

Automatic vapour sorption analysis as new methodology for assessing moisture content of water based foundry coating and furan sands

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Gas generated during the casting process can cause defects that increase the cost of the components and possibly lead to scrapping the parts. Gases are produced during evaporation of water and by decomposition of organic materials present in the foundry coating and in the moulding sand.

This study investigates how equilibrium water content varies in foundry coating and in different furan based binding systems with the objective to determine what variables are critical for material moisture process control. The influence of relative humidity, temperature, dust levels and binder type are investigated.

Results show that highest effects are given by relative humidity and binder type. They can cause moisture level variations from 0.1% to about 0.8%. Temperature and dust levels play a minor role. Hysteresis effects between sorption and desorption curves are limited. Finally, the sorption curves are fitted with 3rd order polynomial equations.

Keywords: Water based coating, furan sand, automatic sorption analysis, sorption/desorption curves, drying process control, moisture control.

Introduction

When cast parts are produced, the molten metal in contact with the mould causes the production of gases that can lead to defects and scrapped items (Fig 1.a). Possible gas related defects are: hydrogen pin holes, blow holes, cracks and explosive penetrations.^{1,2,3} These gases are composed by a mixture of water vapour, decomposition products of the coating and moulding materials and from gases dissolved in the molten iron.^{1,2} Gas defects can be correlated directly to vapour generated in the mould and coating material due to a high level of residual moisture.^{3,4,5} In particular for furan sands, water vapour is a significant component of the gases generated during the decomposition.⁶ Moisture is present in furan sand as product of the binder and catalyst reaction but its amount can change over time.⁵ Literature shows that gas defects probability can be predicted by simulation if models are calibrated with experimental data for the specific binding system used.^{7,8,9} Other studies show that gas evolution rates can vary for different materials.^{10,11,12,13}

All the current studies however focus on different classes of binding system and foundry material but do not provide information about the influence of parameters such as temperature, air humidity and dust levels and about different brands of furan binders used in Global Castings production facilities.

In this study the objective is to identify how the moisture contents in foundry coating and in sands bonded with different brands of furan binders (Fig.1.b) are affected by relative humidity, temperature and dust levels (Fig.1.c). In order to do this, we use an automatic vapour sorption analyser to determine the equilibrium sorption/desorption curves of the considered materials. The reason for choosing an automatic moisture analyser are: a shorter test time (due to the use of a small sample), the increased precision in weight measurement (due to eliminating manual handling operations of the samples during the tests) and easy and precise control of temperature and humidity.

Sorption/desorption curves are typically used in other industries (such as food, wood, paper) to design and optimise drying processes (by knowing the initial moisture and final moisture achievable at the drier's air humidity and temperature levels)¹⁴, to provide limits for production processes control and monitoring, to predict shelf life by knowing what moisture level a material will reach in an environment at a given air humidity (i.e. shelf life prediction in food packaging depends on moisture content)¹⁵ or to predict possible moisture migration between different materials.^{14,15} These curves are a property of the material and show how its moisture levels vary as a function of relative humidity at a given temperature. In particular they will show the minimum possible level of moisture achievable in given environmental conditions for a given material.

These tests are normally not used in the foundry industry but are thought to be relevant by the authors for the following reasons:

- to understand which parameters have the highest effect on moisture levels in the considered material and therefore on the generation of water vapour and the risk of gas defects

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- to create a set of data that can be used for the design and control of driers of furan moulds and foundry coatings
- to support foundry engineers making the right choices when optimizing the production and drying process of coated furan sand moulds.
- to provide a new methodology for testing foundry coatings and binding systems

