FUNDAMENTAL ANALYSIS INTO PROPERTIES AFFECTING INVESTMENT CASTING SHELL STRENGTH

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THANKS

A word of thanks to Matthew Everden for his work on this project

PRESENTATION OUTLINE

- Introduction
- Testing Review
  - Flexural Strength Review
  - GRR of strength measurement
- Drying analysis
  - Dry time analysis
  - Polymer analysis

FLEXURAL STRENGTH REVIEW

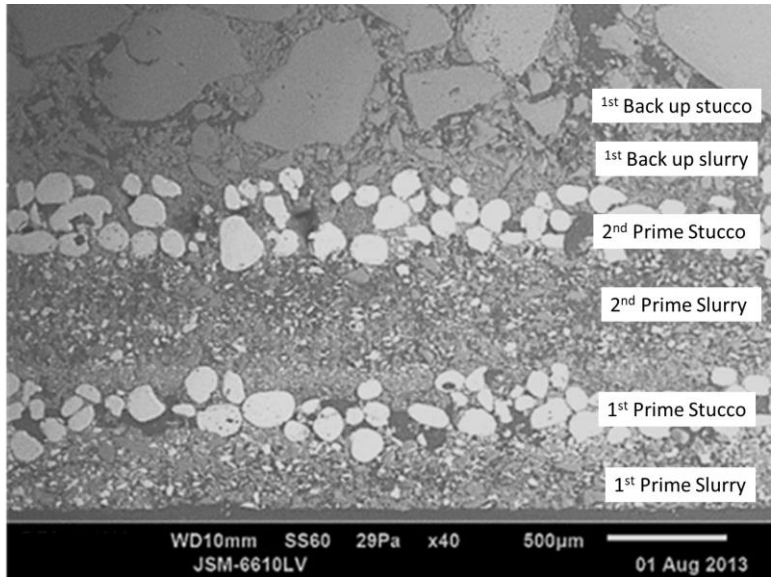
REMET.COM

YOUR CONCEPT TO CASTING PARTNER

MOR STRENGTH TESTING

FUNDAMENTALS

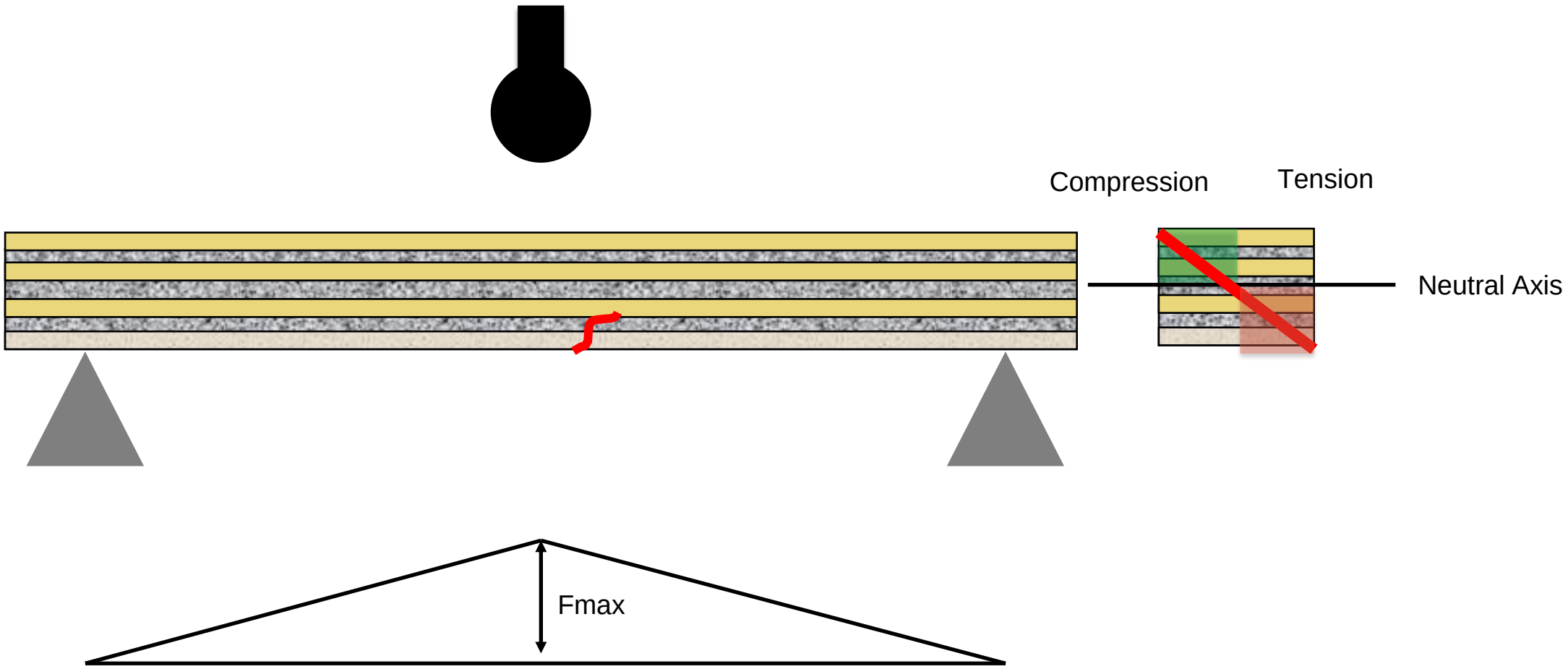
- The strength of the shell is critical for the successful casting of metal parts
- Shells are made up of a laminar structure of slurry and stucco layers
- These layer structures change depending on the stucco application [1]
- The ceramic shells fail in tension at the point of the largest force
- Ceramic will fail when subjected to a stress σ, if a crack reaches some critical size *a*, or, alternatively, when material containing cracks of size a is subjected to some critical stress σ [2]



[1] Dooley, G., S Blackburn (2013). Effect of Stucco Application Method on the Mechanical Performance & Microstructure of Investment Casting Shells, *60th ICI Technical Conference, Pittsburgh, PN*
[2] Ashby, M.F. and Jones, D.R., 2012. *Engineering materials 1: an introduction to properties, applications and design* (Vol. 1). Elsevier.

MOR STRENGTH TESTING

FUNDAMENTALS



MOR STRENGTH TESTING

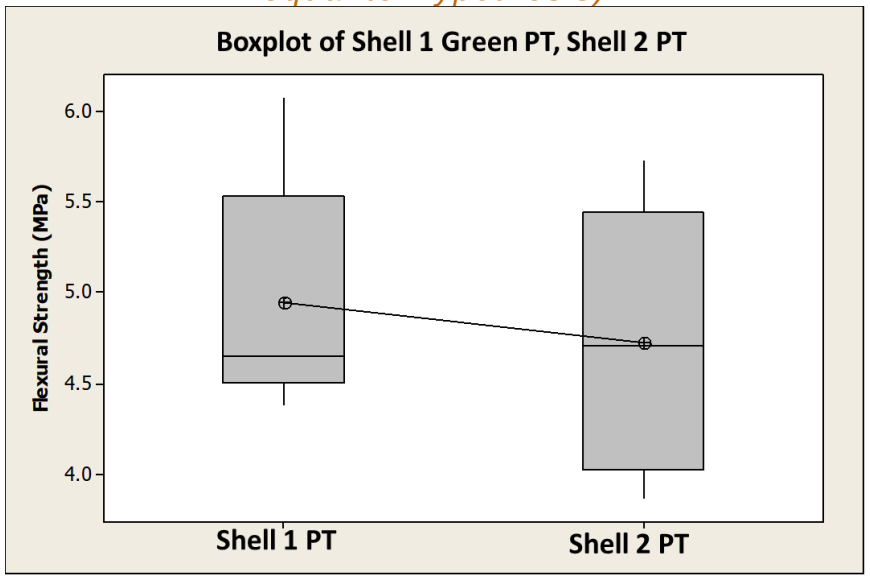
FUNDAMENTALS

- Depending on the shell composition and microstructure, there may be differences in strength measurement depending on which layers are in tension – Prime or back up
- Previous testing has shown there can be statistical differences between these tests depending on the orientation
- It is important to understand and make sure testing occurs in the same orientation for continuity

MOR STRENGTH TESTING

FUNDAMENTALS

Green Dry Prime Tension (2 Sample T-Test T 95% CI for not equal to Hypothesis)



Two-sample T for SHELL 1 Green DRY PT vs SHELL 2 Green DRY PT

	N	Mean	stDev	SE Mean
SHELL 1 Green DRY PT	5	4.944	0.666	0.30
SHELL 2 Green DRY PT	5	4.726	0.747	0.33

Difference = mu (SHELL 1 Green DRY PT) - mu (SHELL 2 Green DRY PT)
Estimate for difference: 0.218
95% CI for difference: (-0.840, 1.276)
T-Test T of difference = 0 (vs not =): T-Value = 0.49 P-Value = 0.641 DF = 7

MOR STRENGTH TESTING

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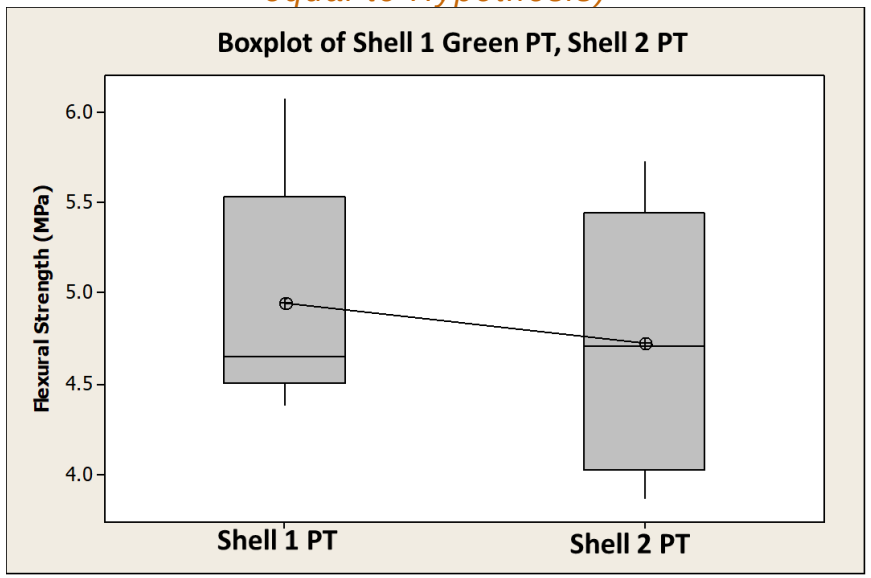

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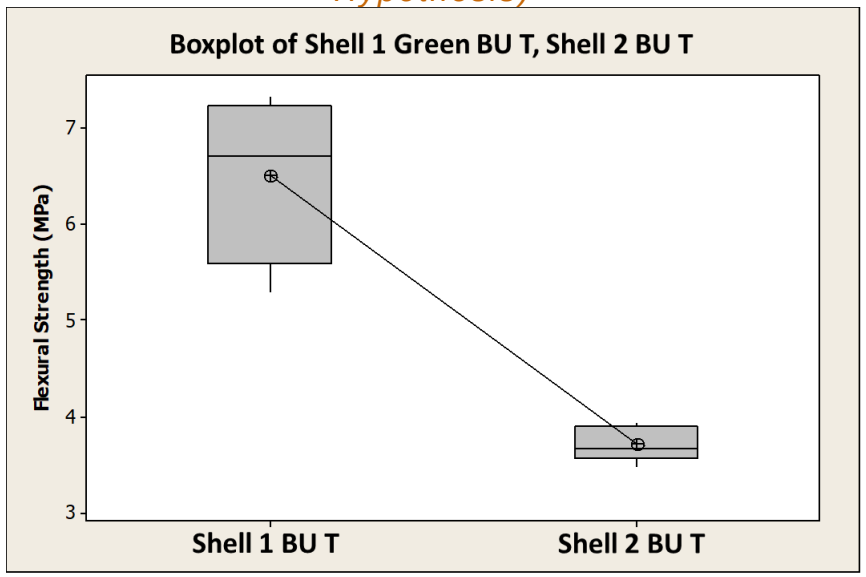
Green Back up Tension (2 Sample T-Test T 95% CI for Greater than Hypothesis)



