution. Besides roughness, there was significant burn-on with the ceramic sand (B). That issue was augmented with the silica sand blends leading to penetration (C and D).

The results of this study indicate that the cast iron interfacial surface quality issues for chemically bonded blended sand binder systems are much more complex than a simple relationship between GFN and surface finish. This has been demonstrated in Table 5, by comparing the surface roughness of the disc-shaped specimens to their resulting as-cast surfaces. Moreover, the sand binder chemistry interacting with cast iron thermochemistry at the specimen/metal interface coupled with an in-mold atmosphere contributes to surface quality (freedom from surface anomalies and the resulting surface roughness).

LIMITATIONS

The work in this paper represents data for just a few sand blends at cast iron temperatures and a head pressure representative of a medium size iron casting. There are several other chemically bonded sand binder blends not to mention engineering sand additives from which additional data could be gathered to learn more about their thermal properties and behaviors. In addition, the authors acknowledge that the specimens used in this study were produced using only one chemical sand binder process.

CONCLUSION AND RECOMMENDATIONS

The use of the disc-shaped specimen is a simple cost-effective casting trial that helps minimize the effect of mold geometry by removing another factor. The casting trial permits researchers to identify a sand binder system's processing window for an alloy, at head pressure, and super-heat. Furthermore, the casting trial allows for a meaningful analysis of the thermomechanical interactions and issues at mold/iron interfaces to extract important and useful findings.

The coarse 100% ceramic sand logically provides better venting characteristics. The 100% silica sand and silica sand with small amounts of a glass media provided superior mechanical properties such as scratch hardness, abrasion resistance, and toughness in the chemical sand binder system. This study identified that a nobake silica system can provide a superior as-cast surface condition for a gray cast iron alloy.

The iron casting trials in this work showed differences among the sand binder systems evaluated. This suggests there are relationship(s) between sand blends and casting issues at the mold/metal interface. Should the chemically bonded sand systems be incapable of providing a satisfactory as-cast cast iron surface quality; a sand blend can be considered. There is no panacea, foundry engineers can qualify molding materials at the mold/metal interface for a given alloy using the methodologies of this study. To better understand the merits of sand blends it is recommended that additional sand systems of the same size, distribution, and grain shape be studied.

ACKNOWLEDGMENTS

The authors thank Dr. Robert Tuttle at the WMU-CEAS Metal Casting Laboratory for assistance with the casting trial.

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