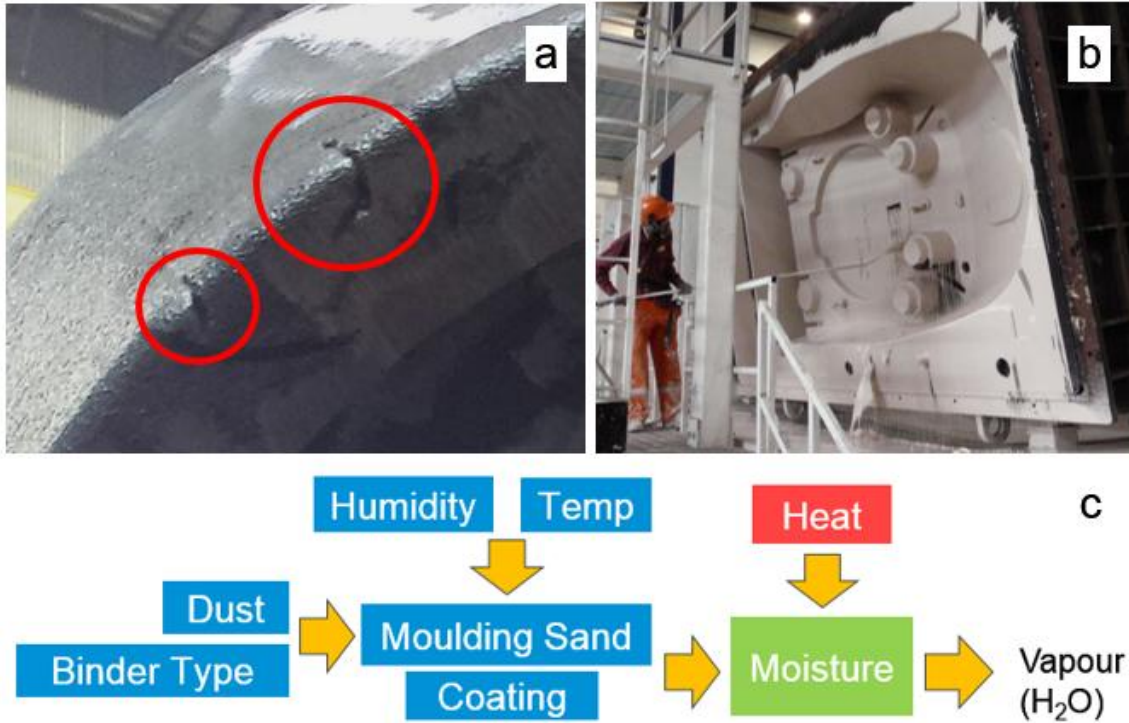


Fig.1: a) Example of moisture related casting defect, b) coating process of furan bonded sand mould, c) parameters affecting vapour generation in a castings process.

Experimental Procedure

In order to investigate the effect of different variables, the experimental plan described in Table 1 was designed. First, the effect of temperature on the two main classes of material is studied (coating and GCX F sand). Then the effect of dust levels are investigated (no dust and 2% dust) and different binder system brands (GCX S, GCM and GCGG). Finally pure dust and un-bonded sand were tested to provide baselines for comparison.

Table 1: Overview of Experimental Plan.

Material	Temperature [°C]		
	15	25	35
Coating	X	X	X
GCX F	X	X	X
GCK No Dust		X	
GCK 2% Dust		X	
GCX S		X	
GCM		X	
GCGG		X	
Pure Dust		X	
Un-bonded Sand		X	

The temperature levels were chosen as the minimum (15°C), typical (25°C) and maximum (35°C) temperature allowed in the production facilities. Similarly, dust levels representing the maximum allowed (2%) and the minimum (0%) possibly achievable levels were used. The binder brands are the same as used in the considered production facilities.

For the bonded sand, the sample preparation started by mixing of sand, binder and catalyst (Fig.2a), followed by curing for one week at 23-25 °C and 45-50% RH and finally manual crushing (Fig.2b) (for easier handling during tests).

Binder addition was 1% of sand weight and catalyst addition was 40% of binder weight. The coating samples were obtained by drying the liquid coating (typically containing an initial moisture of about 40% on wet basis) at same conditions and time used for the sand samples and then manually crushing the dry coating into powder (Fig.2c). Pure dust and un-bonded sand were taken directly from filter bags and silos in the factory and then let equilibrate at the same temperature and humidity conditions as described for the other samples.