Two-sample T for SHELL 1 Green DRY BU T vs SHELL 2 Green DRY BU T

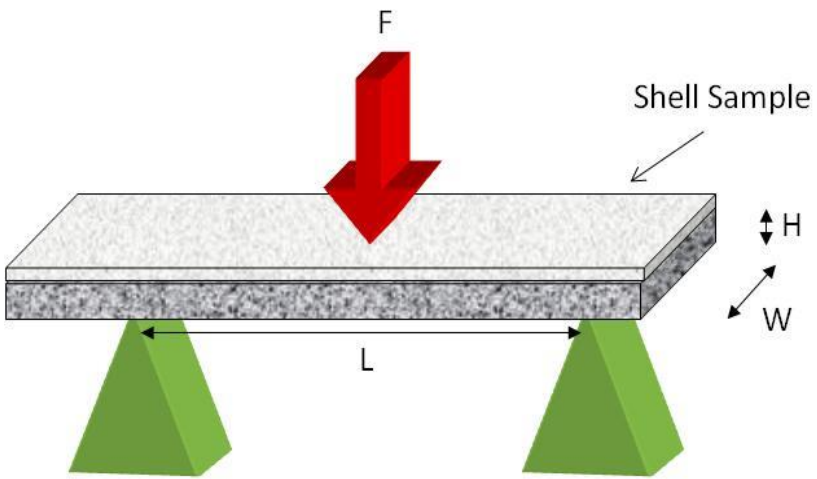
	N	Mean	Step	SE Mean
SHELL 1 Green DRY BU T	4	6.510	0.884	0.44
SHELL 2 Green DRY BU T	5	3.724	0.181	0.081

Difference = mu (SHELL 1 Green DRY BU T) - mu (SHELL 2 Green DRY BU T)
Estimate for difference: 2.786
95% lower bound for difference: 1.728
T-Test T of difference = 0 (vs >): T-Value = 6.20 P-Value = 0.004 DF = 3

MOR STRENGTH TESTING

FUNDAMENTALS

- Work was carried out within REMET to understand and reduce the error of the flexural 3 PB testing of ceramics
- Testing of ceramic is fundamentally prone to error from various sources
- Assumptions –
  - The build regime of the material is consistent
  - Vernier is calibrated
  - Technicians are trained

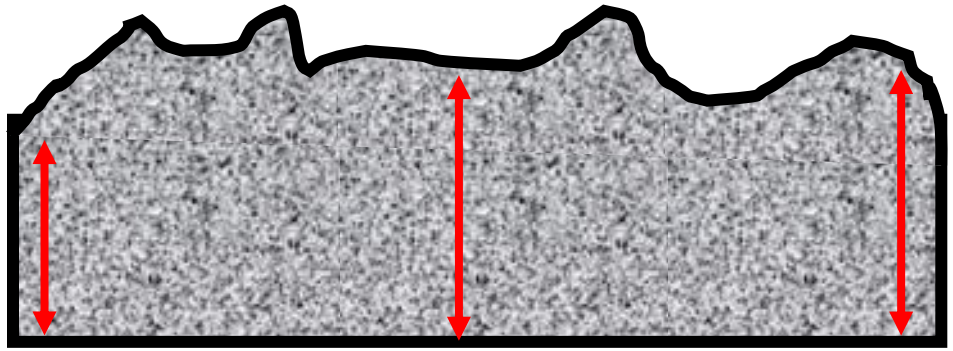


$$\sigma_{3\_Point\_Flexural} = \frac{3P_{MAX}L}{2WH^2} = \frac{3L}{2} * \frac{P_{MAX}}{WH^2}$$

FLEXURAL STRENGTH TESTING

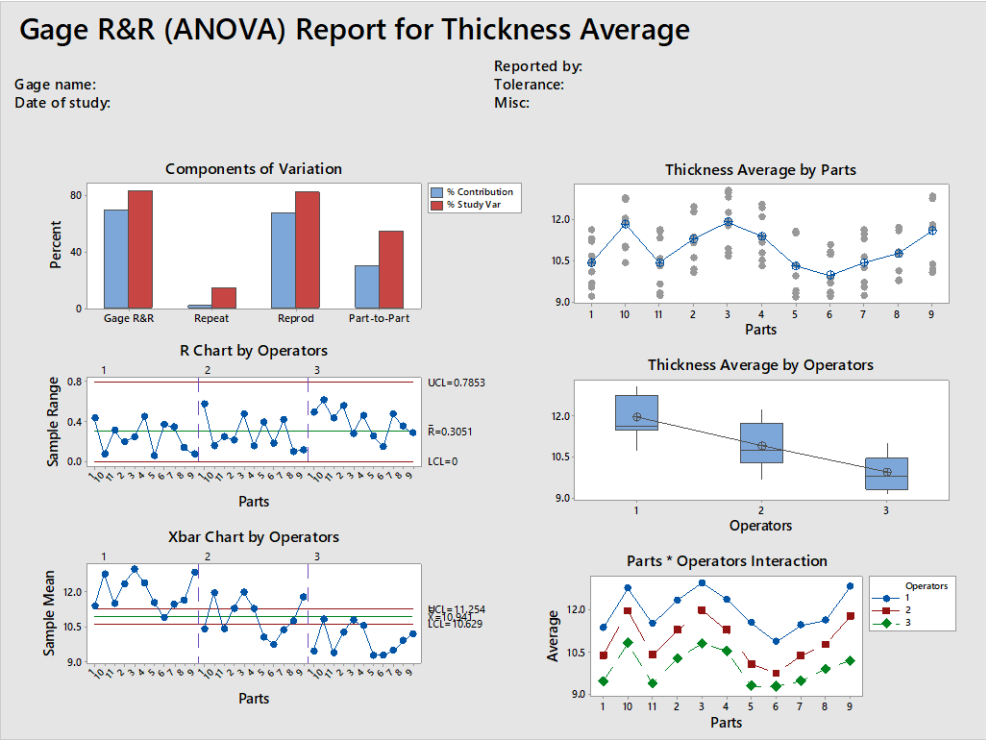
GAUGE R&R

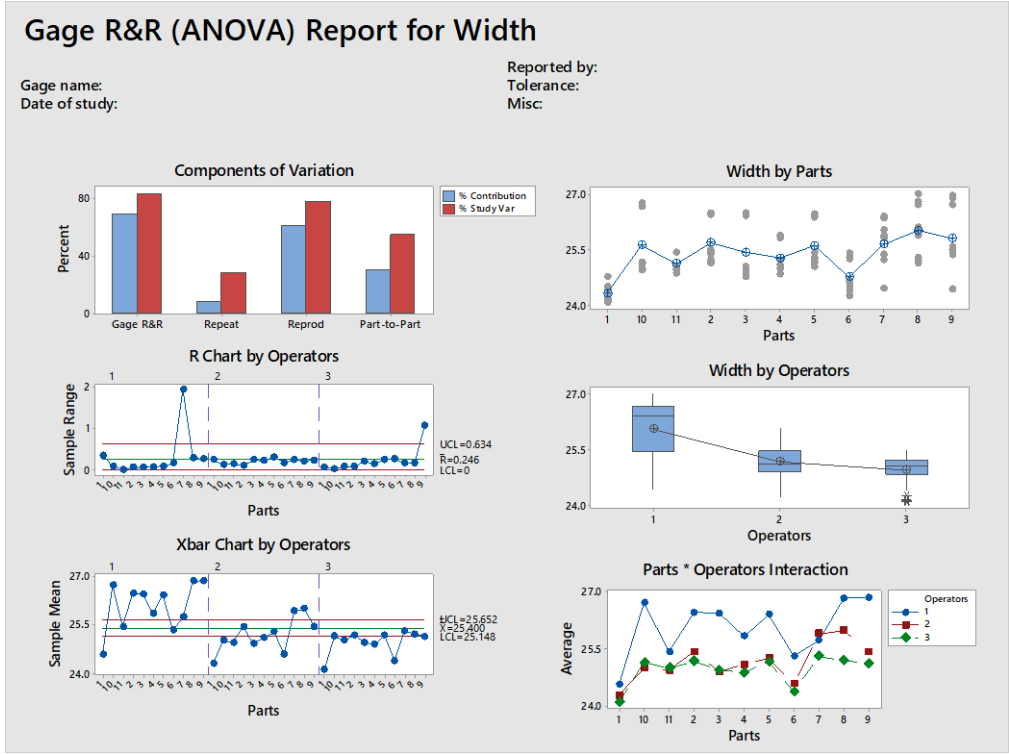
- There are different ways in which the GRR could be carried out
- To best understand the variation in measurement lab technicians were all trained to measure the thickness at the same three points along the fracture surface of the sample
- Samples – 11
- Measurements -3
- Technicians - 3
- 3 measurements of thickness - Side x 2 and middle
- 2 measurements of width – Width of 2 x fractured surfaces



FLEXURAL STRENGTH TESTING

GAUGE R&R





FLEXURAL STRENGTH TESTING

GAUGE R&R

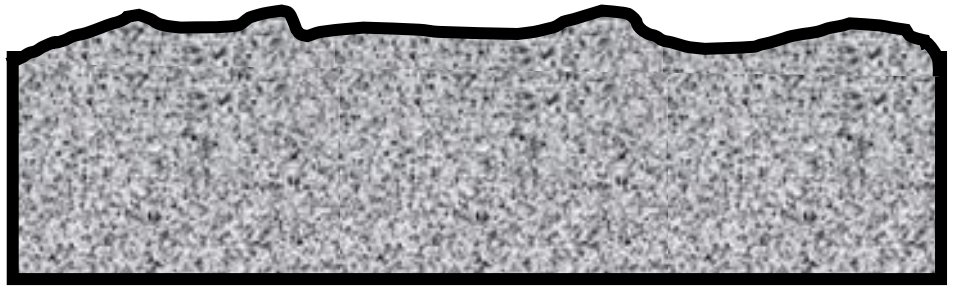
- R bar ($\bar{R}$) is the average range within the data and can be described as the difference which can be accurately measured
- The initial analysis shows an R bar average range of data of 0.31 mm thickness range and 0.246 mm width range
- Utilising this within the MOR equation, using a typical force of 250 N (56 lbs) we can estimate the “worst case scenario” for the measurement error of ± 7.20 % due to measurement error
- This error is high when you account for sample variation and possible machine error
- Retraining was required before we proceeded

Force [N]	Width [m]	Thickness [m]	MOR [MPa]
250	0.025	0.01	7.50
250	0.025216	0.01031	6.97
Difference due to measurement error			7.20%

FLEXURAL STRENGTH TESTING

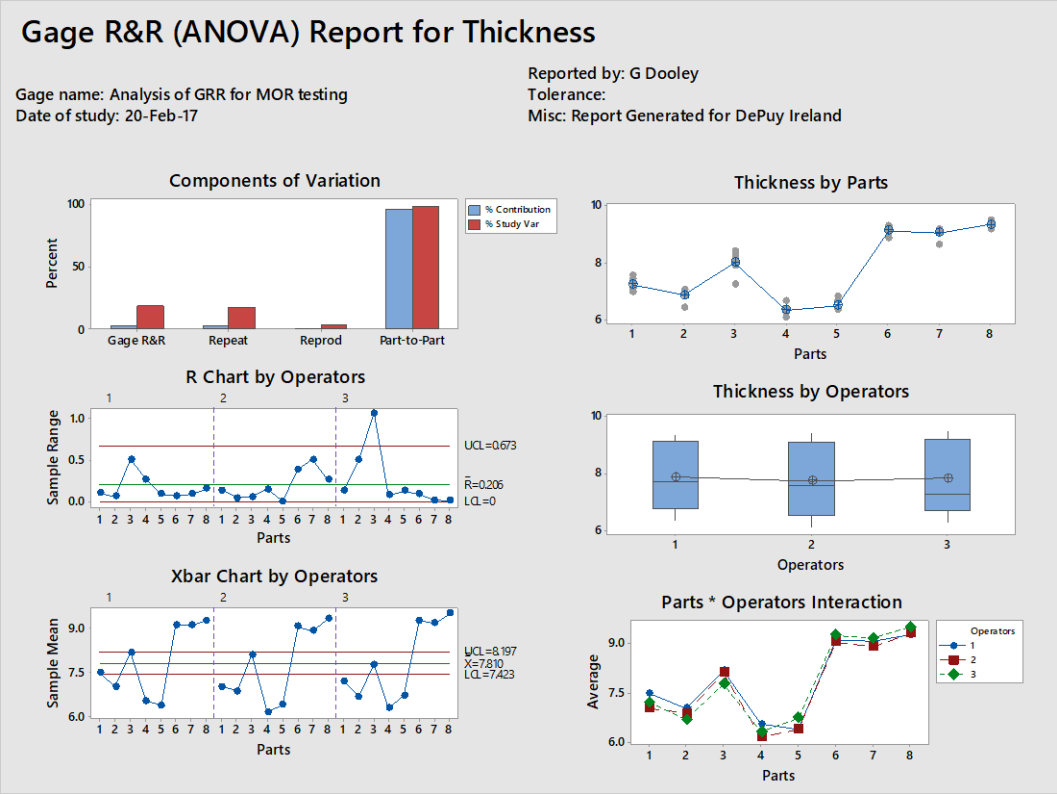
GAUGE R&R

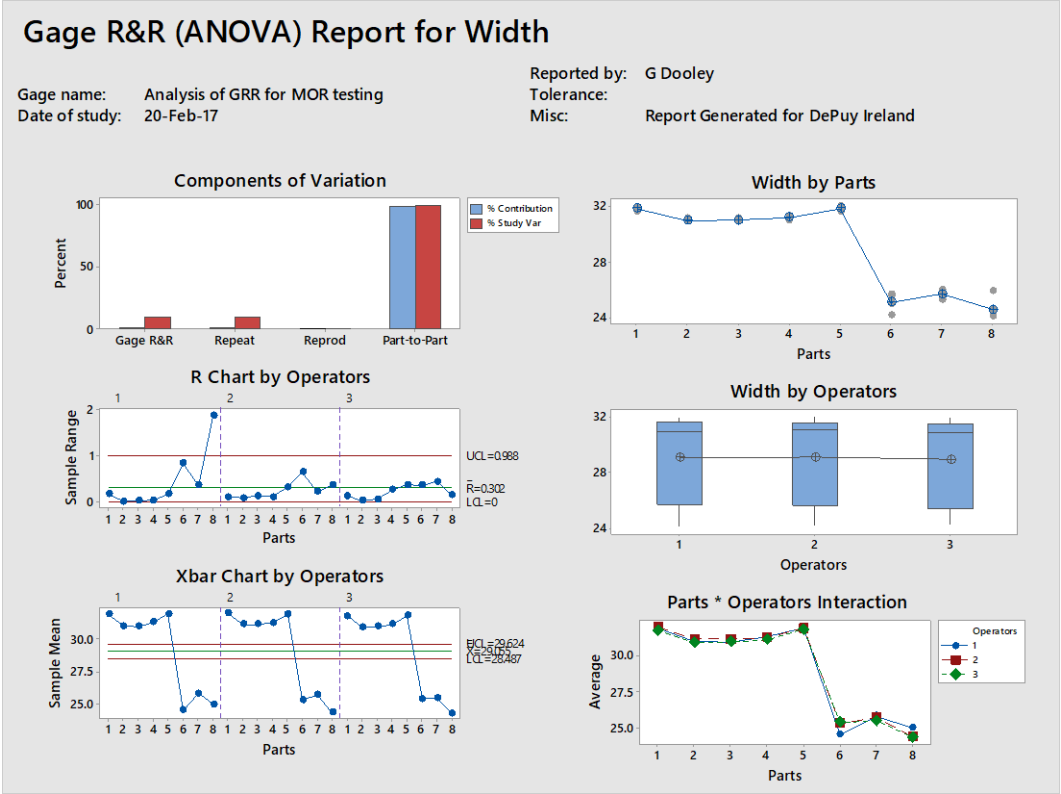
- Measurement training was “too rigid” to account for variation in thickness
- Decided to rely on “Best representation” of thickness measurement
- Accounts for variation in thickness at any point along the surface
- No change in measurement of width was carried out



FLEXURAL STRENGTH TESTING

GAUGE R&R



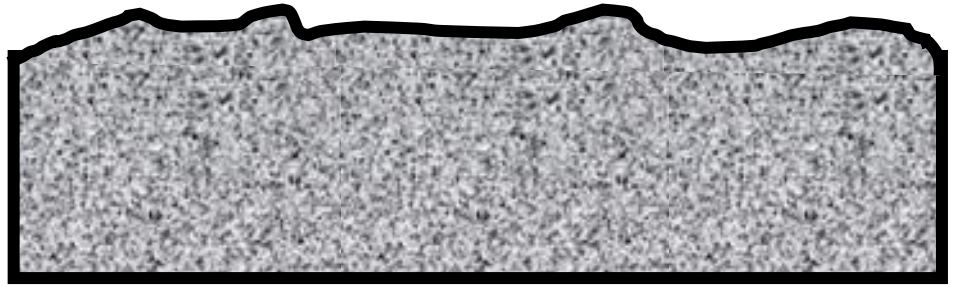


FLEXURAL STRENGTH TESTING

GAUGE R&R

- This revised measurement method reduced the R bar ($\bar{R}$) from 0.31mm to 0.21 mm
- This reduced the error by 2% due to the squared effect of thickness
- We wanted to challenge the other assumption of the study that the material being tested was consistent

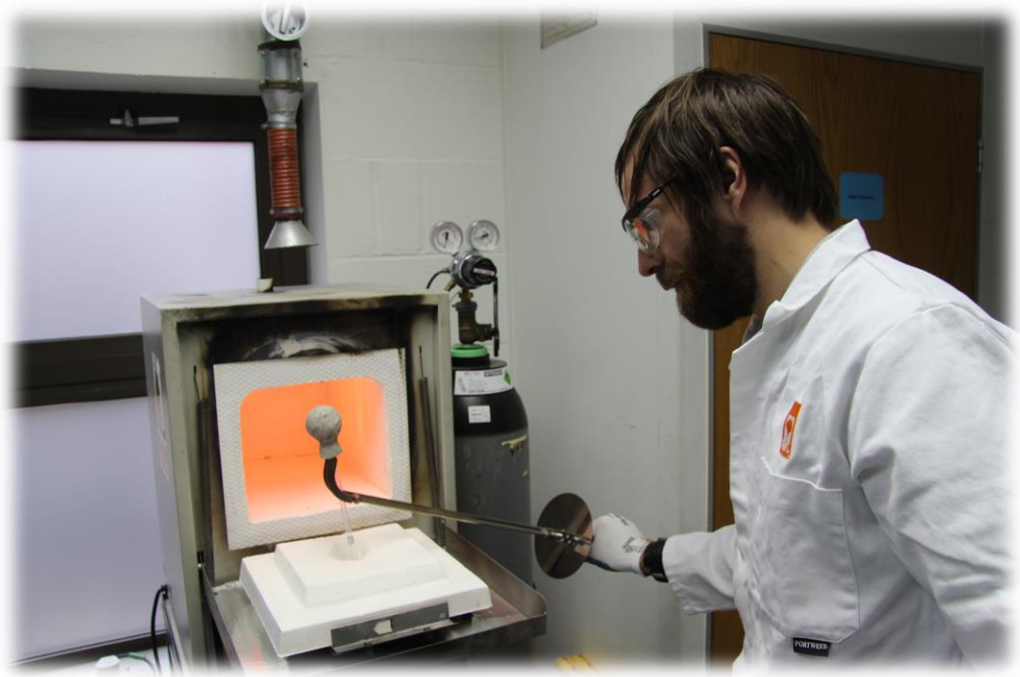
Force [N]	Width [m]	Thickness [m]	MOR [MPa]
250	0.025	0.01	7.50
250	0.025302	0.010206	7.11
Difference due to measurement error			5.14%



FLEXURAL STRENGTH TESTING

GAUGE R&R

- Within REMET UK, over 30 different shells are made in R & D lab scale environments annually
- Typically running a side by side using an OFAT (One Factor At a Time) approach to development
- Used to assess how small changes in materials or properties can effect shell properties
- With this in mind, the samples must be produced in a repeatable way



FLEXURAL STRENGTH TESTING

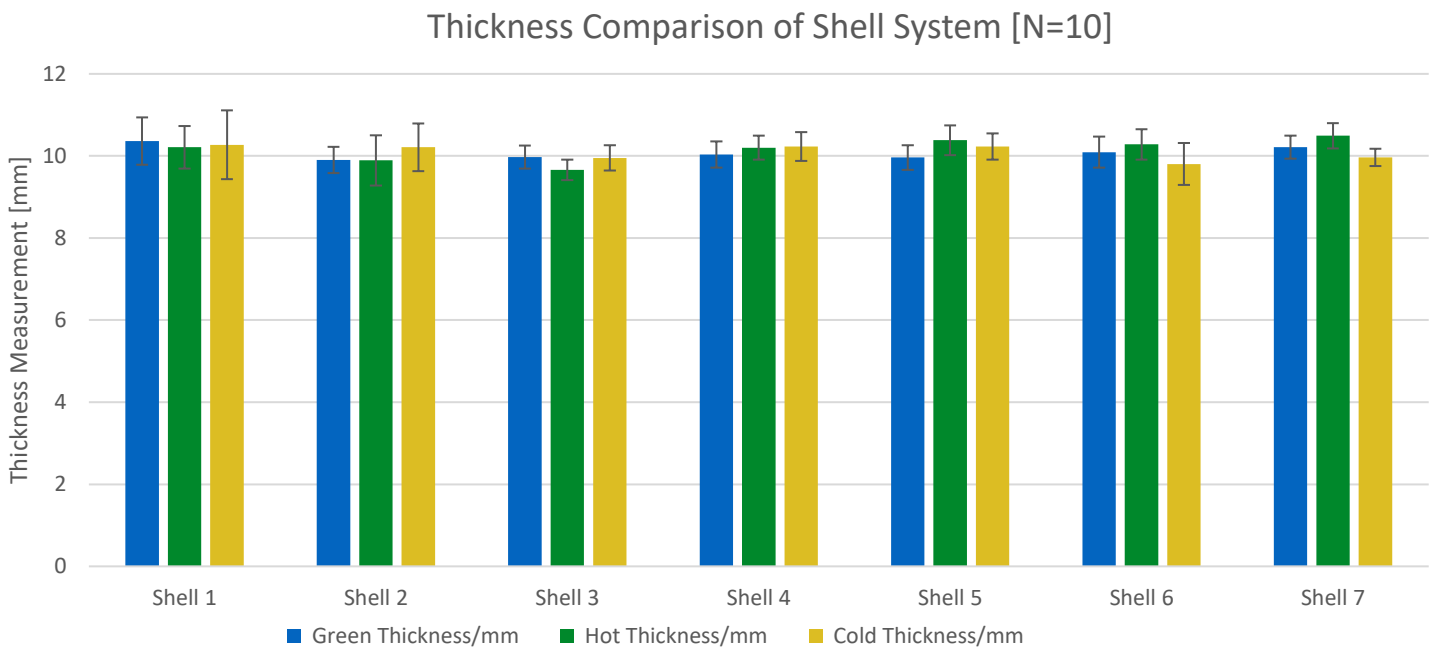
GAUGE R&R

- For R&D, samples are consistently made with new formulations, materials and other changes in a materials
- Typically always made with same “base” formulation
- Back up system change - No prime coat added. This ensures failure is present in the material analysis
- For prime coat changes, 3 layers added to ensure failure point is within the prime layer and the same Back up slurry is always used

FLEXURAL STRENGTH TESTING

GAUGE R&R

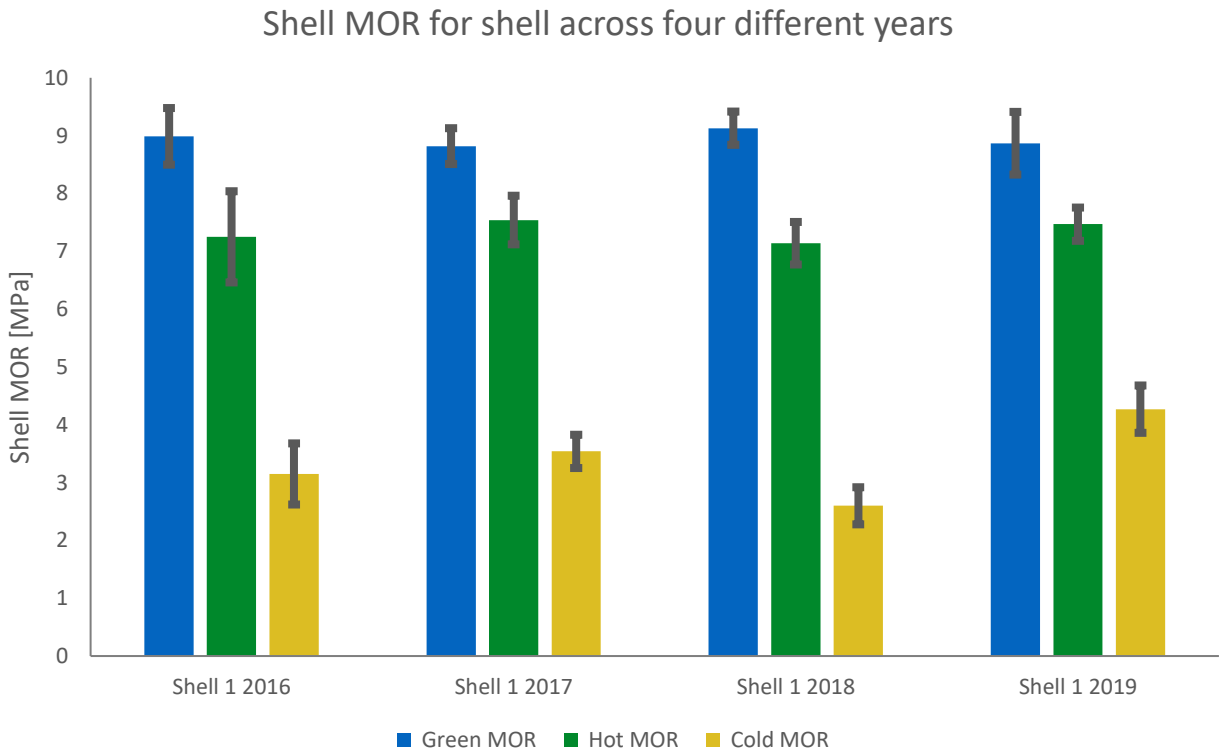
- MOR is a measure of strength per unit area
- Should be independent of thickness but this is rarely the case…
- Thickness & width consistency is key
- With a strict procedure for dipping, draining and stuccoing, changes to shell performance can be measured