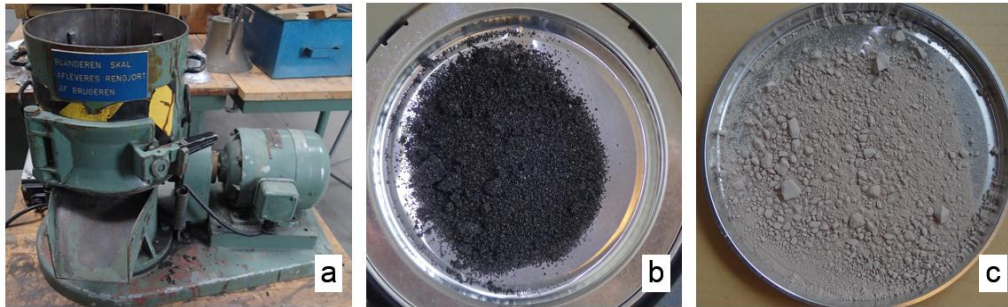


Fig.2: Materials preparation: a) mixing, b) crushed sand and c) crushed coating.

After sample preparation and equilibration at 23-25 °C and 45-50% RH for a week, a sample of each type was tested in an automatic moisture analyzer (Fig.3.a) with an accuracy of 0.05%. The automatic moisture analyzer was set to dry the sample at a temperature of 105 °C. The wet basis moisture (calculated as in equation (1)) values obtained are needed as input in the automatic vapor sorption analyser to compute the sample moisture values during the sorption tests since it is not possible for the automatic moisture analyzer to dry the samples at 105 °C.

$$InitialMoisture_{w.b.} = \frac{InitialWeight - DryWeight}{InitialWeight} 100 \quad (1)$$

The automatic vapor sorption analyser used for this study (Fig.3.c) is equipped with a precision scale with +/- 0.1 mg accuracy, a dew point sensor with 0.5 % RH accuracy and infrared sensor for temperature control. The moisture level can be controlled by supplying either wet air or dry air.

The sorption/desorption tests were carried out by loading a sample of about 10-12g in the automatic sorption analyzer and inputting the initial moisture of the sample at 23-25 °C and 45-50% RH (Fig.3.b) from the previous tests. After sealing the cover, the machine will start recording weight variation and changing temperature and relative humidity according to the test plan.