FLEXURAL STRENGTH TESTING

GAUGE R&R

- To ensure consistency in testing, benchmark slurries are continuously dipped to the same recipe and specifications to ensure no drift in base data is experienced
- This acts as a go/no-go step annually to ensure shells are consistently built, tested and analysed the same
- ANOVA (ANalysis Of VAriance) shows that there is no statistical difference between these sets

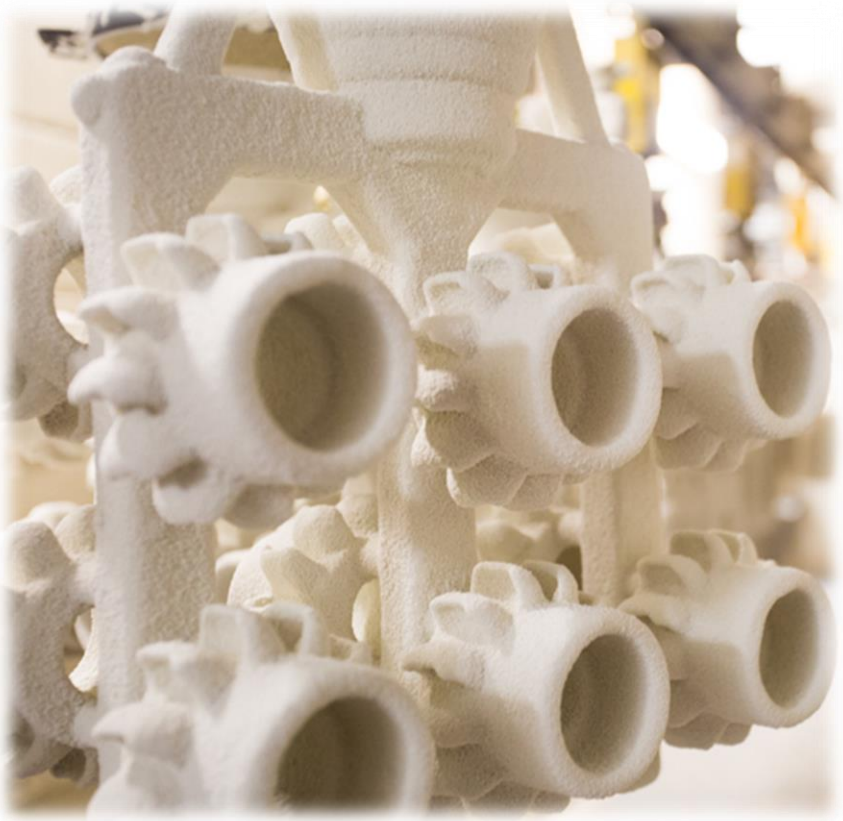


FACTORS AFFECTING SHELL STRENGTH

FACTORS AFFECTING STRENGTH

INTRODUCTION

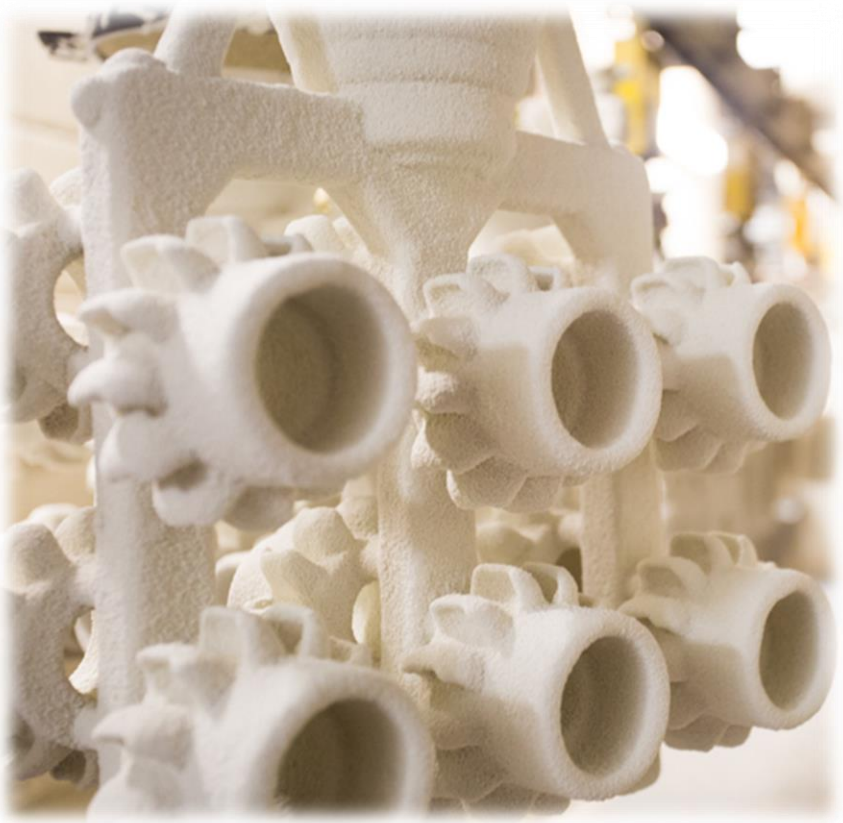
- There are numerous factors affecting shell strength
- “Drying effectiveness”
  - Time
  - Airflow
  - Humidity
  - Temperature
  - “Surface exposure”



FACTORS AFFECTING STRENGTH

INTRODUCTION

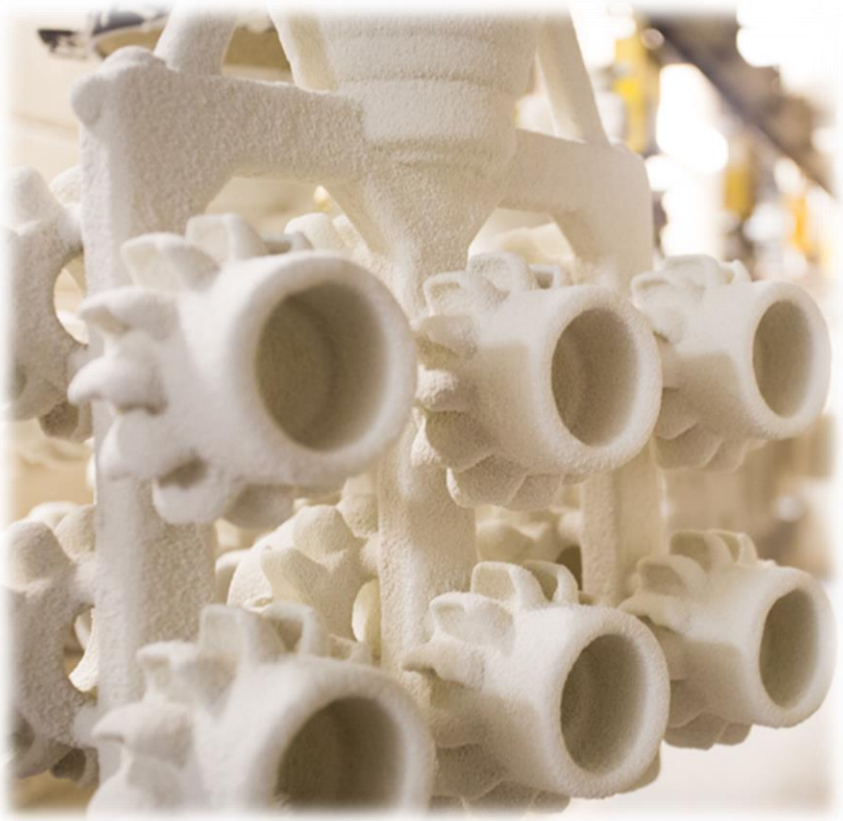
- Slurry properties
  - Material age – Binder and polymer
  - Viscosity
  - Colloidal Silica type, size, concentration
  - Polymer type and concentration
  - Bubbles
  - Any other additives like fibres etc.
  - Refractory type & shape



FACTORS AFFECTING STRENGTH

INTRODUCTION

- Build properties
  - Dip sequence - Soak time etc.
  - Edge and corner thickness
  - Draining characteristics
  - Stuccoing method
  - Stucco PSD & dust



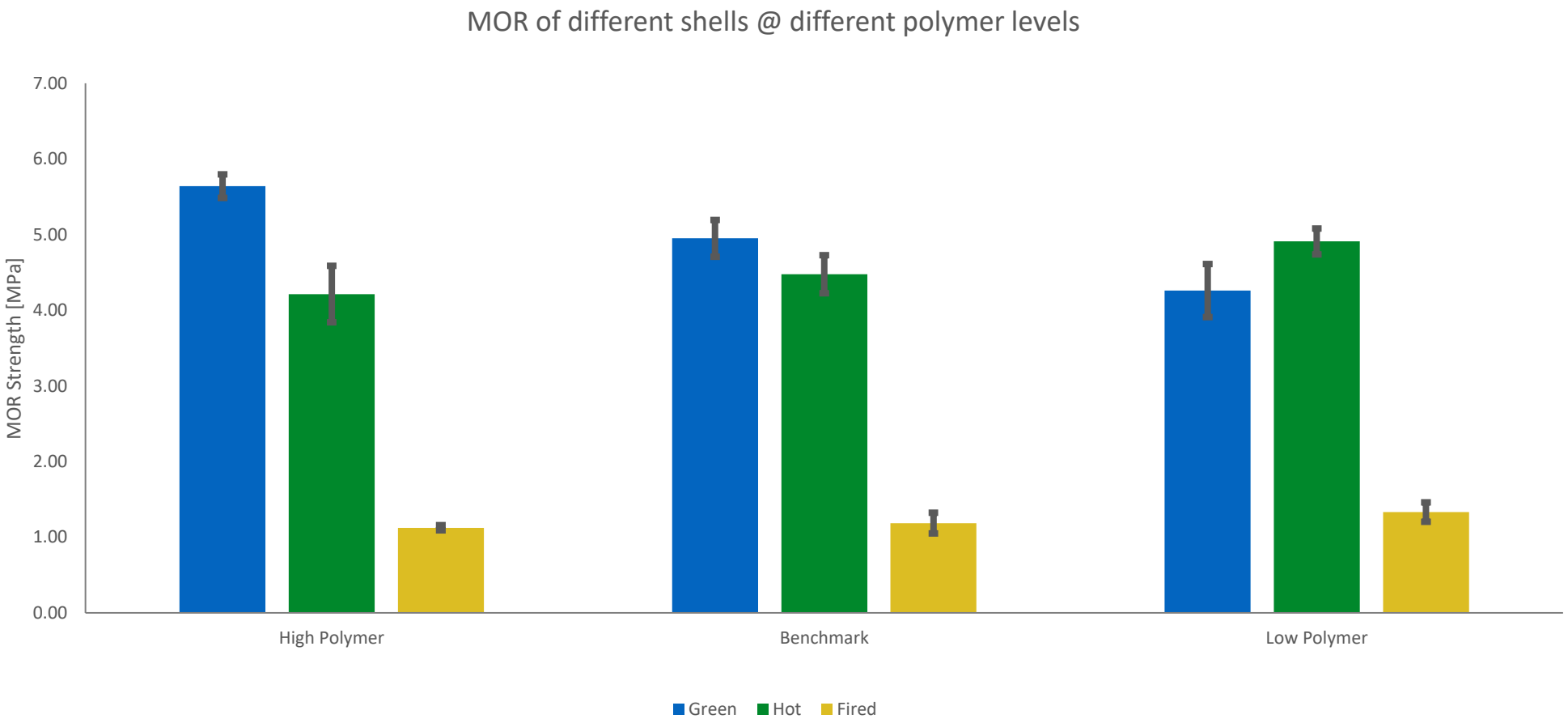
FACTORS AFFECTING STRENGTH

POLYMER LEVELS

- Slurry was made with 3 different levels of polymer level
- Polymer - Quickset
- Flour – Fused Silica RP-2
- Stucco – Fused Silica RG-2
- 2 Hour drying
- Polymer solids were varied from 5%, 7.5% & 10%