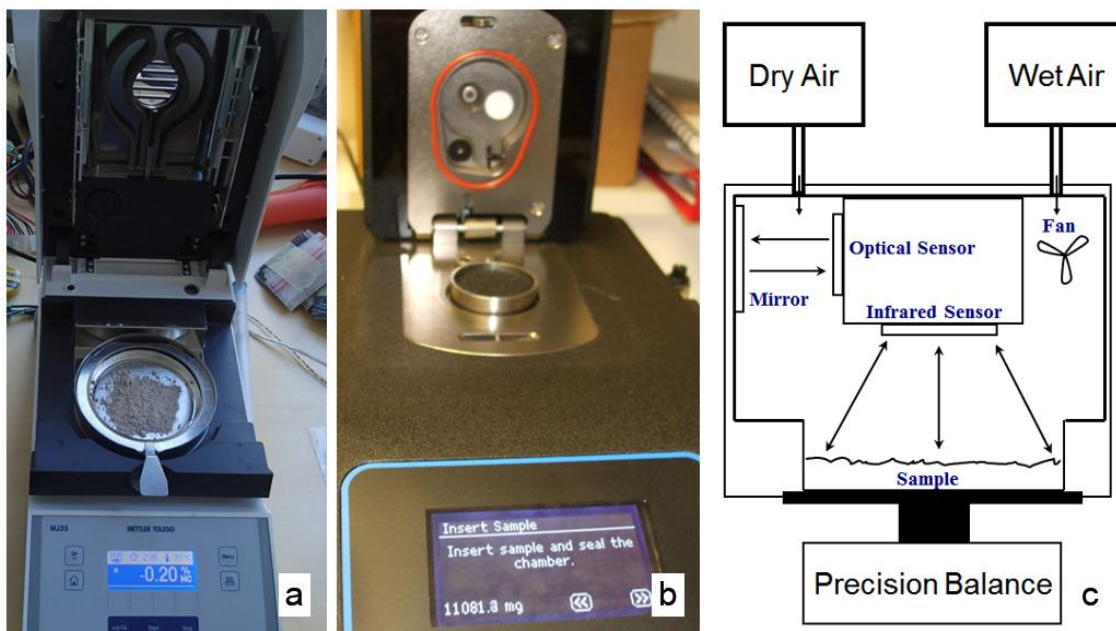


Fig.3: Test Setup: a) initial moisture level measurement, b) automatic vapour sorption analyser and c) schematic.

In order to obtain the sorption/desorption curves, the temperature is held constant at either 15 °C, 25 °C or 35°C while the air humidity is changed stepwise in 5% increments. The current moisture content of the sample is calculated as:

$$CurrentMoisture_{w.b.} = \frac{CurrentWeight - DryWeight}{CurrentWeight} 100 \quad (2)$$

Where dry weight is calculated from the initial moisture and weight as:

$$DryWeight = InitialWeight \left(1 - \frac{InitialMoisture_{w.b.}}{100} \right) \quad (3)$$

During the test, at each imposed air humidity level, the moisture level in the sample is calculated using equation (2). If the variation in moisture is less than 0.02% in one hour, the sample is considered equilibrated and the air humidity can be changed to the value required by the next step (Fig.4a).

Each test begins at 50% RH and the air humidity is increased stepwise up to 95% to initialise the sample (Fig.4b), then the desorption phase starts (humidity is decreased step wise to 5% RH) and finally the adsorption phase is carried out (humidity is increased stepwise to 95% RH). In order to obtain the final sorption curve, the moisture level of each equilibrium point is plotted versus the air humidity. Sorption curves are plotted in the results section without the initialization steps.

Finally, 3rd degree polynomial equations are fitted to the experimentally obtained sorption and desorption curves (Fig.4c and equation (4)). The curves coefficients are reported in the result section for each material, as well as the coefficient of determination R² used to check how well the model fits the data (R² values close to 1 represent a good fit between the curve and the data).

$$MaterialMoisture_{w.b.} = a_0 + a_1 \frac{RH_{air}}{100} + a_2 \left(\frac{RH_{air}}{100} \right)^2 + a_3 \left(\frac{RH_{air}}{100} \right)^3 \quad (4)$$

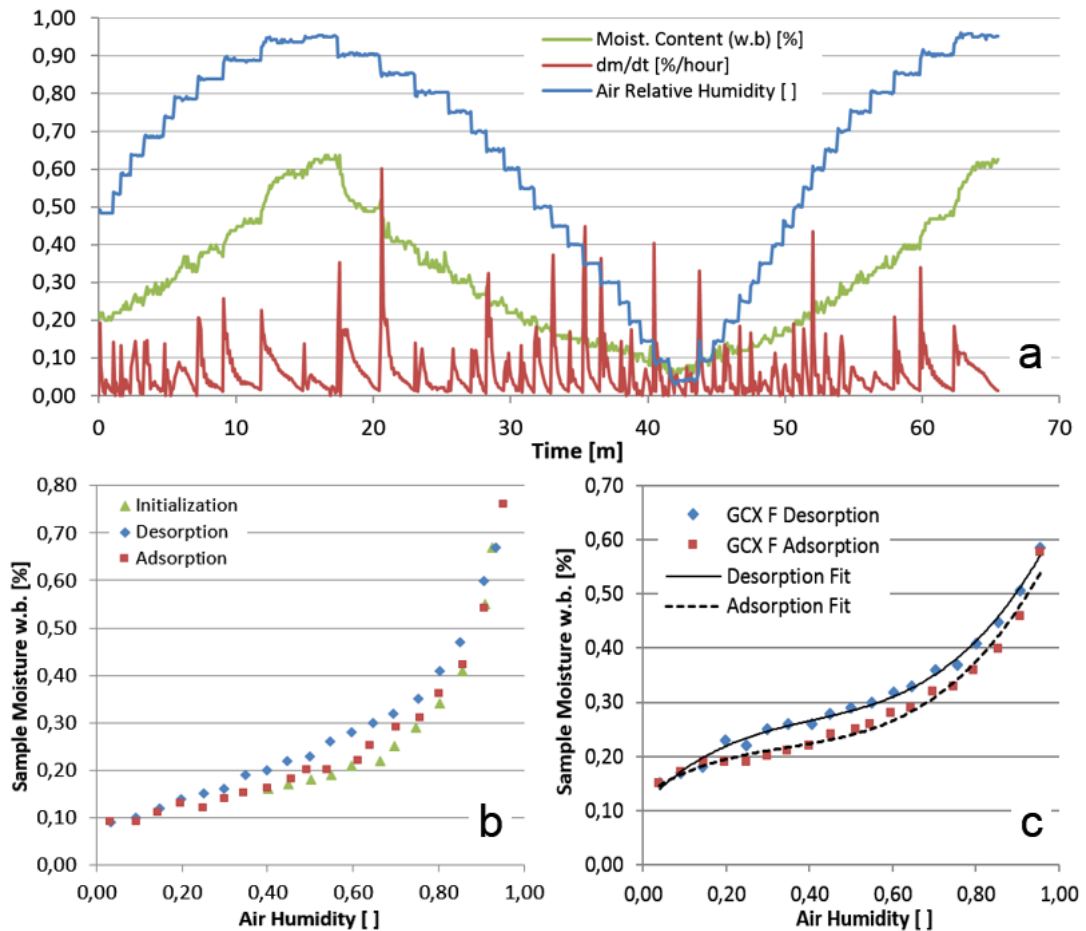


Fig.4: Example of: a) Sorption tests data, b) equilibrated points, c) fitted curves.

Results and Discussion

Table 2 summarises the results of the initial moisture tests carried out on the equilibrated samples at 23-27 °C and 45-55% relative humidity. We can see that pure filter dust has the higher initial moisture level (0.71%), un-bonded sand has the lowest moisture level (0.11%) and all the bonded sands have initial moisture levels between 0.17% and 0.24%.

Table 2: Initial sample moisture after and equilibration at 23-25 °C and 45-50% RH for a week.

Material	Initial Moisture w.b. [%]	Material	Initial Moisture w.b. [%]
Coating	0.20	GCX S	0.17
GCX F	0.24	GCM	0.18
GCK No Dust	0.21	GCGG	0.17
GCK 2% Dust	0.23	Un-bonded Sand	0.11
Pure Dust	0.71		

Figures 5a and 5b show the sorption curves respectively for GCX F furan bonded sand and for foundry coating at 15 °C, 25 °C and 35 °C. It can be seen that, for both materials, temperature does not have a significant effect. On the other hand, air humidity has a major effect. For both materials, moisture can be as low as 0.1% at 5% RH and become as high as 0.6% at 95% RH. Even though the absolute values seem small, we need to notice that from 0.10 % to 0.60% there is a variation of 600%. Additionally, large amounts of moulding sands are used in each mould. For example a 40 tons mould might contain as low as 40 kg of water at 0.1% moisture (if dried at 5% RH for enough time) or as much 240 kg of water at 0.6 % moisture (if stored for enough time at 95% RH). It is therefore important to be aware of this variation when designing the drying process, factory environment conditions and venting channels in the moulds.

Another important conclusion is that the hysteretic behaviour between adsorption and desorption is fairly limited especially for the coating. For the moulding sand, where there is slightly more hysteresis, the difference between sorption and desorption curve is typically less than 0.05% in moisture.