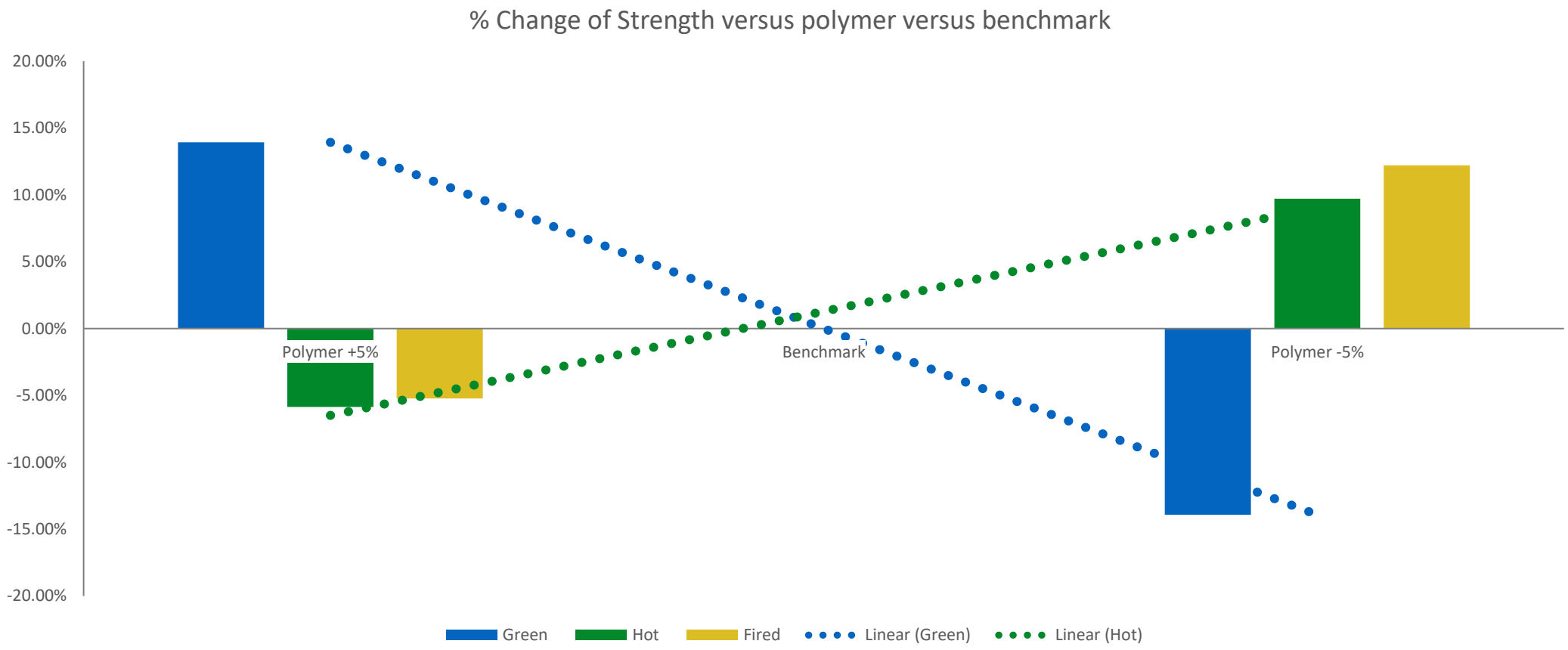
CONCLUSIONS

OVERVIEW



CONCLUSIONS

OVERVIEW



MATERIAL DRYING TECHNOLOGY

DRYING ANALYSIS

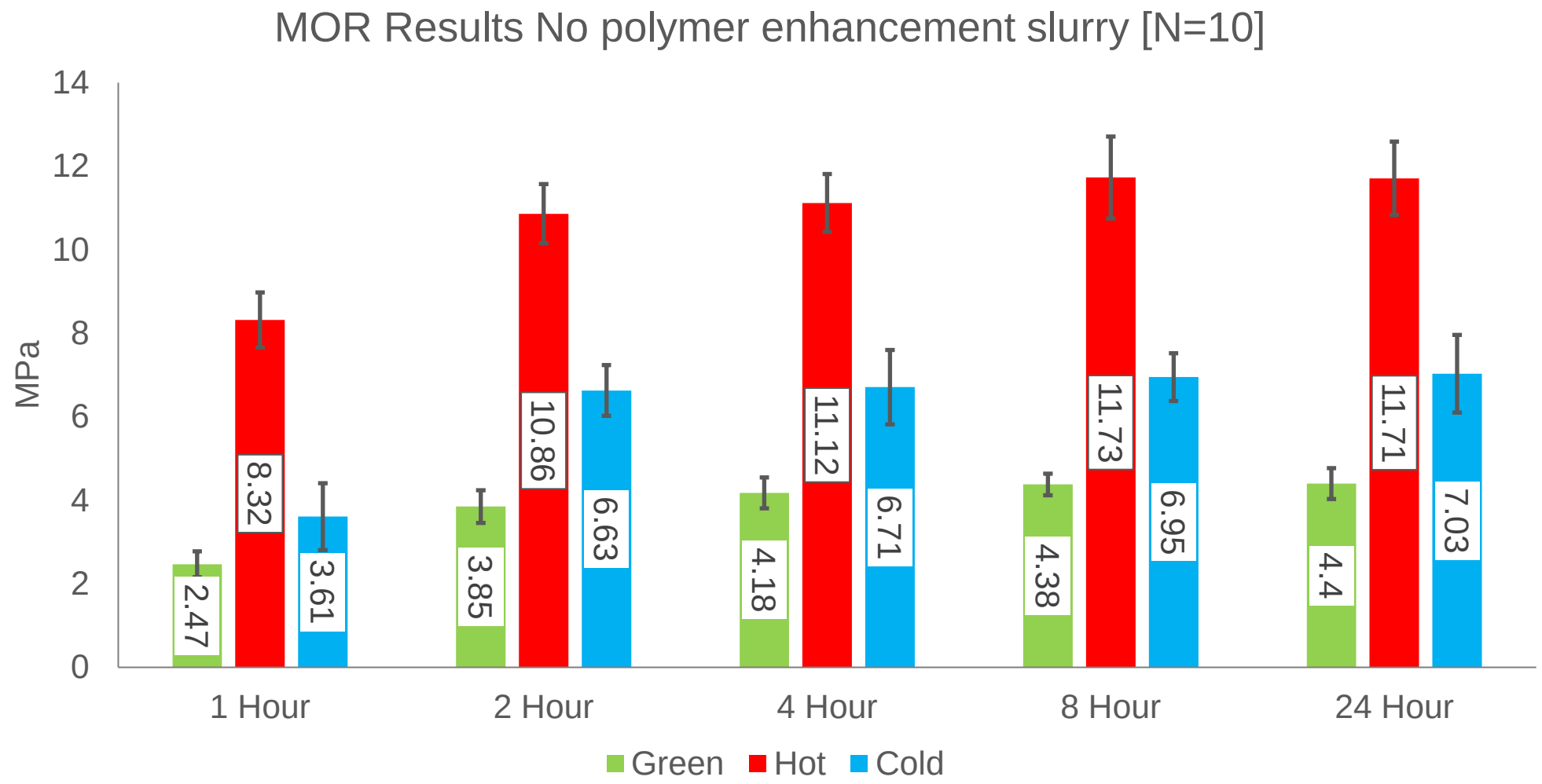
- Drying analysis for shells at 1,2,4,8 and 24 hours
- Over 630 Samples tested
- Assess the drying capability of the system
- No prime layer
- 8 layers and seal

Temperature	Humidity [% RH]	Airflow [m/s]
20-25	45	0.6

Material	No polymer	Polymer Enhanced	QuikSet
Remasol® SP30	36.0%	31.5%	26.2%
AdBond® Ultra™ Polymer	-	4.5%	-
AdBond® QuikSet™ Polymer	-	-	5.3%
Burst 100	0.2%	0.2%	0.2%
Victawet 12	0.9%	0.9%	0.5%
Fused Silica 200 Mesh	62.9%	62.9%	67.8%