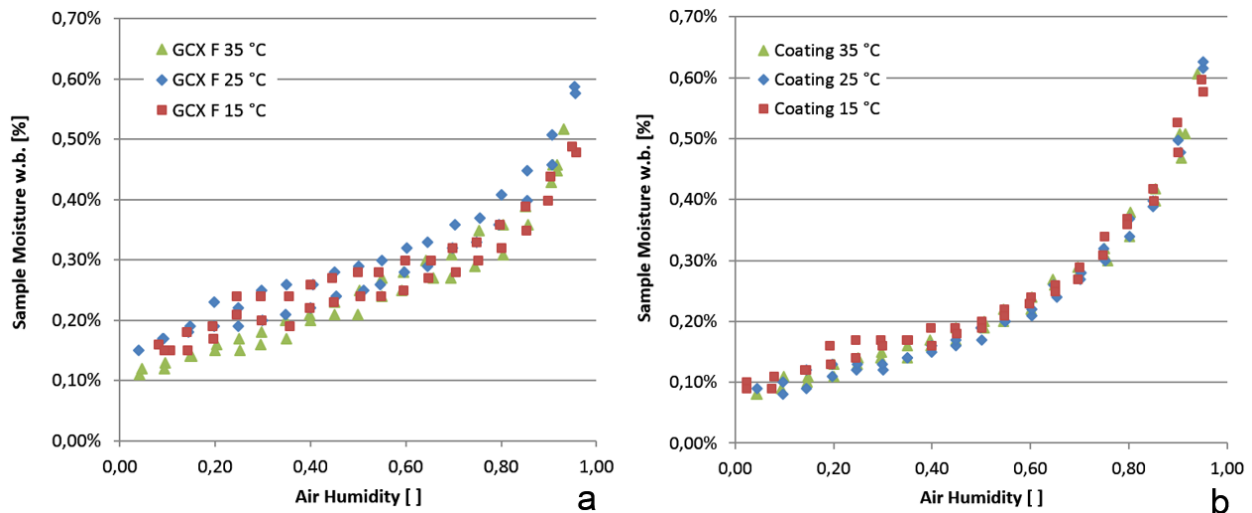


Fig.5: Sorption curves at 15 °C, 25 °C and 35 °C for a) sand and b) coating.

Figure 6a shows that the effect of a 2% dust addition causes a small increase in moisture levels, for example from 0.20% to 0.24% at 50% relative humidity. However, pure dust can contain from 0.30% to 1.70% moisture. It is therefore important to reduce dust segregation in silos to avoid lumps of dust in the moulds.

Figure 6b shows a comparison between moulding sands bonded with different binder types and un-bonded sand. It can be seen that un-bonded sand has the smallest moisture content (between 0.04% and 0.20%), it has no hysteresis between adsorption and desorption and moisture value is a linear function of air humidity. When adding binder the behaviour becomes nonlinear and the moisture level increases up to 4 times that of the un-bonded sand. This is a confirmation of the hydrophilic nature of furan binding systems.

Also we can see that a binder like GCM has significantly lower moisture level compared to the other binders, and it could therefore be used in moulds that are more prone to gas defects. For example, considering a 40 ton mould at 90 % RH where GCM binder is used, it will have a moisture of 0.30 % and therefore a water content of 120 kg. On the other hand if GCK or GCGG binders are used, the same mould will have a moisture content of about 0.55 % at 90% RH, which translates to a water content of 220 kg (almost double the one of VCM binder). Finally, the highest moisture

content is 0.75%, given by GCGG binder at 95% RH, this translates in a quantity of 300 kg of water for a 40 tons mould.

These results show that different amounts and brands of furan binders can have different performance with respect to moisture content. Sorption tests can help to quantify these performances and to choose the right material recipe.