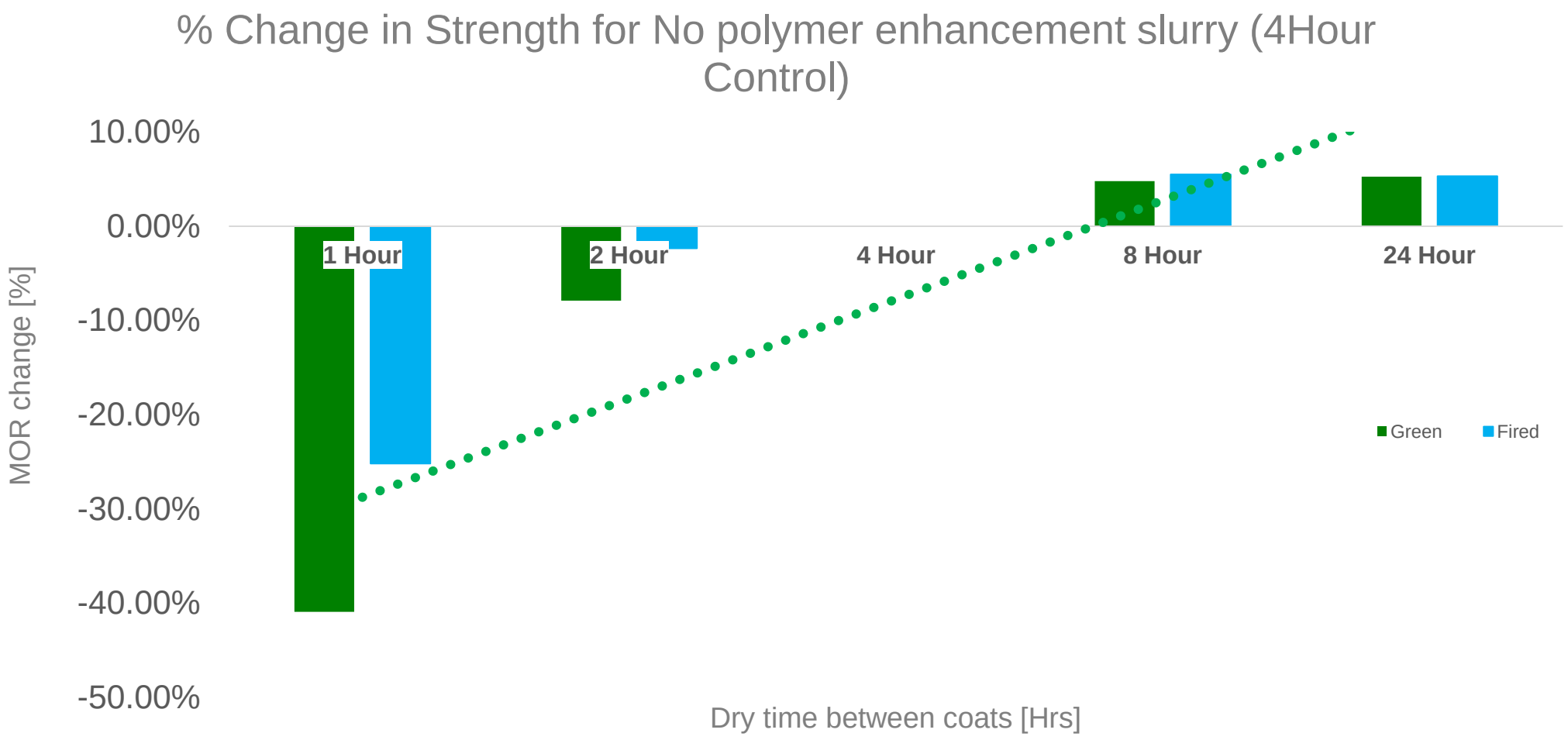
MATERIAL DRYING TECHNOLOGY

DRYING ANALYSIS – NO POLYMER



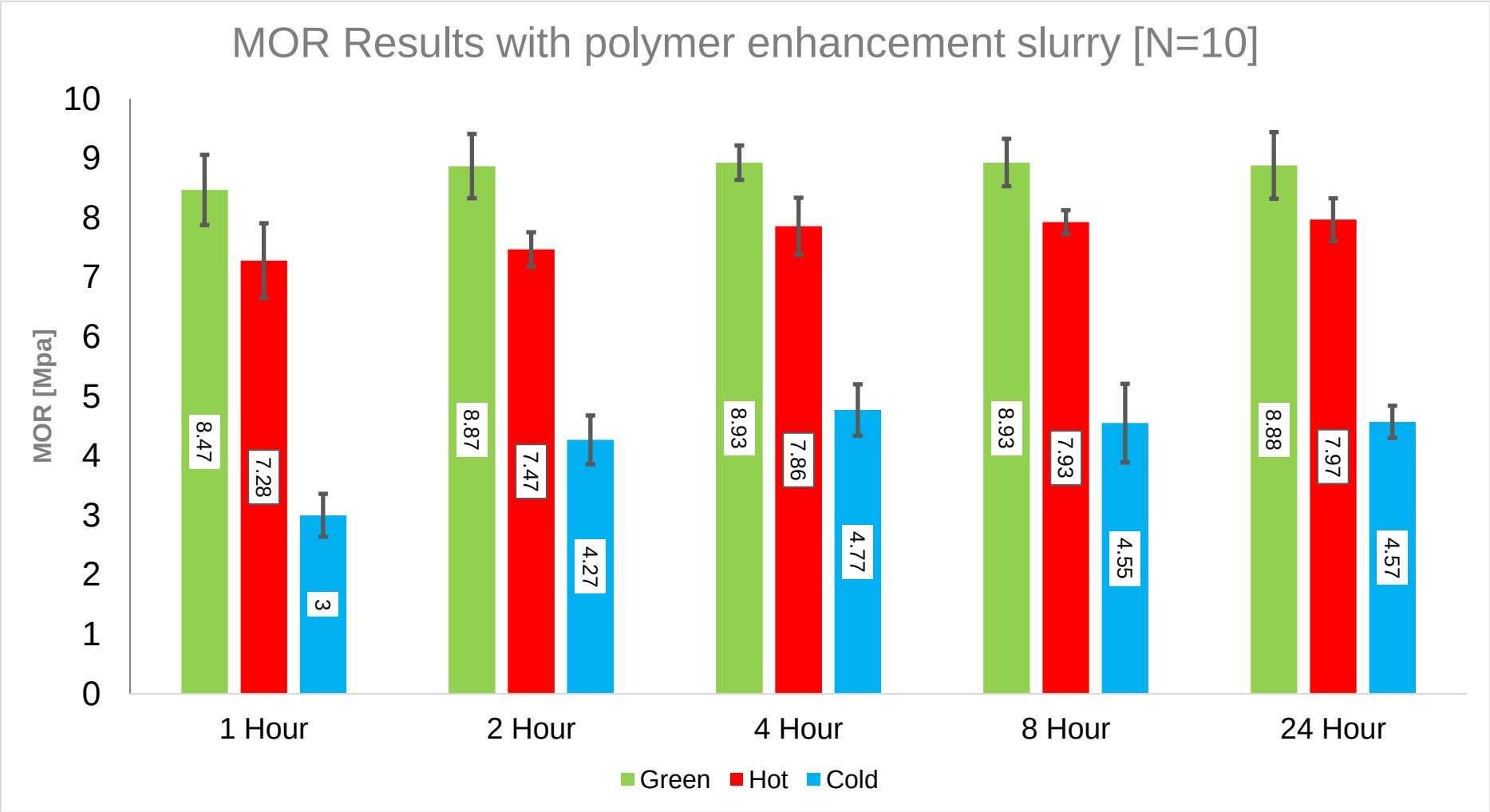
MATERIAL DRYING TECHNOLOGY

DRYING ANALYSIS – VERSUS 4 HOUR BENCHMARK



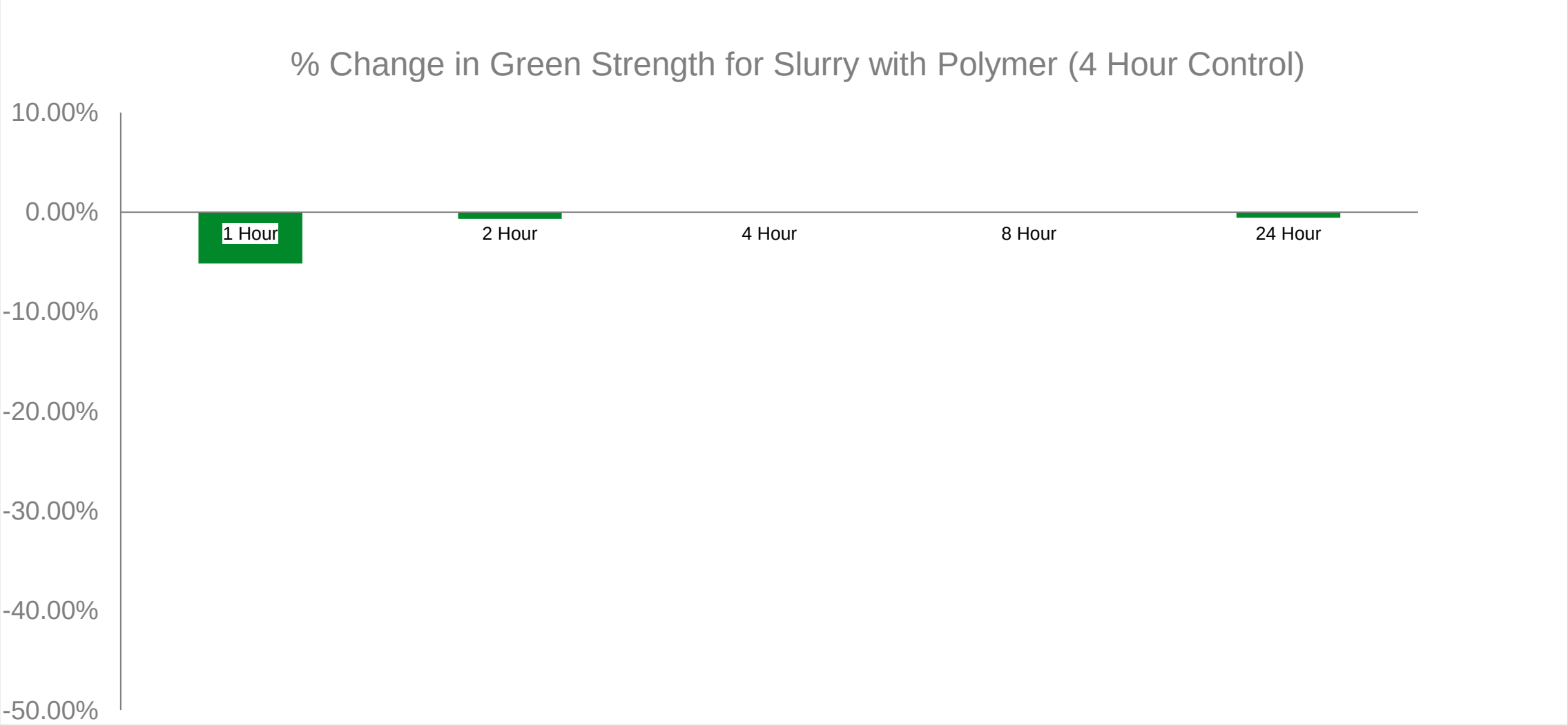
MATERIAL DRYING TECHNOLOGY

DRYING ANALYSIS



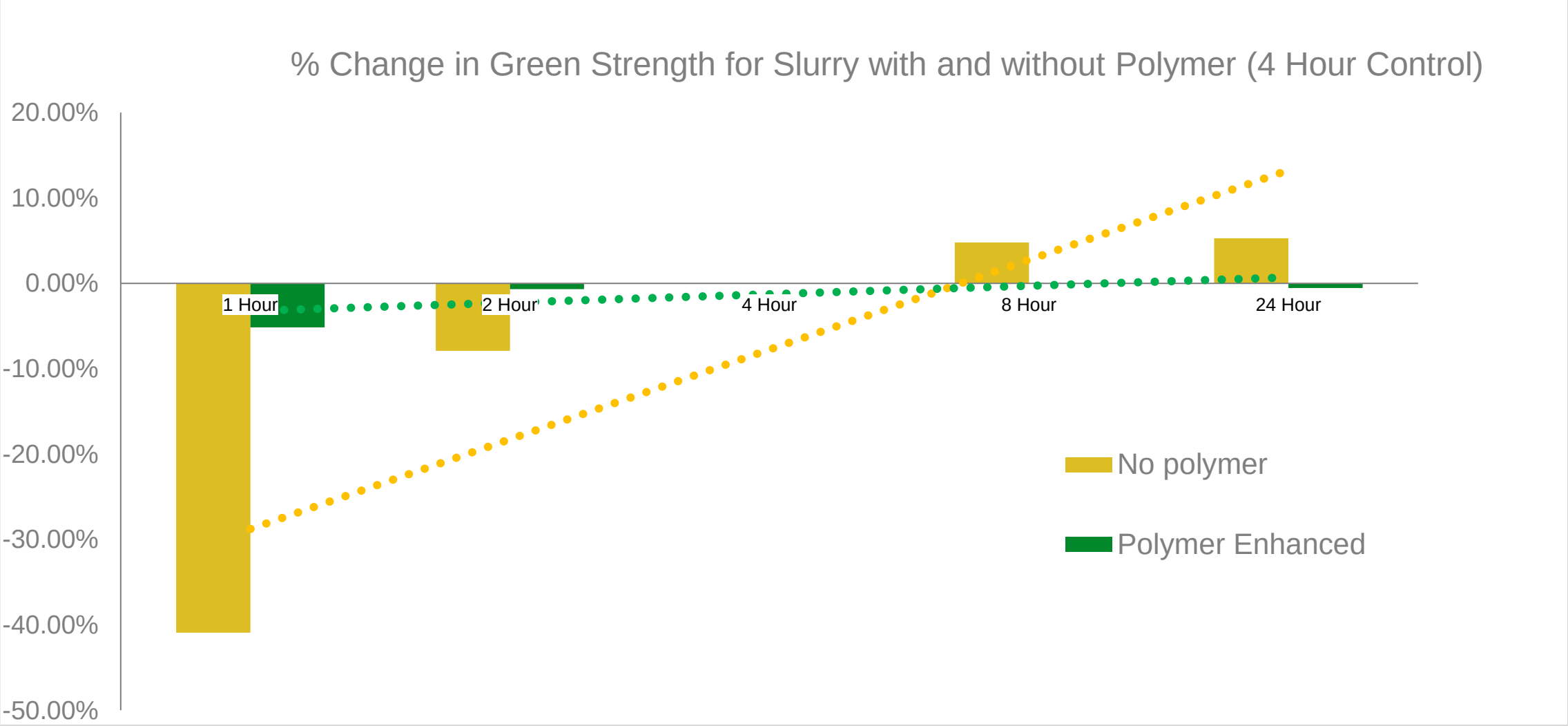
MATERIAL DRYING TECHNOLOGY

DRYING ANALYSIS



MATERIAL DRYING TECHNOLOGY

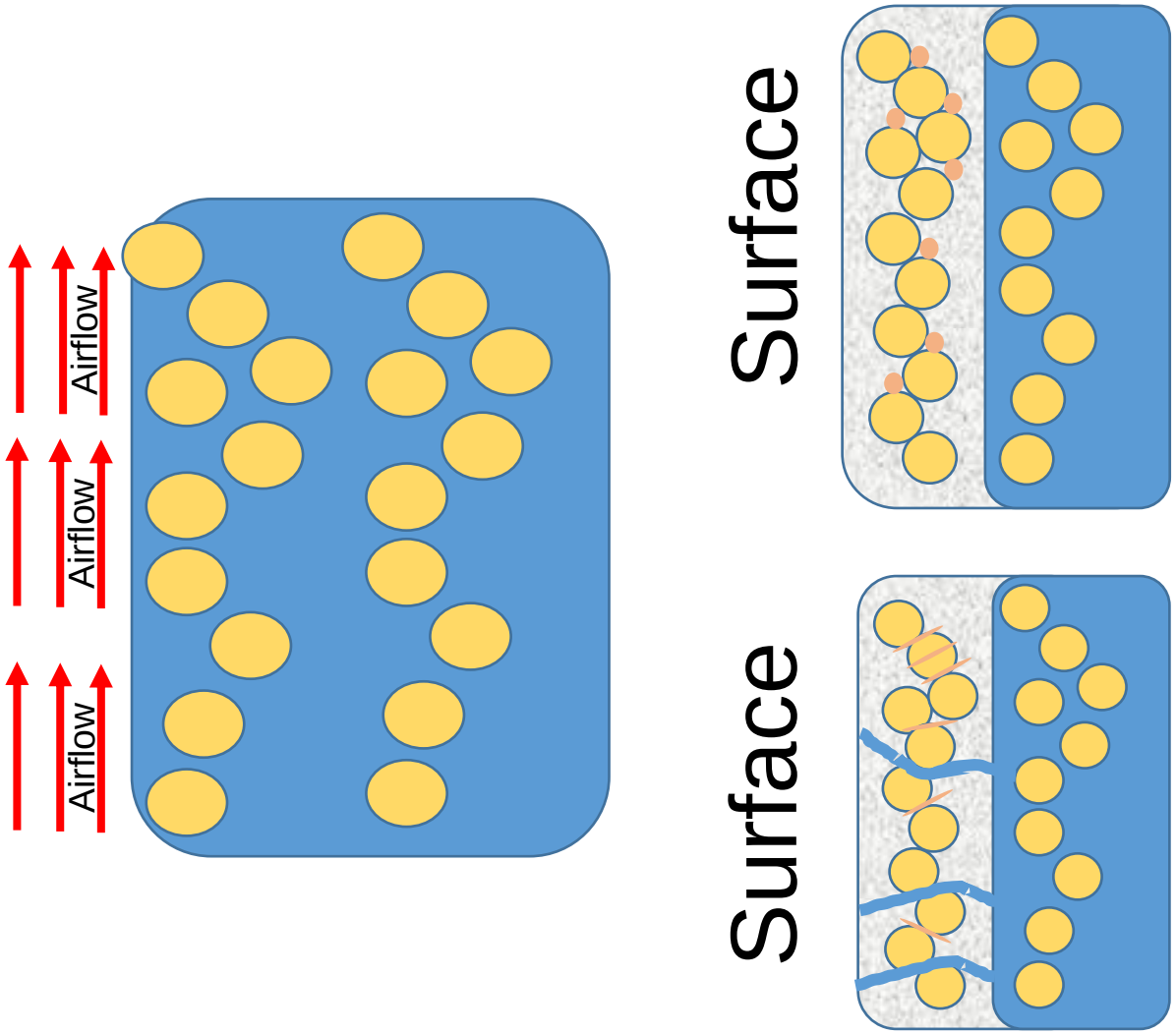
DRYING ANALYSIS



MATERIAL DRYING TECHNOLOGY

OVERVIEW

- Water gets trapped within the shell matrix during drying. This inhibits evaporation and drying
- QuikSet's novel formulation can ensure the water can evaporate while the slurry has gelled
- This also has the ability to increase strength



MATERIAL DRYING TECHNOLOGY

OVERVIEW

- However, the drying improvements have remained relatively static with no slurry consumable to improve drying
- An innovative AdBond® QuikSet™ polymer has been introduced which improves the drying of shells dramatically!
- Shells can be dipped with as little as 30 minute drying time

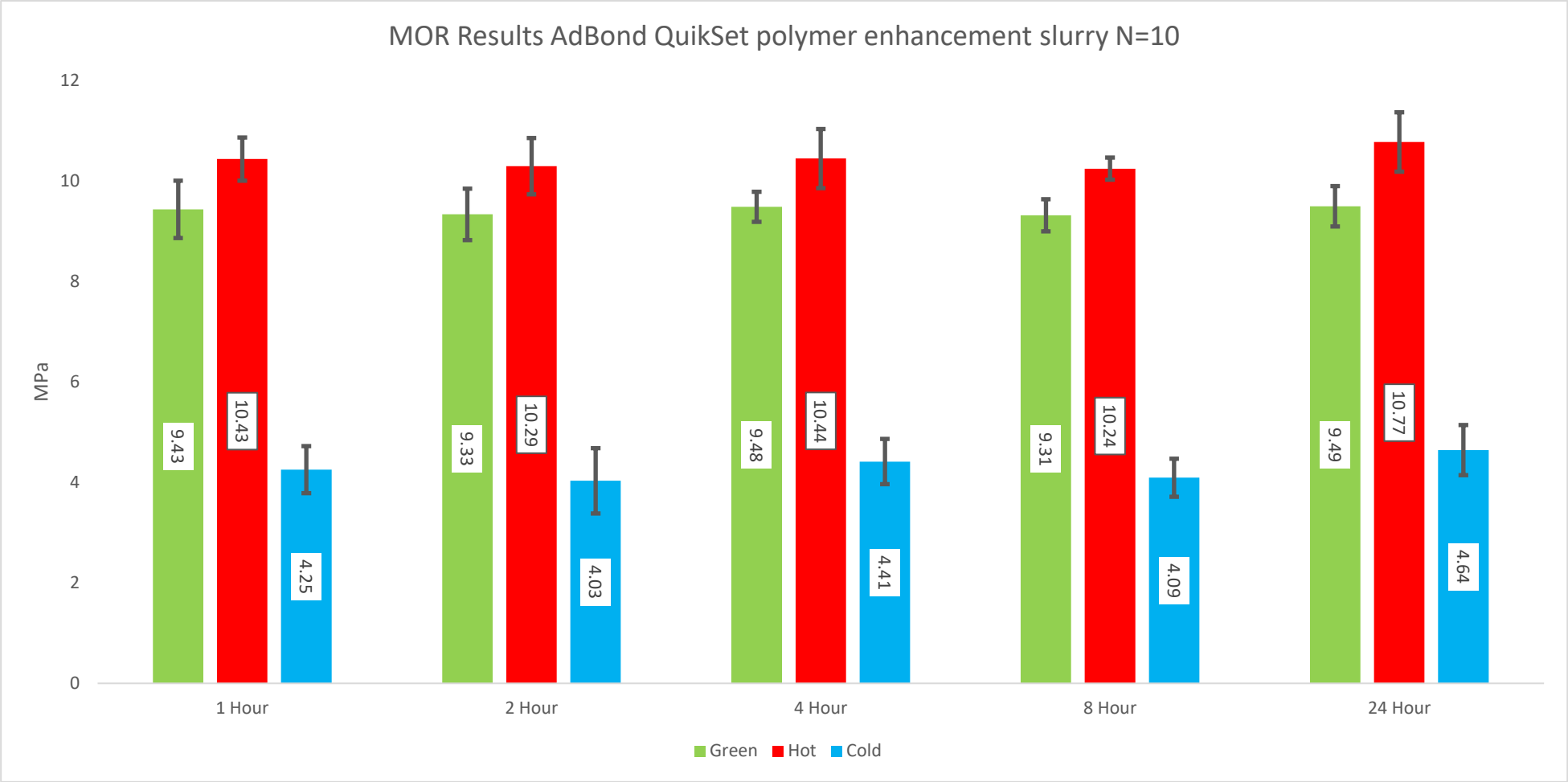
MATERIAL DRYING TECHNOLOGY

OBJECTIVES

1. Strength versus other shell systems
2. Strength development per drying time
3. Strength at shorter dry times

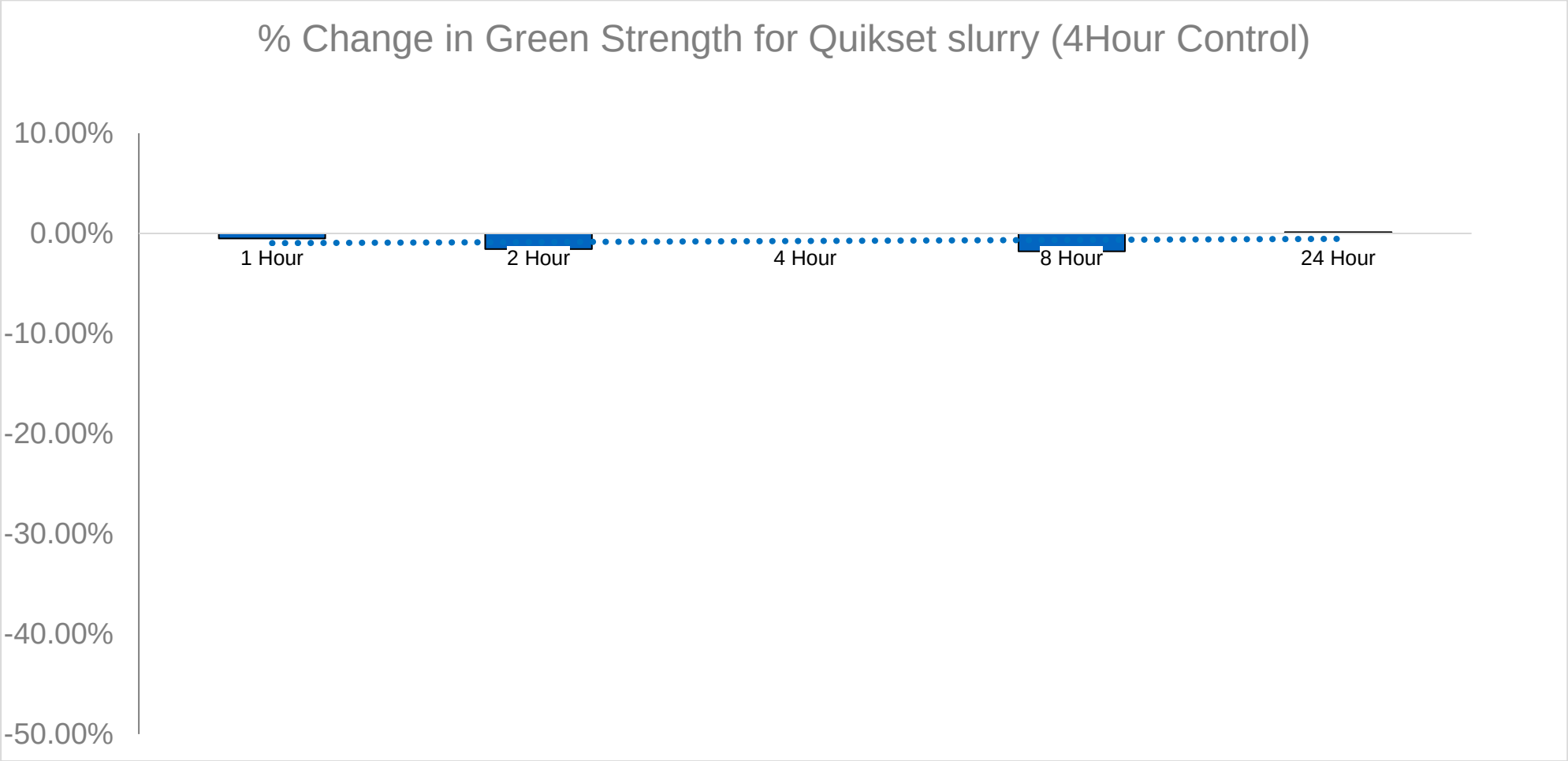
MATERIAL DRYING TECHNOLOGY

DRYING ANALYSIS - BENCHMARK



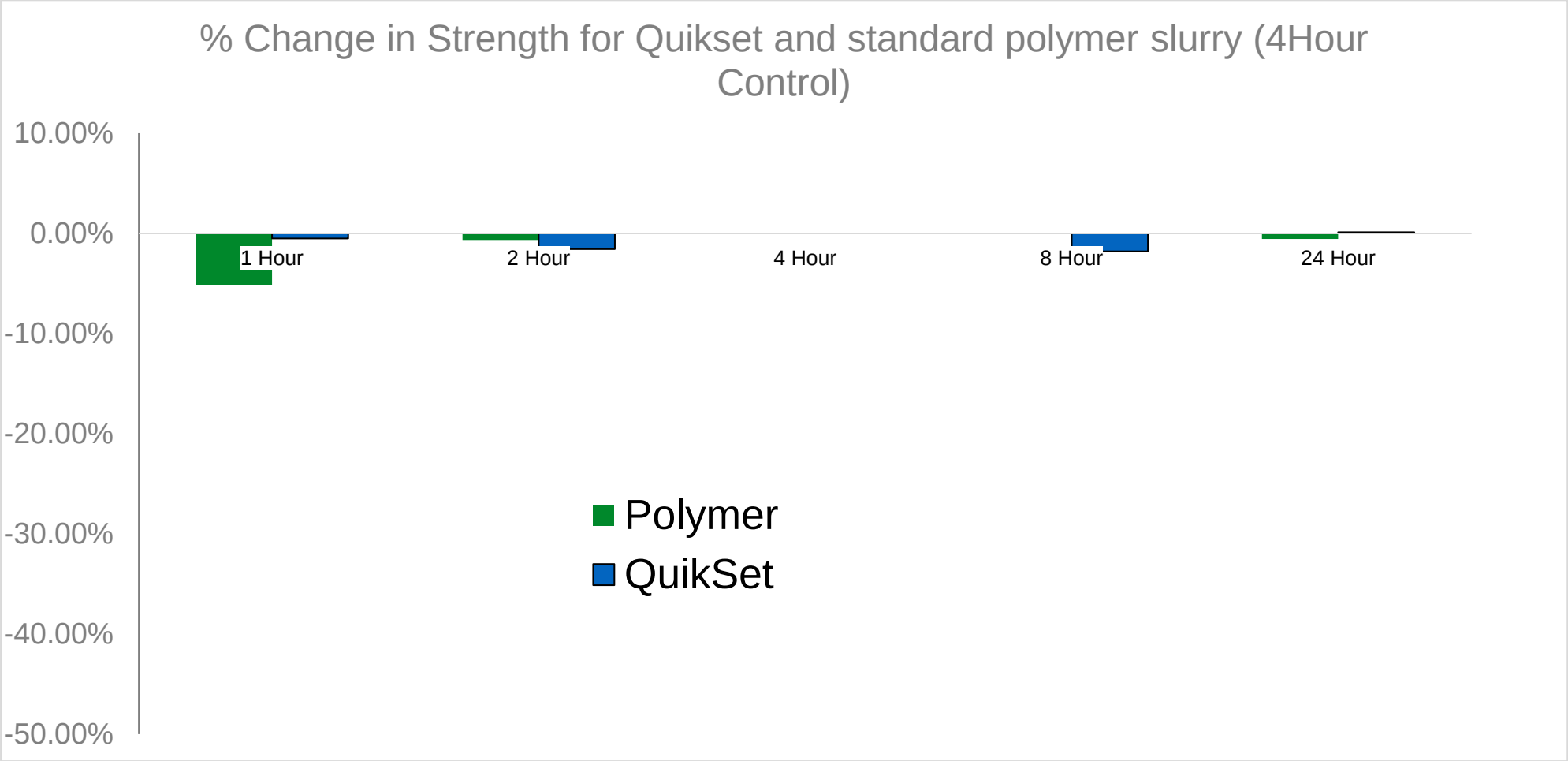
MATERIAL DRYING TECHNOLOGY

DRYING ANALYSIS – STRENGTH DEVELOPMENT



MATERIAL DRYING TECHNOLOGY

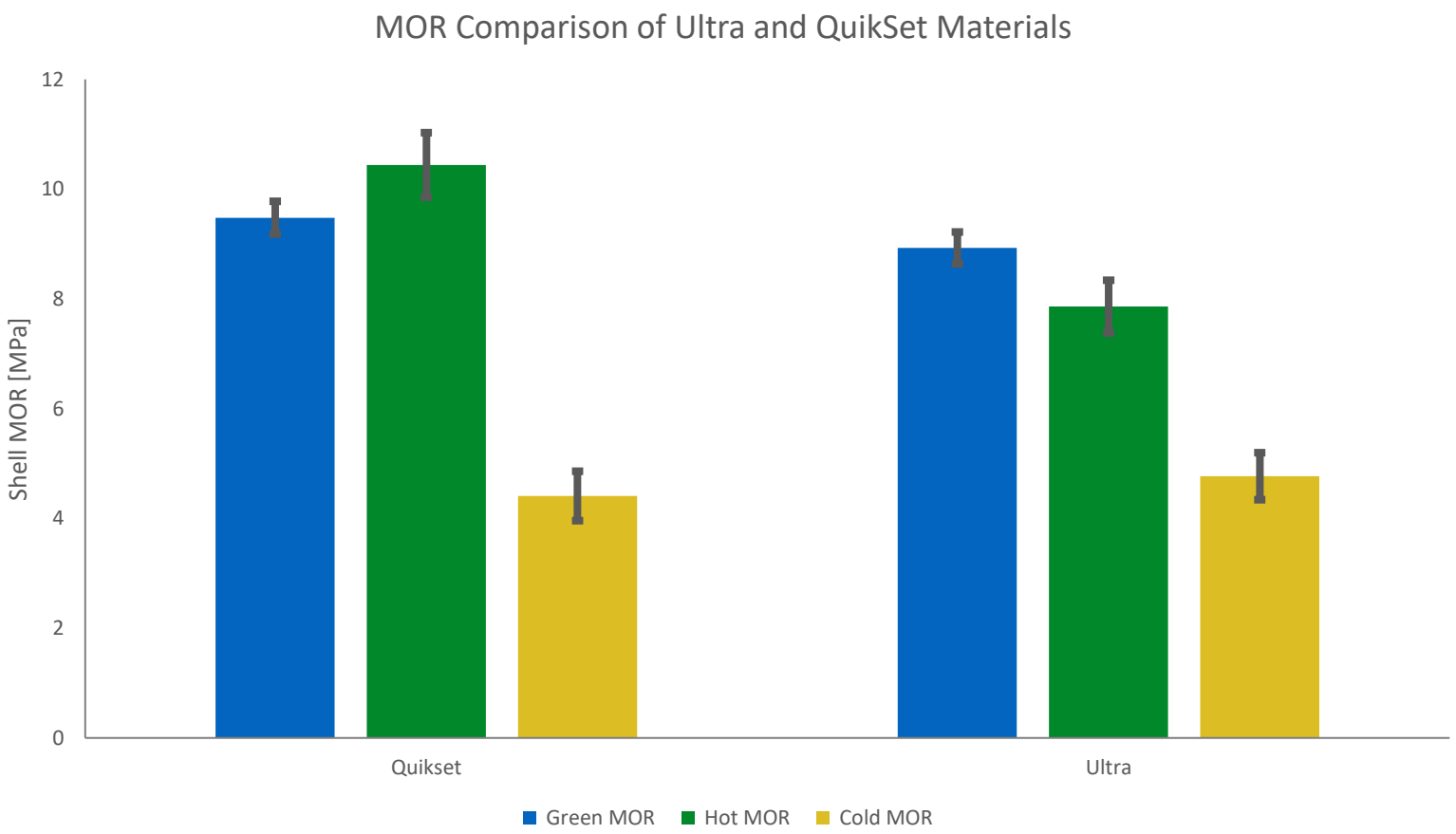
DRYING ANALYSIS – STRENGTH DEVELOPMENT



MATERIAL DRYING TECHNOLOGY

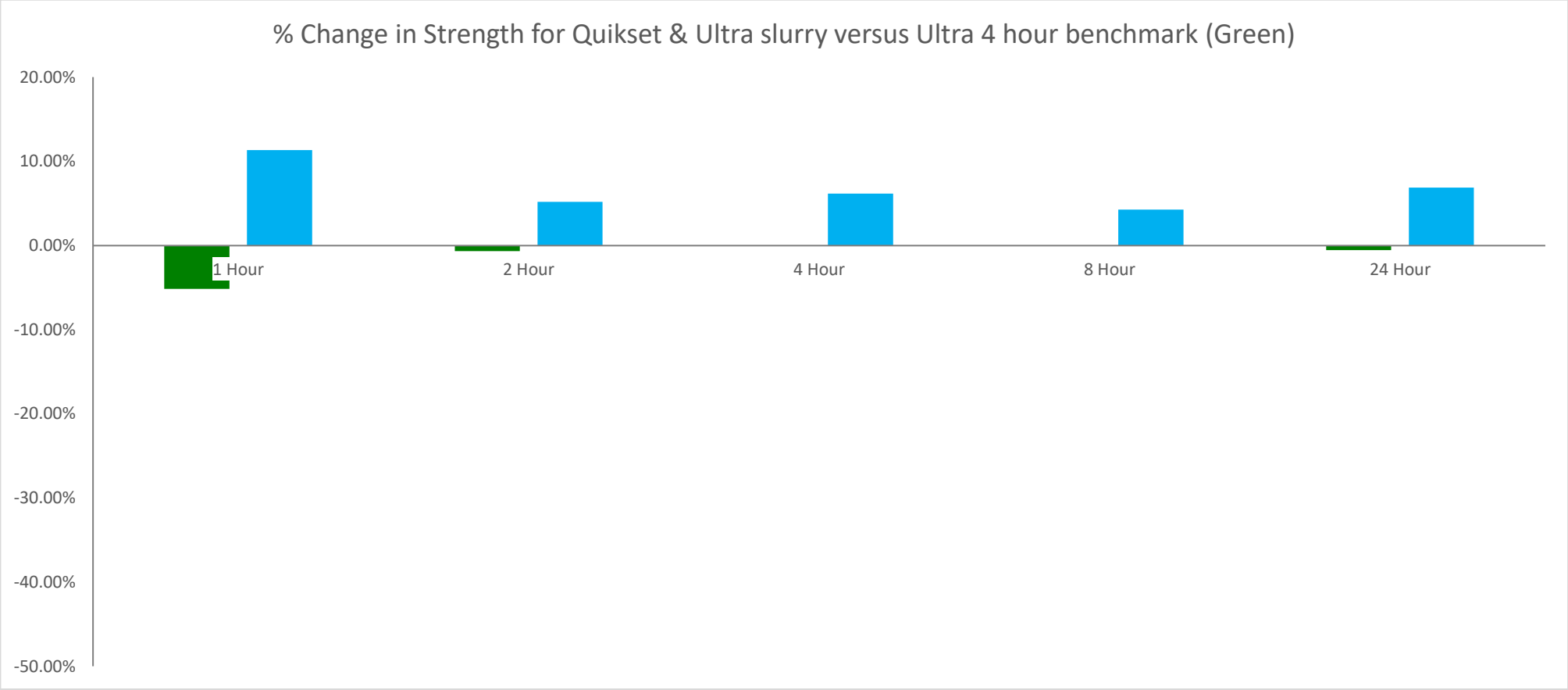
DRYING ANALYSIS – STRENGTH BASELINE

- But the strength of both systems are different
- QuikSet exhibits a higher green and MOR strength
- Therefore, lets also look at strength development of QuikSet versus Ultra benchmark…



MATERIAL DRYING TECHNOLOGY