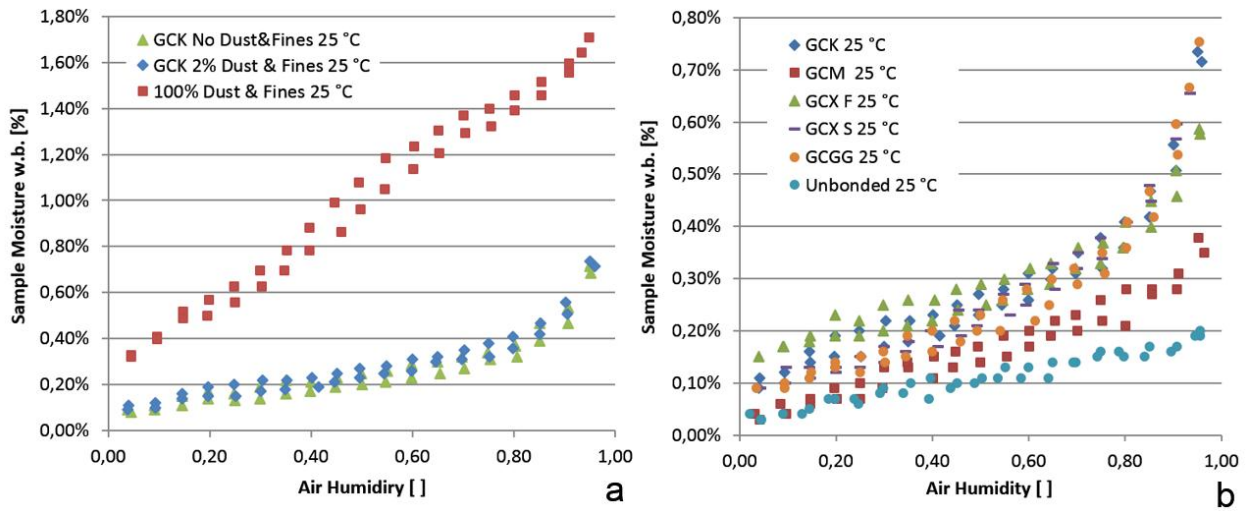


Fig.6: Sorption curves for a) dust, sand with 0% and 2% of dust and fines, b) sand with different binders and un-bonded sand.

Table 2 reports the coefficients of the 3rd degree polynomials used to fit the experimental sorption curves of the different materials as well as the coefficient of determination R^2 . Coefficients are provided for the desorption and the sorption of each material tested but not for the different test temperature and dust levels since these two parameters were found to have little influence on the curves. Additionally, it was chosen to provide the same coefficients for the desorption and sorption curves of coating and un-bonded sand since hysteresis was found to be negligible. Finally, we can see that for un-bonded sand a_3 and a_2 coefficients have a value of 0 since its behaviour can simply be described by a linear curve.

As a final check, we can see that all the curves have good fit since R^2 values are always above 0.95 and above 0.97 for most of the curves.

Table 2: Coefficient of 3rd order polynomials fitted to sorption and desorption curves for furan bonded sands and foundry coating with corresponding coefficients of determination R^2

	Desorption					Sorption				
	a_3	a_2	a_1	a_0	R^2	a_3	a_2	a_1	a_0	R^2
Coating	1.5094	-1.4926	0.6256	0.0444	0.9869	1.5094	-1.4926	0.6256	0.0444	0.9869
GCK	2.1500	-2.5702	1.1754	0.0402	0.9807	2.0139	-2.3105	1.003	0.0371	0.9687
GCM	0.3853	-0.4522	0.4298	0.0215	0.9867	0.4665	-0.5090	0.3853	0.0168	0.9775
GCX F	1.2690	-1.5475	0.8048	0.1099	0.9932	1.0985	-1.1412	0.5195	0.1275	0.9831
GCX S	1.3006	-1.2949	0.6960	0.0484	0.9893	1.3734	-1.1971	0.5098	0.0683	0.9895
GCGG	1.6866	-1.7783	0.8256	0.0425	0.9882	2.2606	-2.4140	0.9222	0.320	0.9692
Un-bonded	0	0	0.1616	0.0284	0.9562	0	0	0.1616	0.0284	0.9562
Pure Dust	-0.6240	0.6183	1.4406	0.2623	0.9951	-0.8065	1.3640	0.8244	0.2958	0.9964

Conclusions

To summarise the main conclusions of the study we can say that:

1. We have shown that automatic vapour sorption tests are useful to detect differences between factors affecting moisture and can help the foundry engineer to choose binders that have lower moisture levels. As a consequence these tests could be used as an evaluation tool for new binding systems recipes and coatings to be introduced in production.
2. Dust effect and temperature effect are not critical in the ranges currently allowed in the factories, it is therefore not critical to tightly control their values as soon as they are within current specification.