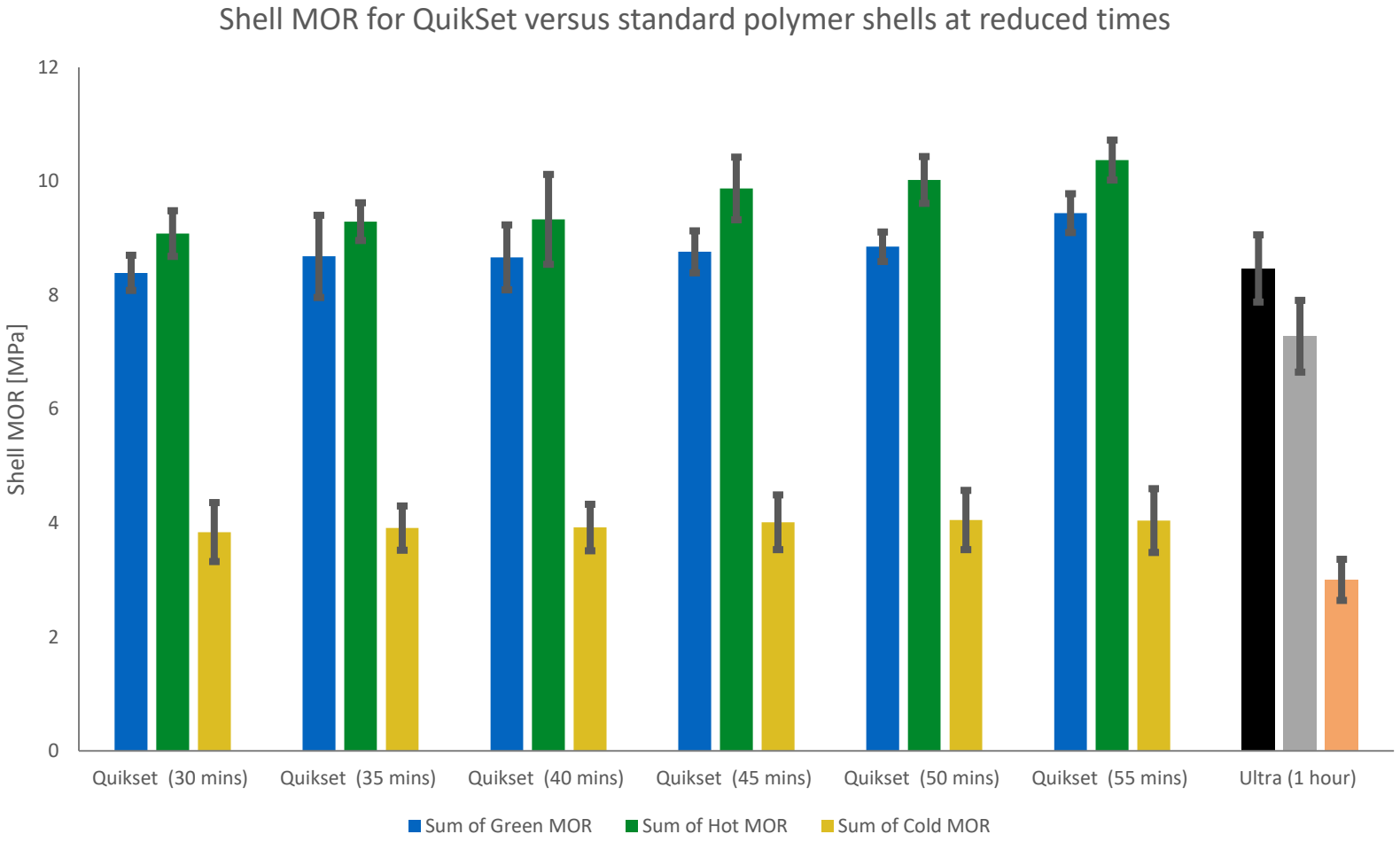
DRYING ANALYSIS – STRENGTH WITH A POLYMER BASELINE



MATERIAL DRYING TECHNOLOGY

DRYING ANALYSIS – STRENGTH BASELINE

- These results show a really promising trait for the QuikSet Polymer
- Therefore it was decided to see how strength development occurred at less than 1 hour dry times



CONCLUSIONS

OVERVIEW

- It is important to understand and reduce the error of MOR testing within the testing setup
- There exists a strong link between the error within the test and the interactions of the operator in the measurement of the final dimensions of the sample
- There exists many different variables which affect shell strength

CONCLUSIONS

OVERVIEW

- Polymer levels within the material can affect the final properties of both green and fired strengths
- MOR testing versus drying time can give a good insight into the performance of materials
- The presence of polymer generate strength within the shells quicker than without polymer
- AdBond® QuikSet™ can be shown to generate strength far quicker than polymer benchmarks and can dry shells to a stronger level in less than 1 hour

QUESTIONS?


LEADING
EDGE TECHNOLOGY
REMET
PROTECTING THE
ENVIRONMENT