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3. Air humidity is a very important parameter, in particular drying at low air humidity can significantly reduce the moisture in the moulds
4. Binder type can heavily affect the moisture retention properties of the mould. It is therefore important to choose binding systems that can reduce the amount of moisture in the sand to reduce the generated vapour and therefore the probability of gas defects
5. Due to the weak hysteresis effect between sorption and desorption curves, moisture lost during drying can be regained when moulds are stored for enough time in an open environment at higher humidity. This might jeopardise the positive effects of expensive drying processes.
6. The data obtained from this study can be used as basis for the design of dryers and to help define control limits for the drying of moulds and cores in the foundry industry.
7. Simple calculation examples have been performed using the results from the experiments to show a possible use of this new test methodology
8. Coefficients of 3rd order polynomials fitted to sorption and desorption curves for the tested materials have been obtained.

References

1. J. Campbell, R.A. Harding: 'Solidification Defects in Castings', Lecture 3207, The University of Birmingham, 4-8, 1994.
2. L. Elmquist: 'Defect formation in cast iron', Presentation, School of Engineering, Jonkoping University, Sweden, 2012.
3. IKO: 'Description of Casting Defects', Chapters 04,10,12, S&B Industrial Minerals
4. A. Chojecki*, J. Mocek: 'Effect of atmosphere in a foundry mould on casting surface quality', Archives of Foundry Engineering, Volume 12, Issue 1/2012, 13-18.
5. D - Elkem: 'Hydrogen Pinholes', Technical Information 30, Elkem Foundry Products, Rev. 1.2, 2007.
6. A. Siewiorek, R. Nowak, A. Chojecki, J. Mocek: 'Gas evolution rate from heated moulding sands bonded with organic binders', Archives of Foundry Engineering, ISSN (1897-3310), Volume 11, Issue 1/2011, 87 – 92.
7. A.Starobin, C.W. Hirt, D. Goettsch: 'A Model for Binder Gas Generation and Transport in Sand Cores and Molds', Modeling of Casting, Welding, and Solidification Processes XII, TMS (The Minerals, Metals & Materials Society), 2009.
8. A.Starobin, T. Hirt, H. Lang, M. Rode: 'Core Drying Simulation and Validation', International Foundry Research 64 (2012) No. 1, 2-5.
9. P. Scarber, C.E. Bates: 'Simulation of Core Gas Production During Mold Fill', AFS, 2006.
10. N.Tiedje, R. Crepaz, T. Eggert, N. Bey: 'Emission of organic compounds from mould and core binders used for casting iron, aluminium and bronze in sand moulds', Journal of Environmental Science and Health, Part A, 45: 14, 1866 – 1876.
11. G. Samuels and C. Beckermann: 'Measurement of Gas Evolution from PUNB Bonded Sand as a Function of Temperature', University of Iowa, International Journal of Metal Casting, Spring 2012.
12. A. Shepherd: 'Understanding Emission Characteristics of a Foundry Sand Binder', Proceedings of The National Conference On Undergraduate Research (NCUR) 2012, Weber State University, Ogden, UT, March 29-31, 2012.
13. BCRA: 'Venting of mould and cores', BCIRA Broadsheet 188, 1980.
14. A.S. Mujumdar: 'Handbook of industrial drying', 3rd edition, Ch. 1-2, 2006.
15. Decagon Devices: 'Vapor Sorption Analyzer', Operator's Manual, Ver.5, Ch. 2.

Acknowledgement

This work was financed by Global Castings A/S, the Danish Agency for Science, Technology and Innovation (DASTI) and the Technical University of Denmark (DTU). LabCell Ltd. provided support in executing the tests on the AquaLab automatic vapour sorption analyser.